Calibration and performance of the ATLAS Tile Calorimeter during the LHC Run 2

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Abstract. The Tile Calorimeter (TileCal) is the central section of the hadronic calorimeter of the ATLAS experiment and provides important information for reconstruction of hadrons, jets, hadronic decays of tau leptons and missing transverse energy. It also assists in muon identification. This sampling calorimeter uses steel plates as absorber and scintillating tiles as active medium. The light produced by the passage of charged particles through the latter is transmitted by wavelength shifting fibres to photomultiplier tubes (PMTs). The readout is segmented into about 5000 cells (longitudinally and transversally), each of them being read out by two PMTs in parallel. Among the TileCal calibration systems we mention a Cs radioactive source that illuminates the scintillating tiles, a laser light system to test the PMT response, and a charge injection system (CIS) for the front-end electronics. These, together with data collected during proton-proton collisions, provide extensive monitoring of the instrument and a means for equalizing the calorimeter cell response at each stage of the signal propagation. The performance of the TileCal has been established with cosmic ray muons and a large sample of proton-proton collisions. Response to high-momentum isolated muons is used to study the energy response, isolated hadrons are used as a probe for the hadronic response. The time resolution of the cells response is studied with multi-jet events. A description of the different TileCal calibration systems and results obtained during the LHC Run 2 are presented together with those from pile-up noise and response uniformity studies. The experimental results are compared with the simulated ones.

1. Introduction

In high energy physics experiments, hadronic calorimeters are crucial in identification of hadronic jets and measurement of their energy and direction. They also provide information for triggers and participate in the measurement of the missing transverse momentum carried by non-interacting particles.

The barrel portion of the hadronic calorimeter employed by ATLAS [1], one of the two general-purpose experiments at the Large Hadron Collider (LHC) [2], is called the Tile Calorimeter (TileCal) [3]. Two cylinders limit its volume. The inner (outer) has a radius equal to 2.28 (4.23) m. The central barrel covers pseudorapidities\(^1\) up to \(|\eta| < 1.0\). The extended barrel

\(^1\) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, \(\phi\)) are used in the transverse plane, \(\phi\) being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle \(\theta\) as \(\eta = -\ln \tan(\theta/2)\).

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part provides a coverage of the region $0.8 < |\eta| < 1.7$. TileCal is divided along the $z$-axis (the beams axis) into four partitions, two long barrels (LBA and LBC) and two extended barrels (EBA and EBC), as seen in Figure 1a. It is a sampling calorimeter that uses iron absorber and scintillating plastic tiles as active material. When a charged particle passes through the scintillating tiles, ultraviolet light is emitted and collected at the edges of each tile. The light is then transported via wavelength shifting fibers to Photomultiplier Tubes (PMT) located in a steel girder at the back of each barrel module. The scintillator tiles are grouped together into cells. The alternating layers of scintillating plastic and iron together with wavelength shifting fibers and PMTs are shown in Figure 1b.

![Figure 1: Cut-away view of the ATLAS calorimeter system (a). Tile Calorimeter consists of two barrel and two extended barrel sections. An illustration of the mechanical assembly and optical read-out of a single Tile Calorimeter module (b). A total of 256 such modules make up the full Tile Calorimeter. Source tubes are used to circulate a $^{137}$Cs radioactive source contained in a capsule for calibration purposes [1].](image1)

![Figure 2: Segmentation in depth and $\eta$ of the Tile Calorimeter modules in the central and extended barrels. The central barrel has a coverage up to $|\eta| < 1.0$. The extended barrel covers the region $0.8 < |\eta| < 1.7$ [1].](image2)

Each TileCal partition consists of 64 modules of equal azimuthal width $\Delta \phi = 0.1$. The cell layout of long and extended barrel modules is shown in Figure 2 for $z > 0$. A mirroring of those
in the other direction in \( z \) defines the four partitions of the calorimeter. TileCal is subdivided into three separate longitudinal sampling layers to sample the shower at three different depths. The longitudinal sampling layers, denoted A, BC and D have a granularity \( \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \) in the two innermost layers and \( \Delta \eta \times \Delta \phi = 0.2 \times 0.1 \) in the outermost one.

Most Tile Calorimeter cells are read out by two PMTs, accounting for 9856 read-out channels in total corresponding to 5182 cells. The PMT output is a shaped current pulse read out in two gains, high and low. The ratio between the high gain and the low gain amplification is 64.

2. Calibration Systems
At each level of the TileCal signal reconstruction, there is a dedicated calibration system to monitor the behavior of the different detector components. Figure 3 shows the different calibration systems along with the paths followed by the signals from different sources. The reconstructed energy of each TileCal channel, \( E \) [GeV], is derived from the raw response, \( A \) [ADC], as follows:

\[
E \text{ [GeV]} = A \text{ [ADC]} \cdot C_{\text{pC} \rightarrow \text{GeV}} \cdot C_{\text{Cs}} \cdot C_{\text{Las}} \cdot C_{\text{ADC} \rightarrow \text{pC}}
\]

(1)

The different \( C \) factors are calibration constants explained in the next paragraphs.

![Figure 3: Flow diagram of the readout signal path of the different TileCal calibration tools. The physics signal is denoted by the thick solid line and the path taken by each of the calibration systems is shown with dashed lines [4].](image)

The factors can evolve in time because of variations in PMT high-voltage, stress induced on the PMTs by high light flux or aging of scintillators due to radiation damage. The calibration systems are used to monitor the stability of these factors and provide corrections for each channel. The electromagnetic scale calibration constant \( C_{\text{pC} \rightarrow \text{GeV}} \), converting the calorimeter signals measured as electric charge in pC to the energy deposited by measured electrons which produced the signals, was fixed during dedicated test beam campaigns [5]. The remaining calibration constants are provided by individual systems during the ATLAS operations:

- a moveable Cesium radioactive \( \gamma \)-source to calibrate the optic components and the PMTs,
- laser system to monitor the PMTs and the electronic components,
- calibrations of digital gains and lineairties with the charge injection system (CIS),
- monitoring of beam conditions ("Particles" in Figure 3) and TileCal optics with the integrator system minimum bias (MB).

2.1. Cesium Calibration
The Cesium calibration system employs three radioactive sources that can be moved using a hydraulic system to scan all TileCal cells. Each \( ^{137}\text{Cs} \) \( \gamma \)-source emits 0.662 MeV photons to
illuminates the scintillators. The signal is collected through a special readout that integrates over 10 ms the analog PMT signals. This system is used to calibrate the optical components of the calorimeter as well as the PMTs. The channel response to the energy deposits is used to equalize the response of all the cells and maintain global response of the calorimeter at the electromagnetic scale. A deviation of measured Cesium signals from expected values, corrected for the Cesium decay curve, is interpreted as cell light collection and PMT gain variations and translated into calibration constants, $C_{Cs}$. Before Run 2 of the LHC, a new water storage system, lower pressure in the hydraulics, and more precise water level metering during the scans were installed to improve stability and safety of the operation. The deviation of $C_{Cs}$ calibration constant from 1 (in %) over the period between 2009 and 2018 is shown in Figure 4a. The precision of the system is at the order of 0.3%. Cesium calibration scans were spaced by one to three months up to 2015. During 2016 the frequency was reduced, and scans were taken only at the beginning and end of the proton-proton collisions period. The frequency of the Cesium calibration can be insufficient to track fast drifts of the PMT responses. The Laser system is used between two Cesium scans to correct for this.

![Figure 4a](image1.png)
![Figure 4b](image2.png)

Figure 4: The variation in TileCal response over a period of 8 years measured in Cesium calibration runs (a). The points represent the average values of the responses of the cells in a given layer. All cells were equalized at the beginning of Run 1 in June 2009 and at the beginning of Run 2 in February 2015. Detector-wide CIS calibration constant averages of all the low gain channels for each CIS calibration run during proton-proton data taking period in 2017 plotted as black circles (b). The CIS constants from a typical channel are additionally plotted as blue triangles for comparison. The RMS value in the figure (0.03%) corresponds to the channel fluctuations present in calibrations. In addition, there is a 0.7% systematic uncertainty present in individual calibrations, represented by the blue error bars [6].

2.2. Laser Calibration

The gain stability of each PMT is measured using a Laser calibration system [7] that sends a controlled amount of light onto the photocathode of each PMT in the absence of collisions. Deviations in a channel’s response with respect to its nominal value (at the time of the latest Cesium calibration) is then translated into a calibration constant: $C_{Las}$. The Laser calibration runs are usually taken twice a week to monitor the individual PMT gain variations between Cesium scans. During the LHC Long Shutdown from 2012 to 2015, a new Laser II system [8] was developed to correct shortcomings in electronics and light monitoring of the first system,
which in turn resulted in an improved resolution. The typical precision on the gain variation is better than 0.5% per channel. The new system has been used since the beginning of Run 2 in 2015 to monitor deviations in channel gain. Figure 5 shows the mean gain variation per cell type observed after five months of proton-proton data taking in 2016. Due to photocathode degradation the observed down-drift mostly affects cells at the inner radius, which are the cells with higher current. Laser pulses are also sent during empty bunch crossings of the LHC, with a frequency of 4 Hz during Run 2. Using this events, the evolution in time of the time calibration is monitored.

![Figure 5: The mean gain variation (%) in the TileCal cells, as a function of $|\eta|$ and radius observed after five months of proton-proton data taking in 2016. The gain in each PMT is measured using a Laser calibration system [6].](image)

### 2.3. Charge Injection Calibration

A Charge Injection System is used to monitor the electronics and extract the conversions factor from ADC counts to pC, $C_{\text{ADC}\rightarrow \text{pC}}$. The CIS simulates physics signals in TileCal channels by injecting a known charge into the ADC and measuring the electronic response. The corresponding calibration runs are taken from daily to weekly. The overall stability of the calibration factor is at the level of 0.03% as shown in Figure 4b and usually less than 1% of the channels exhibit large fluctuations.

### 2.4. Minimum Bias System

LHC proton-proton collisions (“Particles” in Figure 3) are dominated by soft parton interactions, so-called Minimum Bias (MB) events. The PMT currents caused by MB events are integrated using the integrator system over a time window of 10 ms. Data produced by the integrator are continuously recorded during proton-proton collisions. The response of the TileCal to signals induced by the MB interactions scale with instantaneous luminosity [9]. Therefore, this response is used to measure the luminosity delivered to ATLAS. It is used also to monitor the stability of

![Figure 4: Example of a Charge Injection System run showing the response of different TileCal channels to a known charge injection.](image)
the full optical chain providing an independent cross-check of the Cesium calibration. Figure 6a shows the variations in the response of the most highly irradiated regular cells observed by MB and Laser systems during 2017 data taking period. The difference between Minimum Bias and Laser is interpreted as an effect of the scintillators’ irradiation. The correction factors measured with Minimum Bias system are applied during absence of Cesium calibration. This allows to account for optical effects that are not corrected by the Laser calibration.

Figure 6: The variation of the response to Minimum Bias and Laser for cells in the inner layer of the extended barrel, covering the region \((1.2 < |\eta| < 1.3)\), as a function of time in during 2017 data taking period (a). The response variation is derived with respect to a reference cell D6 \((1.1 < |\eta| < 1.3)\), in the outermost layer of the calorimeter). The variations observed by the Minimum Bias are sensitive to PMT gain drift and scintillator irradiation. The variations observed by the Laser are sensitive to PMT gain drift. The percentage of masked cells and channels as the function of time from December 2010 to April 2018 (b). The shaded regions correspond to maintenance periods, when the front-end electronics could be accessed and repaired [6].

3. Performance

3.1. Detector Status and Data Quality

The performance of TileCal is monitored online during data-taking. Additional detailed offline monitoring is performed within two days after the stable run and the calibration constants are corrected if needed. The cells or readout channels with severe problems that can affect the physics measurements are masked. If the problem is considered intolerable, then the affected data are removed from the ATLAS Good Run List and are not used in physics analyses. TileCal achieved 100% data quality efficiency in 2015, 98.8% in 2016 and 99.4% in 2017. The evolution of the fraction of masked cells and channels in TileCal from the beginning of ATLAS operations in 2010 is shown in Figure 6b. The shaded regions correspond to maintenance periods, when the front-end electronics could be accessed and repaired. Regular maintenance helped to keep the fraction of inefficient cells below 1%.

3.2. Noise

Measurement of the noise is essential for energy reconstruction of physics objects using the Tile Calorimeter. The noise in TileCal consists of two components: electronics and pile-up noise. Electronics noise is defined as the width of the gaussian fit to the reconstructed cell energy distributions obtained in special runs without collisions. Pile-up noise arises from multiple interactions occurring at the same bunch crossing or from the events from previous/following
Figure 7: Total noise measured in TileCal cells in data (closed markers) and Monte Carlo simulation (open markers) in three different cell types as the function of $\langle \mu \rangle$ (a) [6]. Calorimeter response to single isolated charged hadrons as a function of momentum measured in $\sqrt{s} = 13$ TeV data and Monte Carlo (b) [10].

bunch crossings. It contributes to the signal response and to the widening of the cell energy distribution that increases with the average number of interactions per bunch crossing, $\langle \mu \rangle$. The electronics noise is approximately independent of $\langle \mu \rangle$. The increase of the total noise, defined as the standard deviation of the cell energy distribution, as the function of $\langle \mu \rangle$ is shown in Figure 7a. The experimental results are compared with the ones obtained using simulated events.

### 3.3. Single Particle Response

An important Tile Calorimeter characteristic is the ratio of energy measured by TileCal to track momentum measured by ATLAS Inner Detector [1] ($E/p$) for isolated, charged hadrons in minimum bias events. In order to ensure that a large fraction of the tracks reach and deposit their energy in the TileCal layers, cuts limiting energy in electromagnetic calorimeter are applied. This quantity is used to evaluate calorimeter uniformity and linearity during data taking. Figure 7b shows the mean $E/p$ as the function of track momentum measured in data and in Monte Carlo simulation. The data and simulation agree within 5%, showing linearity and uniformity in detector response.

### 3.4. Muons

The interaction of muons with the detector material is well understood, so response to their passage can be predicted reliably. Therefore, muons from cosmic rays are used to study in-situ the electromagnetic energy scale and inter-calibrate the detector cells. The TileCal cell response is expressed by muon energy loss per unit distance defined as the energy deposited of the muon per track path length within the cell ($dE/dx$). Figure 8a shows double ratio formed by the ratio of the muon energy loss per unit distance as a function of $\eta$ over the detector average of muon energy loss per unit distance. The response uniformity across $\eta$ is within 5%.

### 3.5. Jet Performance

One of the main uses of the hadronic Tile Calorimeter is the measurement of jet energy and missing transverse energy, $E_{T}^{\text{miss}}$. Figure 8b shows the ratio of the jet response in data to that in the nominal MC event generator as a function of jet transverse momentum. The difference
Figure 8: Uniformity of the muon energy loss per unit distance, $dE/dx$, as a function of $\eta$ obtained using 2015 cosmic data (a) [6]. Jet response ratio of the data to the Monte Carlo simulation as a function of jet transverse momentum (b) [11]. The error bars indicate the statistical and the total uncertainties.

in measured response is on few per cent level and is applied as correction in physics analyses. The energy resolution constant term agrees with the expected value of 3% [11].

4. Conclusion

The Tile Calorimeter is an important component of the ATLAS detector at the LHC. It performed very well during LHC Run 2. Thanks to regular maintenance, the fraction of inefficient cells is kept below 1%. Several calibration systems are used in conjunction: Cesium, Laser, Charge Injection and Minimum Bias systems. They allow the electromagnetic scale to remain within the required precision and provide an efficient monitoring and corrections of minute instabilities of Tile Calorimeter cells response. The performance of the calorimeter is studied using isolated charged hadrons and muons from cosmic rays. The stability of the absolute energy scale was maintained at the percent level, cell by cell, during LHC data-taking.

References
[1] The ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. JINST, 3:S08003, 2008.
[2] L. Evans, P. Bryant (editors). LHC Machine. JINST, 3 S08001, 2008.
[3] The ATLAS Collaboration. ATLAS Tile Calorimeter Technical Design Report. CERN-LHCC-96-042, 1996.
[4] The ATLAS Collaboration. Operation and performance of the ATLAS Tile Calorimeter in Run 1, 2018. arXiv:1806.02129 [hep-ex]
[5] P. Adragna et al. Testbeam studies of production modules of the ATLAS Tile Calorimeter. Nucl. Instrum. Meth. A 606 362, 2009.
[6] The ATLAS Collaboration, Approved Tile Calorimeter Plots, 2018. https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTile
[7] The ATLAS Tile Calorimeter system. The Laser calibration of the Atlas Tile Calorimeter during the LHC run 1. JINST 11 T10005, 2016.
[8] F. Scuri. Performance of the ATLAS Tile LaserII Calibration System. IEEE Nucl. Sci. Symp. Conf. Rec, 2015.
[9] The ATLAS Collaboration. Improved luminosity determination in $pp$ collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector at the LHC. Eur. Phys. J. C 73 2518, 2013.
[10] The ATLAS Collaboration, Public Tile Calorimeter Plots for Collision Data, 2018. https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TileCaloPublicResults
[11] The ATLAS Collaboration, JES Public Plots for Moriond 2017. JETM-2017-003, 2017. https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2017-003