Operation and Performance of the ATLAS Tile Calorimeter

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Abstract. The Tile Calorimeter (TileCal), the central hadronic calorimeter of the ATLAS detector, is a key system to measure jets and the missing transverse energy. It uses plastic scintillators interleaved by steel plates, with optical fibre readout and photomultipliers to detect the scintillating light produced by the passage of particles. The TileCal energy scale was obtained in tests with beam tests and, during operation, dedicated calibration systems monitor each step of the readout chain to address response fluctuations. The detector performance in Run 2 was studied with isolated particles and data quality was assessed with the large sample of proton–proton collisions. In this proceeding, the methods and results of the TileCal calibration, operation and performance in Run 2 are presented.

1. Introduction
The Tile Calorimeter (TileCal) is the central hadronic calorimeter of the ATLAS detector [1], covering a pseudorapidity range of $|\eta| < 1.7$. It is a sampling, non-compensating, calorimeter that employs plastic scintillator tiles as the active medium and steel plates as the absorber, in a density ratio of 1:4.7. This detector plays a central role in the ATLAS experiment: it is used in the measurement and reconstruction of hadrons, jets, hadronic decays of $\tau$-leptons and missing transverse energy. It also participates in the muon identification and provides input to the Level 1 calorimeter trigger system.

The scintillation light produced by the passage of particles in the detector is collected at the tiles’ edges and transported by wavelength-shifting (WLS) optical fibres to photomultiplier tubes (PMTs). The tiles have double PMT readout (each associated to one edge of the tile) ensuring redundancy of the signal detection.

The TileCal was designed to attain a jet energy resolution $\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 3\%$, and comprises a central Long Barrel (LB) and two Extended Barrels (EB) in the forward region. They are segmented along the azimuthal direction $\phi$ in 64 wedged modules and have three radial layers: A, B(C) and D. Moreover, WLS fibres bundled together are read by a unique PMT, defining the detector unit readout cells. The detector granularity in ($\eta, \phi$) is $0.1 \times 0.1$ in the A and B(C) layers and $0.2 \times 0.1$ in the D layer. Special scintillators, the E cells, are placed in the gap between LB and EB. In total, the TileCal comprises 5182 cells and 9852 PMT readout channels. Figure 1 shows the Tile Calorimeter optical readout and segmentation.
2. Signal and Energy Reconstruction
The PMT signals are shaped and amplified in two gains (low/high gain ratio of 1:64) for large/small signal measurements \[3\]. Then, the amplified signal is digitised every 25 ns, at the frequency of the LHC clock (40 MHz), by a 10-bit analog to digital converter (ADC). The signal amplitude $A$ and time $\tau$ are determined with the optimal filter algorithm from 7 digital samples $S_i$ as

$$A = \sum_{i} a_i S_i \quad \tau = \frac{1}{A} \sum_{i} b_i S_i,$$

where the optimal filter coefficients, $a_i$ and $b_i$, were derived from reference pulse shapes of the high and low gain signals. The cell energy $E$ is reconstructed from the signal amplitude as

$$E[\text{GeV}] = A[\text{ADC}] \times f_{\text{ADC}} \rightarrow pC \times f_{pC} \rightarrow \text{GeV} \times f_{\text{Cs}} \times f_{\text{Laser}}. \quad (2)$$

The $f_{pC} \rightarrow \text{GeV}$ conversion factor is the absolute electromagnetic (EM) energy scale constant measured in tests with electron beams of known energy (2001–2003) \[3\]. The remaining factors, $f_{\text{ADC}} \rightarrow pC$, $f_{\text{Cs}}$ and $f_{\text{Laser}}$, are adjustable calibration factors measured regularly with the TileCal calibration systems, intended to maintain the cell energy response stable.

3. Calibration and Detector Noise
The TileCal is equipped with dedicated calibration systems that allow to monitor and calibrate the response of the different components of the detector – from optical to electronics readout (figure 2). Besides, two other aspects are involved in the detector calibration: the timing of the signal sampling and the noise level in the cells.

3.1. Calibration with the Cesium System
A moveable $^{137}\text{Cs}$ $\gamma$-source ($E_\gamma=662$ keV) scans the detector cells with a hydraulic system contained within tubes installed along the cell drills (figure 1). The Cs signal is read by the
3.2. Calibration with the Laser System

A laser source is installed in the USA15 cavern, off the ATLAS detector site. This system was upgraded during the LHC Long Shutdown 1, which lead to an improvement in the light source stability. Besides the laser head, the hardware comprises a wheel of light filters of different transmittance that permit to vary the intensity of the laser scan, monitoring photodiodes and a chain of optical fibres that dispatch the laser light into the TileCal. Dedicated laser runs are taken daily with 532 nm light pulses sent to each PMT. The light pulses are also fired during LHC operation, in empty bunches, to monitor the detector timing. The response of the PMTs to the laser light is evaluated with a precision around 0.5% with respect to a reference run close to a previous Cs scan to derive the relative calibration factors $f_{\text{Laser}}$ in equation (2) updated weekly. The PMT response down-drifts during LHC operation and recovers when there are no collisions. Larger variations are observed for the PMTs reading the A layer, reaching an average $-6\%$ response loss in Run 2. A positive response fluctuation around $2\%$ was observed in the D layer PMTs at the end of Run 2 (Figure 3).

3.3. Calibration with the Charge Injection System (CIS)

The Charge Injection System calibrates the response of analog amplifiers and ADCs allowing also to evaluate their linearity. A signal of known charge (0 to 800 pC) is injected and shaped to match a PMT pulse to extract the pC to ADC conversion factors $f_{\text{ADC}\to\text{pC}}$ in equation (2) for both low and high gain channel readouts, which are employed both for cell energy reconstruction and for the analog Level 1 calorimeter trigger calibration. Dedicated runs are taken daily and the CIS factors are updated on a monthly-basis. The precision of the system is 0.7% and the stability of the constants with time is 0.03% (figure 4).
3.4. Monitoring with the Integrator Readout of Minimum Bias Events

Soft inelastic interactions, known as minimum bias events, are the most frequent processes in high energy proton–proton collisions. Here, the total energy deposit in the calorimeter summed over a large time is proportional to the instantaneous luminosity. Therefore, the integrator readout of the PMT signals (with constant of 10 ms) provides an independent measurement of the luminosity, once given an absolute initial calibration scale. Besides, measuring regularly the dependence of the minimum bias currents on the luminosity is an additional way to monitor the full detector (figure 4). This allows to derive finer-grained calibration between Cs runs, which is important for the most drifting A cells and especially for E cells, not scanned with Cs.

3.5. Combined Calibration and Optics Robustness

The difference between the cell response to Cs or minimum bias events and Laser pulses allows to isolate the relative response of the scintillators and fibres (figure 4). In 2015, for which the delivered luminosity was only 4.3 fb$^{-1}$, resulting in a small dose deposited in the detector, there was no difference between the PMT and full detector responses, indicating no degradation of the TileCal scintillators and WLS fibres. Since 2016, the relative light yield of the optical components has been decreasing with dose exposure (figure 5) for the more irradiated A cells. No significative degradation is observed for the remaining TileCal cells.

3.6. Time Calibration

Time calibration consists in adjusting the digitiser sampling clock to the peak of the signal produced by a particle travelling through the cell. It directly impacts the cell energy reconstruction since a bad timing can underestimate the reconstructed signal amplitude as indicated by equation (1). The time calibration constants are derived from the time distribution in cells associated with jets and are additionally monitored with laser-based signals. The average cell time offset is better than 0.4 ns for a cell energy above 20 GeV (figure 5) and the time resolution is better than 1 ns from 4 GeV.
Figure 5. (a) Average relative light yield of the A13 scintillators and fibres as a function of the dose in Run 2. (b) Average cell time as a function of the cell energy.

Figure 6. (a) Pile-up noise in the A5, BC5 and D2 cell versus the average number of interactions per bunch crossing in data and simulated (MC) events. (b) Evolution of the number of masked channels and cells in the TileCal from Run 1 to the end of Run 2.

3.7. Noise Measurement
The total noise per calorimeter cell comes from the electronics and from multiple interactions per proton bunch crossing, known as pile-up. The electronics noise, around 20 MeV for all cells, is measured in dedicated runs without any physics or calibration signal. The pile-up noise sources are energy deposits from multiple collisions in the same event or from the previous/next bunch crossing. The innermost cells in the A layer are thus more affected by pile-up noise, which increases with the average number of interactions per bunch crossing (figure 6).

4. Operation and Performance
4.1. Detector Operation and Data Quality
The TileCal operation is controlled and monitored through a Detector Control System using SCADA software, and run coordination, maintenance and data quality (DQ) activities ensure a smooth workflow. Continuous monitoring permits to identify and mask problematic channels, correct for miscalibrations, detect data corruption and hardware issues. Here, the redundancy in cell readout is very relevant to reduce the impact of masked channels. Maintenance campaigns...
4.2. Response to Isolated Particles

The ratio of the calorimeter energy response to isolated charged hadrons, at the electromagnetic (EM) scale, to the track momenta $<E/p>$ is employed to evaluate the uniformity and linearity of the TileCal during data taking. This ratio is expected to be $<1$ due to the non-compensating nature of the TileCal ($\varepsilon/h=1.36$) and therefore jets are further calibrated to the jet energy scale. The value of $<E/p>$ was measured in minimum bias events and agree with simulation within 5% (figure 7). High-energy muons from cosmic rays are explored to study the EM energy scale and the cell inter-calibration. The cell response is evaluated as the energy deposited by the muon path length $dE/dx$. A uniformity of $\sim 1\%$ across $\phi$ and a maximum non-uniformity of 5% in $\eta$ was obtained (figure 7).
4.3. Response to Jets
A faithful description of the cell energy and noise distributions are crucial for building energy clusters, the seeds to the calorimeter jet finding algorithms [5]. A good agreement between the measured contributions of the total cell energy and simulation is found (figure 8). This also contributes to a good jet energy resolution, better than 10% for jets with transverse momenta above 100 GeV (figure 8). The resolution asymptotically approaches the constant value of 3% with increasing energy, matching the TileCal design goals.

5. Summary and Conclusions
The Tile Calorimeter is an important part of the ATLAS detector, it contributes to the measurement of the 4-momenta of jets and the missing transverse energy. Each step of the signal production is monitored and calibrated with dedicated systems. Inter-calibration and uniformity are assessed with isolated particles. The stability of the absolute cell energy scale was kept better than 1% during Run 2, and maintenance and DQ activities led to an overall detector DQ efficiency of 99.7%.

References
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