PROCEEDINGS OF SCIENCE

Performance of the ATLAS Tile Calorimeter

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The Tile Calorimeter (TileCal) is a sampling hadronic calorimeter covering the central region of the ATLAS experiment, with steel as absorber and plastic scintillators as active medium. The scintillators are read-out by the wave-length shifting fibres coupled to the photomultiplier tubes (PMTs). The analogue signals from the PMTs are amplified, shaped, digitized by sampling the signal every 25 ns and stored on detector until a trigger decision is received. The TileCal frontend electronics reads out the signals produced by about 10000 channels measuring energies ranging from about 30 MeV to about 2 TeV. Each stage of the signal production from scintillation light to the signal reconstruction is monitored and calibrated. During LHC Run-2, high-momentum isolated muons have been used to study and validate the electromagnetic scale, while hadronic response has been probed with isolated hadrons. The calorimeter time resolution has been studied with multi-jet events. A summary of the performance results, including the calibration, stability, absolute energy scale, uniformity and time resolution, will be presented.

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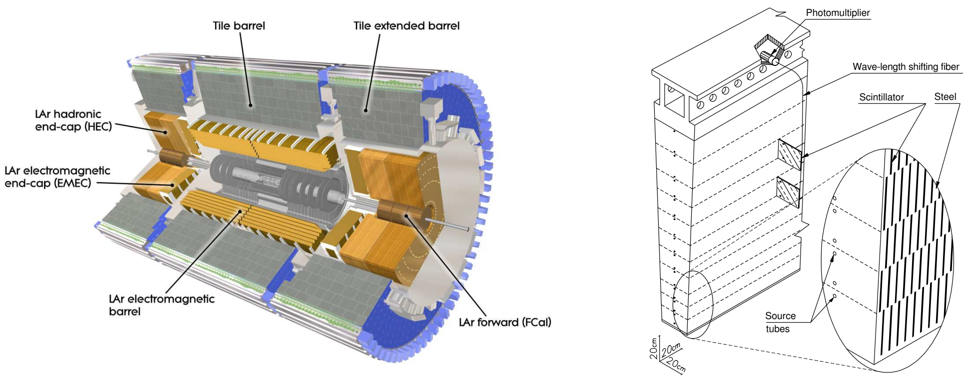
1. Introduction

The Tile Calorimeter (TileCal) [1] is the central hadronic calorimeter in the ATLAS experiment [2] at the Large Hadron Collider (LHC) [3]. It plays crucial role in the measurement of hadrons, jets, and missing transverse energy. The TileCal also provides input to the Level 1 Calorimeter trigger and assists in muon identification. Along the beam axis, it is divided into a central barrel, covering $|\eta| < 1.0$ region, and two extended barrels, covering $0.8 < |\eta| < 1.7$ region, presented in Figure 1a. Azimuthally each barrel is segmented into 64 modules with equal $\Delta\phi$ width. The Tile Calorimeter is sampling calorimeter with steel plates as absorber and plastic scintillating tiles as active medium (steel:scintillator ratio is 4.7:1). Tiles are read out from both sides by photomultiplier tubes (PMT) via wave-length shifting fibers, see Figure 1b. In each module the readout cells are defined by grouping fibers from individual tiles to the same PMT. In total there are 9852 readout channels (PMTs) and 5182 cells (typical cells are read out by two PMTs), with granularity $\Delta\eta\times\Delta\phi = 0.1\times0.1$ in the first two innermost A and BC (just B in the extended barrels) layers and $\Delta\eta\times\Delta\phi = 0.2\times0.1$ in the outermost D layer, see Figure 2a. The E layer of special cells, which are read out by one PMT, is attached to the extended barrels. The designed standalone TileCal energy resolution for jets is $\sigma/E = 50\%/\sqrt{E\,[\mathrm{GeV}]} \oplus 3\%$.



(a) **(b)**

Figure 1: The ATLAS calorimeters (a) [1]. The geometry and optical readout of one TileCal module (b) [1].

2. Signal Processing and Calibration

The signal from each PMT is shaped, amplified in low and high gains with ratio 1:64, and digitized each 25 ns. Upon receiving the ATLAS Level 1 trigger acceptance, amplitude A and time τ are reconstructed from 7 consecutive measurements S_i using the Optimal Filtering technique:

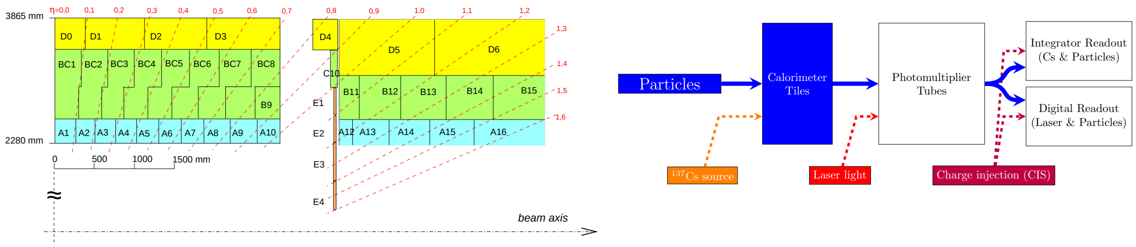
$$A = \sum_{i=0}^{n=7} a_i \cdot S_i, \qquad \tau = \frac{1}{A}\sum_{i=0}^{n=7} b_i \cdot S_i$$

where a_i and b_i are weights derived, using a reference pulse shape, to minimize the resolution of the amplitude and time. The energy of each channel, E_{channel}, is evaluated from the amplitude using calibration coefficients C_i, provided by different TileCal calibration systems, explained below:

$$E_{\mathrm{channel}}[\mathrm{GeV}] = A[\mathrm{ADC}] \cdot C_{\mathrm{ADC}\to\mathrm{pC}} \cdot C_{\mathrm{pC}\to\mathrm{GeV}} \cdot C_{\mathrm{Cesium}} \cdot C_{\mathrm{Laser}}$$

The overall electromagnetic (EM) scale, $C_{\text{pC}\to\text{GeV}}$, was measured and fixed during dedicated test beam campaigns with electrons (2001-2003) [1].

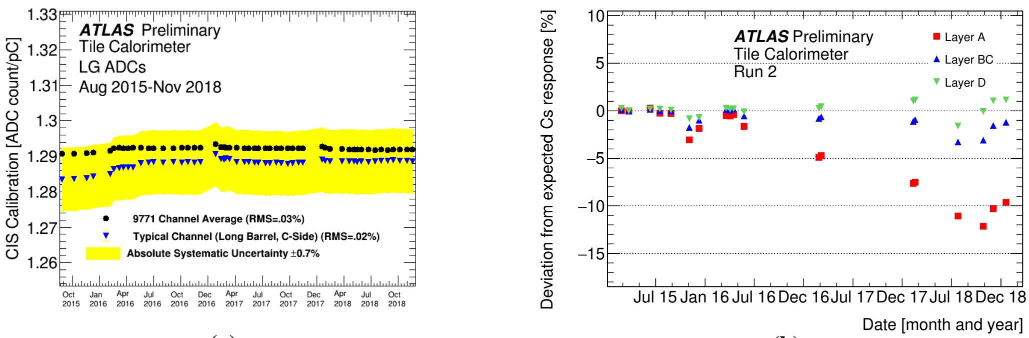
The calibration systems are used to maintain a time independent global EM energy scale and monitor the signal propagation on different levels in the Tile Calorimeter, see Figure 2b.



(a) **(b)**

Figure 2: The TileCal cell layout in a half long central barrel and one extended barrel modules (a) [4]. The signal path of different TileCal calibration systems, which partially overlaps allowing cross checking (b) [4].

The Charge injection system (CIS) injects a signal of known charge into the on-detector electronics, spanning full ADC range (0-800 pC) in two gains, for each channel and measures the response of the electronics. That allows to extract the conversion factors from ADC counts to pC: $C_{\text{ADC}\to\text{pC}}$. The CIS is used to monitor the electronic chain stability and linearity. Calibration is performed ~ weekly during dedicated calibration runs. The precision of this system is ~ 0.7%, its stability is ~ 0.03%, see Figure 3a. The CIS is also used to calibrate the analog Level-1 Calorimeter trigger.

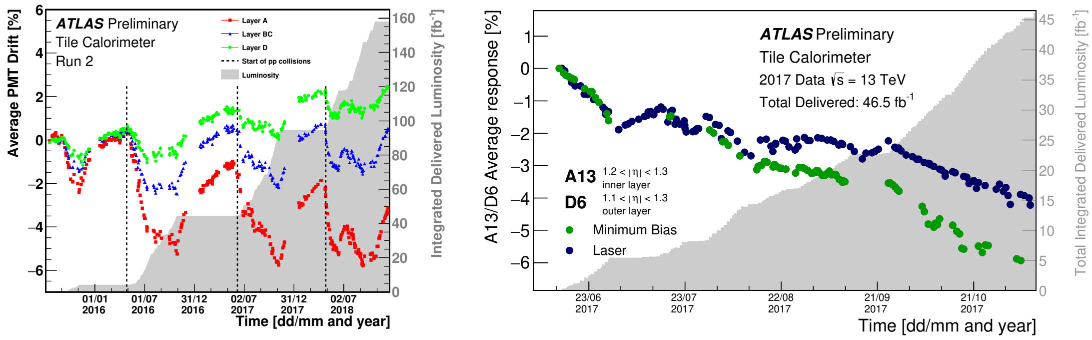


(a) **(b)**

Figure 3: The time evolution of CIS calibration constant averages of all low gain channels during Run 2 (a) [5]. The variation in the Tile Calorimeter response measured by the Cesium system during Run 2 (b) [5].

The Cesium calibration system uses a hydraulically movable radioactive source ^{137}Cs which emits γ-rays with energy 662 keV. The source passes through the calorimeter body via net of steel tubes and illuminates each scintillator. It is done several times per year in Run 2 during special scans. Independent readout is used, which integrates the signal over 10 ms during the source movement. This system is used to monitor all optics components and PMTs, since deviation of the cell response in time is caused by PMT gain variation and scintilator degradation. The deviation from expected one, corrected for Cs decay (-2.3%/year), is converted into calibration factor: C_{Cesium}. Maximal drift is observed in the layer A, which is the closest to the collision point, see Figure 3b. The precision of this system in typical cell is ∼ 0.3%. It allows to adjust the PMT gain by changing the high voltage and restore the calorimeter response uniformity.

The Laser calibration system sends a controlled amount of light onto photo-cathode of each PMT at wave-length of 532 nm. It is done ∼ weekly during dedicated calibration runs. This system measures the drift seen in the PMTs with respect to the last Cesium scan. It also allows to detect the high voltage changes. The maximal drift is observed in A- and E-cells which are the cells with highest energy deposits, see Figure 4a. The channel response deviation with respect to nominal one gives C_{Laser}. The precision of this system is better than 0.5%.



(a) **(b)**

Figure 4: Time evolution of average PMT drift during Run 2 (a) [5]. The variation of the response measured by the Minimum Bias and Laser systems for the cell A13 in the extended barrel as a function of time (b) [5].

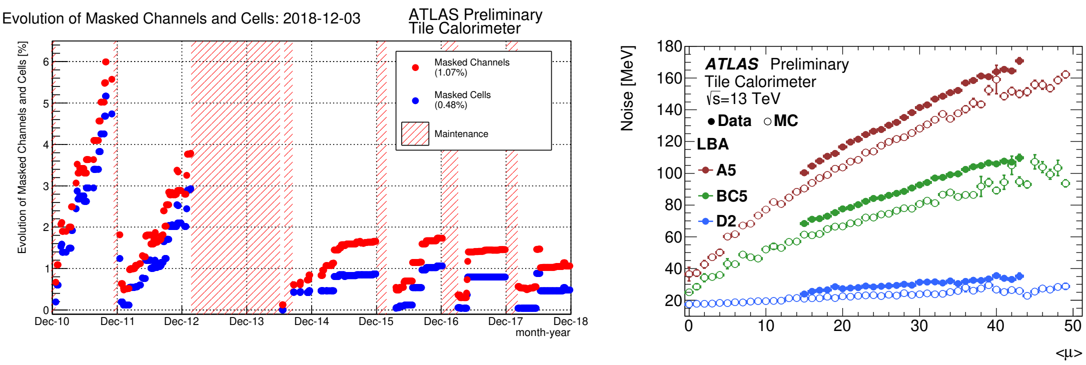
Minimum Bias system measures the response to events dominated by soft inelastic parton interactions in proton-proton collisions. It shares readout with the Cesium system, i.e. integrates PMT signals over ∼ 10 ms during data taking. This system monitors the full optical chain and calibrates E-cells and Minimum Bias Trigger Scintillators. The measured PMT currents are linearly dependent on the instantaneous luminosity, which allows to measure and monitor the instantaneous luminosity in the ATLAS experiment.

Comparison of the cell response variation between the Laser and Minimum Bias systems allows to get additional information, as Minimum Bias system sees both the PMT gain drift and scintillator ageing, while the Laser system only monitors the PMT gain drift. So, difference between the Laser and Minimum Bias measurements is interpreted as scintillator ageing due to irradiation and this effect is clearly seen after 2015, see Figure 4b. Down (Up) drifts are observed during collisions (maintenance) periods.

Precise time calibration is important for the cell energy reconstruction and can be also used in time-of-flight analyses, searching for hypothetical long lived particles (e.g. heavy R-hadrons). It sets the phase so that a particle traveling from the interaction point at the speed of light gives the signal with measured time equal to zero. The time calibration is calculated using jets and monitored with laser in empty bunches during proton-proton collisions.

3. Performance during Run 2

The Tile Calorimeter status and data quality monitoring include identification and masking of the problematic channels due to data corruption and other hardware issues as well as correction for the energy miscalibration and timing. The identified issues are fixed during maintenance campaigns and that allows good recovery of the system, see Figure 5a. The TileCal data quality efficiency is 100% in 2015, 99.3% in 2016, 99.4% in 2017, and 100% in 2018.



(a) **(b)**

Figure 5: Evolution of fraction of the masked Tile Calorimeter channels and cells as function of time (a) [5]. The total noise dependence on average number of interactions (b) [5].

The total cell noise in the calorimeter comes from two sources: electronic noise, which is measured in dedicated runs without signal in the detector, and pile-up noise, which originates from multiple interactions in the same or neighboring collisions. The electronic noise is below 20 MeV for most of the calorimeter cells. The total noise is increasing with pile-up, see Figure 5b. The largest noise is in the region with highest exposure (A- and E -cells).

Muons from cosmic rays are used to study in situ the EM scale and the calorimeter cells inter-calibration. The cell response is estimated as the energy deposited by the muon in the cell per unit of the path length in it: dE/dx. Good energy response uniformity between the calorimeter cells in ϕ is observed. The cell response non-uniformity in η is better than 5%, see Figure 6a.

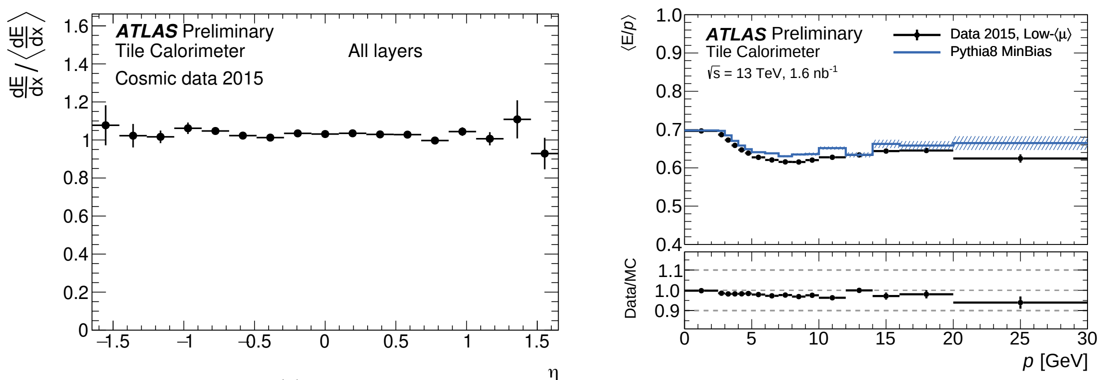


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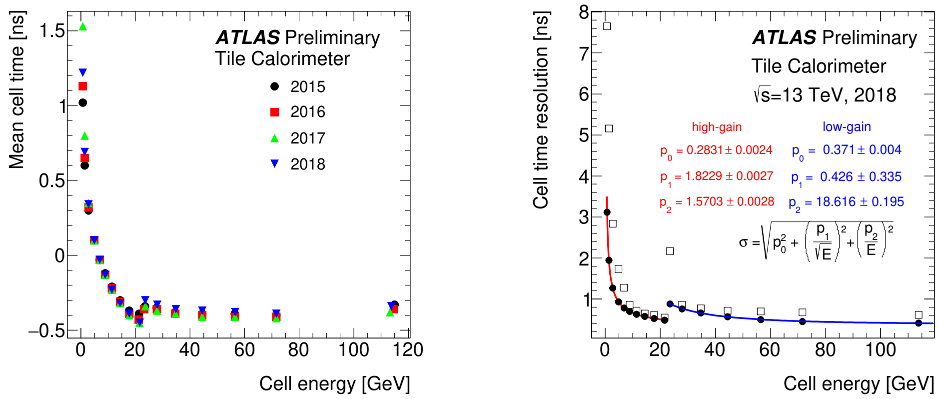
Figure 6: Uniformity of the cosmic muon energy loss in the Tile Calorimeter per unit of the path length as function of η (a) [5]. The TileCal response to single isolated hadrons as function of momentum (b) [6].

The ratio of the calorimeter energy at EM scale to the track momentum $\langle E/p \rangle$ for isolated charged hadrons is used to evaluate uniformity and linearity during data taking period. It is measured in Minimum Bias events and is expected to be < 1 due to the non-compensating nature of the sampling calorimeter. Data and Monte Carlo simulation do agree well (within 5%), see Figure 6b.

Figure 7a shows overall good stability of the cell time calibration during Run 2. The cell time resolution in jet events is better than 1 ns for $E_{\rm cell} > 4$ GeV, see Figure 7b.



(a) **(b)**

Figure 7: The mean cell time (a) and time resolution (b) in jet events as a function of the cell energy [6].

4. Conclusion

The Tile Calorimeter is an important part of the ATLAS detector at the LHC. It is a key detector to measure hadrons, jets, and missing transverse energy. Each stage of the signal production from scintillation light to the signal reconstruction is monitored and calibrated using a set of calibration systems. Inter-calibration and uniformity are monitored with isolated charged hadrons and high-momentum cosmic muons. The stability of the absolute energy scale at the cell level was maintained to be better than 1% during Run 2. The overall data quality efficiency was ~ 99.7 % in Run 2.

References

[1] ATLAS Collaboration, *Readiness of the ATLAS Tile Calorimeter for LHC collisions*, *Eur. Phys. J. C* **70** (2010) 1193 [1007.5423].

[2] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* **3** (2008) S08003.

[3] L. Evans and P. Bryant, eds., *LHC Machine*, *JINST* **3** (2008) S08001.

[4] ATLAS Collaboration, *Operation and performance of the ATLAS Tile Calorimeter in Run 1*, *Eur. Phys. J. C* **78** (2018) 987 [1806.02129].

[5] ATLAS Collaboration, *Public Tile Calorimeter plots (2020)*, *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTile* .

[6] ATLAS Collaboration, *Public Tile Calorimeter plots for Collision Data (2020)*, *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TileCaloPublicResults* .