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# Performance and upgrade of the ATLAS Hadronic 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 wavelength 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 upcoming High-Luminosity phase of the LHC (HL-LHC), starting in 2030, will increase the nominal instantaneous luminosity by a factor of 5 to 7.5, alongside an upgraded ATLAS Trigger and Data Acquisition architecture. This upgrade necessitates a complete redesign of the readout electronics and power systems of TileCal. Both the on- and off-detector TileCal electronics will be replaced during the shutdown of 2026-2030. PMT signals from every TileCal channel will be digitized and sent directly to the back-end electronics, where the signals are reconstructed, stored, and sent to the first level of trigger at a rate of 40 MHz. This will provide better precision of the calorimeter signals used by the trigger system and will allow the development of more complex trigger algorithms. The TileCal upgrade programme has included extensive research and development, including test beam studies and the construction of a Demonstrator module. The Tile Demonstrator module with reverse compatibility with the existing system was inserted in ATLAS in July 2019 for testing in actual detector conditions. A summary of first LHC Run 3 performance results including the calibration, stability, absolute energy scale, uniformity and time resolution is presented. The ongoing HL-LHC developments for on- and off-detector systems, together with expected performance characteristics and results of test-beam campaigns with the electronics prototypes is also discussed.

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## 1. Introduction

The Tile Calorimeter (TileCal) [1] is the central hadronic calorimeter of the ATLAS experiment [2] at CERN. It is crucial for reconstruction of jets, hadronically decaying tau leptons and missing transverse energy. It is also used for Level 1 calorimeter trigger and for identification of muons. The TileCal is built of alternating layers of steel absorber plates and plastic scintillators arranged perpendicular to the beam direction.

TileCal is composed of three mechanical parts – two extended barrels and one long barrel as shown in Figure 1 (left). The read-out of the long barrel is divided into two parts forming four read-out partitions in total. Each partition is composed of 64 modules defining the segmentation of the calorimeter in the azimuthal angle. The optical components of each module are shown in Figure 1 (right). The signal produced in the scintillator tiles is collected on both sides of the module and transmitted by wavelength shifting (WLS) fibres to the photomultipliers (PMTs). The cell is commonly read-out by two PMTs, resulting in total of 5182 cells. The calorimeter is segmented into three longitudinal layers with the thickness of 1.5, 4.1 and 1.8 interaction lengths ($\lambda$) in the barrel, resp. 1.5, 2.6, 3.3$\lambda$ in the extended barrels. The cell sizes in $\Delta\eta \times \Delta\phi$ are approximately $0.1 \times 0.1$ in the two inner layers (A, BC), resp. $0.2 \times 0.1$ in the outermost layer (D).

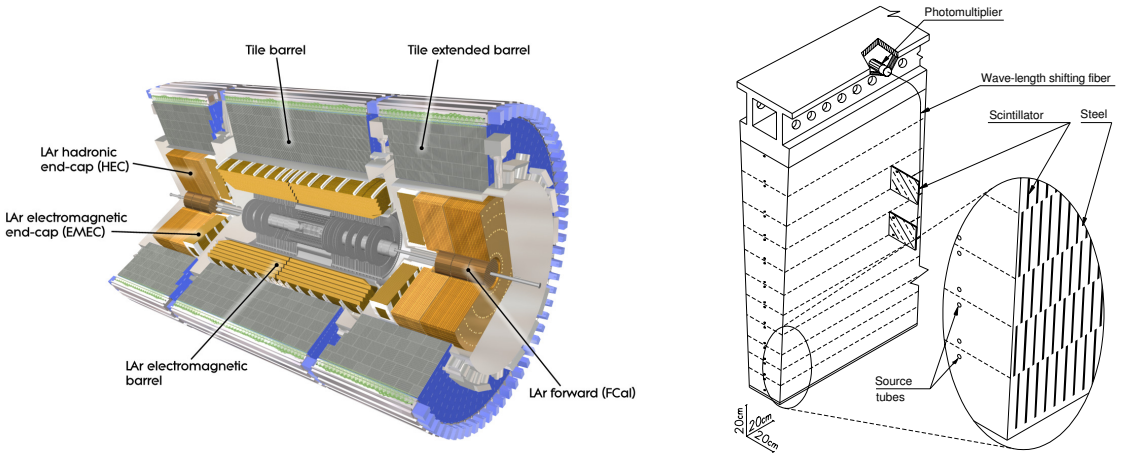


**Figure 1:** Scheme of the ATLAS calorimetry system [1] (left), module of TileCal with its optical components [1] (right).

## 2. Signal reconstruction and calibration

The electrical signal from each PMT is amplified using two gains with a ratio 1:64, shaped and digitised each 25 ns. The amplitude $A$ and time phase are reconstructed as a linear combination of the digitised samples using Optimal Filtering method [3]. The amplitude in ADC counts is calibrated to the energy at the electromagnetic scale using dedicated calibration systems:

$$E_{\text{reco}}[\text{GeV}] = \frac{A[\text{ADC}]}{C_{\text{ADC}\to\text{pC}} \cdot C_{\text{pC}\to\text{GeV}} \cdot C_{\text{Cs}} \cdot C_{\text{MB}} \cdot C_{\text{Las}}}$$



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where $C_X$ are corresponding calibration constants described below. The conversion factor from pC to GeV ($C_{\mathrm{pC}\to\mathrm{GeV}}$) is derived by measuring the response to the electrons entering the calorimeter under the angle of 20° in the beam tests [4].

The charge injection system releases a predefined charge in the front-end electronics. The conversion factor from ADC count to pC ($C_{\mathrm{ADC}\to\mathrm{pC}}$) is derived from the linear fit of the amplitude dependence on the inserted charge. The conversion factors for both gains are measured with the precision of 0.7% and are very stable in time.

The laser source [5] located 100 m from the detector sends monochromatic light by optical fibres simultaneously to all PMTs. The PMT gain degrades during the LHC proton-proton ($pp$) collisions, while it partly recovers during periods without beam. The variations in the PMT response are measured and corrected for by the use of corresponding laser calibration constants $C_{\mathrm{Las}}$.

The Caesium system [6] is composed of three independent tube systems through which a capsule with $^{137}$Cs travels. The emitted photons have an energy of 662 keV and are used for the calibration of the whole optical chain. The response is measured by a dedicated read-out which integrates the signals over 10-20 ms. The Caesium system is used to equalise the response of individual read-out channels with time dependent constants $C_{\mathrm{Cs}}$. The integrated current for events from low momentum collisions is used for calibration of cells where the Caesium calibration is not available (factor $C_{\mathrm{MB}}$). The most irradiated cells in the inner layer A experience degradation of energy response on average around 6% between beginning of 2022 and end of 2023 data taking as shown in Figure 2 (left).

The response degradation of scintillators and WLS fibres related to the radiation exposure was studied using LHC Run 2 data [7]. These optical components of the calorimeter can not be replaced for the High-Luminosity LHC (HL-LHC) [8] operation. The projections of the light yield losses have been performed for the dose rates expected in TileCal during HL-LHC running. The extrapolations indicates that the cells in the BC and D layers will degrade by no more than 25% until the end of the HL-LHC phase, assuming an integrated luminosity of 4000 fb$^{-1}$. The most exposed cells in the inner layer A are expected to lose around 50% of their light response with the relative uncertainty of this prediction being approximately 50%, shown in Figure 2 (right).

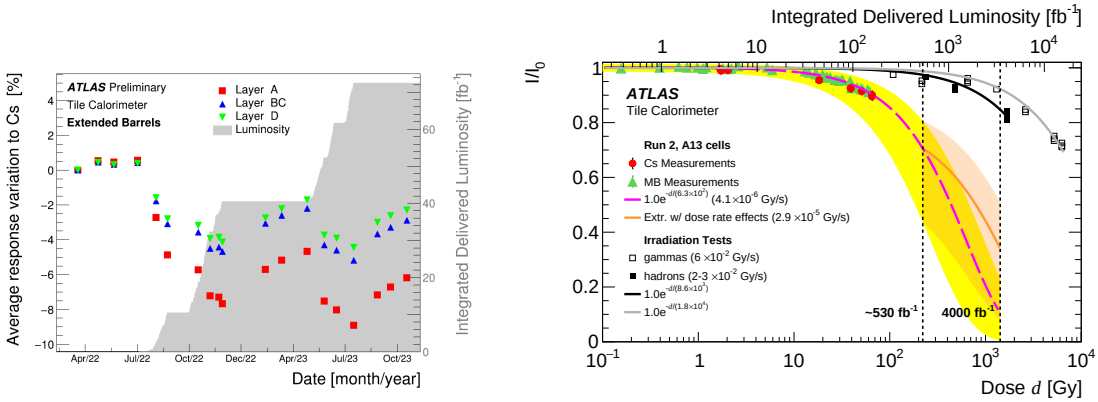


**Figure 2:** Average response variation per individual layers measured with Ceasium system in Run 3 [9] (left), average light yield for cells in layer A measured during LHC Run 2 and extrapolated to doses expected at HL-LHC [7] (right).



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## 3. Performance studies

The performance of the calorimeter and the justification of the calibration procedure is done using LHC Run 3 $pp$ collisions' data and muons from the cosmic-rays.

The cell response uniformity along the azimuthal angle is studied using isolated muons originating in decays of $W$ boson. Events with lowest un-prescaled single muon trigger are considered and selection criteria to enhance muons from $W$ decays are applied. The muons are required to be isolated from other objects and reconstructed with high quality. Only muons with momenta in the range from 20 GeV to 80 GeV, where the ionisation losses are dominant, are used in the analysis. The response of the individual cells is quantified using truncated mean of the deposited energy per muon path length $\Delta E/\Delta x$. The truncation removes 1% of events with the highest $\Delta E/\Delta x$ values, denoted as $\langle \Delta E/\Delta x \rangle_{\mathrm{F=1\%}}$. This quantity is measured separately in data and in Geant 4-based [10] Monte Carlo (MC) simulations. The ratio $R$ defined as

$$R = \frac{\langle \Delta E/\Delta x \rangle^{\mathrm{Data}}_{\mathrm{F=1\%}}}{\langle \Delta E/\Delta x \rangle^{\mathrm{MC}}_{\mathrm{F=1\%}}}$$

is used as the response estimator. The uniformity of the $R$ ratio for one specific cell type, along the 64 azimuthal modules, is shown in Figure 3 (left). The preliminary results show good uniformity of the response across azimuthal angle at the level of approximately 2%.

The TileCal time resolution is studied using cells associated to jets produced in LHC collisions. The time distribution is measured per calorimeter layer and fitted by a Gaussian function. The width of the Gaussian function is plotted as a function of reconstructed cell energy, see Figure 3 (right). A time resolution as good as 1 ns is achieved for energy deposits larger than 5 GeV in most of the cells.

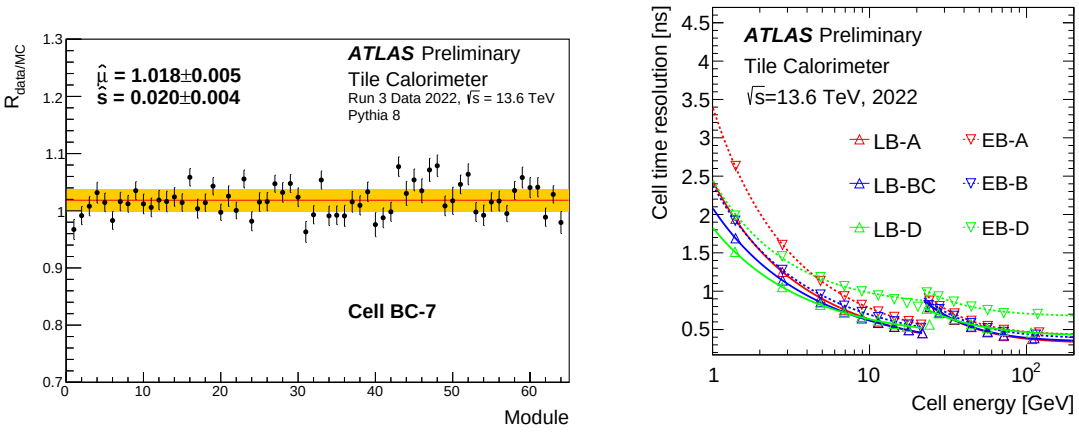


**Figure 3:** Uniformity of the response to isolated muons using LHC Run 3 data for a cell in the layer BC on the C-side ($\eta$<0) of the long barrel [11] (left), cell time resolution of TileCal using cells associated to jets [11] (right).



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## 4. Upgrade for HL-LHC operation

The TileCal will undergo major upgrades to meet the demands of ATLAS operation under the HL-LHC conditions. The HL-LHC is expected to deliver an instantaneous luminosity 5–7 times higher than that of the current LHC, posing several challenges for the calorimeters, including increased radiation levels, higher data rates, and substantial modifications to the trigger system architecture. The TileCal upgrade programme is primarily motivated by the need to enhance system reliability and maintainability. It foresees a complete replacement of both on-detector and off-detector electronics [12]. The scheme of the new read-out system, described below, is presented in Figure 4.

The TileCal PMTs and on-detector electronics are placed in so-called super-drawers. The upgraded design replaces the drawers by so-called mini and micro drawers. There will be 4 mini-drawers (MD) per module in the long barrel, 3 MDs with 2 micro-drawers in the extended barrel. Each MD is split into two independent sides for redundancy. Failure of any component will result in a loss of no more than 6 PMTs. Moreover, the most exposed PMTs will be replaced by a new version of PMT (Hamamatsu R11187) with improved quantum efficiency and better stability against the increase of the integrated anode charge as shown in Figure 5 (right). Active voltage dividers will be installed in all PMTs to enhance stability at high anode currents.

The Front-End board for the New Infrastructure with Calibration and signal Shaping (FENICS) is a key component of the on-detector electronics. It shapes the PMT pulse and provides bi-gain amplification (1:40). The board also includes an integrated charge injection system for calibration purposes. The Mainboard is designed to provide digital control of the FENICS cards via Field Programmable Gate Arrays (FPGA) and to digitise the output signals from FENICS. The dynamical range from 0.2 pC to 1000 pC is covered using 12 bits ADC, compared to 10 bits used in the current (legacy) system. In addition, the Mainboard provides a high-speed connection to the DaughterBoard, which houses two Kintex UltraScale FPGAs and transmits digitised data to the off-detector electronics via optical links using GBT protocol at 9.6 Gb/s through SFP+ transceivers.

The off-detector electronics is composed of Tile PreProcessor (TilePPr) and the TDAQ interface system (TDAQi). These are essential for real-time data processing, handling, and reconstruction. Each TilePPr is formed by Advanced Telecommunications Computing Architecture (ATCA) carrier, four Compact Processing Modules (CPM), Tile Computer-on-Module (TileCoM) and one Gigabit-Ethernet switch. CPM transforms the raw data into deposited energy for up to 90 channels at 40 MHz rate using Kintex UltraScale FPGA. The TDAQi system receives the information about reconstructed cell energies from 4 CPMs synchronously and it produces primitives for ATLAS Level 0 trigger system. It sends the calorimeter data to the FELIX system for further processing.

The upgraded electronics has been intensively tested during several beam tests' campaigns at CERN North Area. The modules equipped with an upgraded and legacy electronics were exposed to the beams of electrons, muons and hadrons. The response to electrons with energies from 10 to 100 GeV entering the module at 20° has been compared with MC predictions using Geant4 version 10.6.3. The data agrees with the simulations within the uncertainties. The response to muons has been measured for the upgraded and legacy electronics using the truncated mean of deposited energy per path length in the individual TileCal layers. The analysis proceeds for each cell type and a comparison with MC predictions shows a reasonable agreement. The normalised longitudinal



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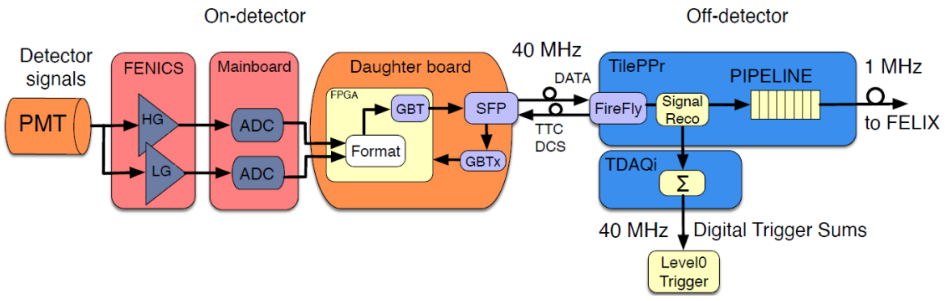


**Figure 4:** TileCal read-out scheme for the HL-LHC upgrade [9]

profiles of hadronic showers from protons and pions has been measured and compared with the simulations using Geant4 version 10.6.3 with FTFP_BERT_ALT physics list. An agreement at the level of 10% was found for shower depths up to 7 interaction lengths, see Figure 5 (right).

So-called demonstrator module operates in a hybrid mode in the ATLAS cavern since 2019. This module is built of an upgraded read-out system using new digital path, but the analogue trigger signals are provided to the legacy system. The demonstrator is fully integrated in the ATLAS read-out and is collecting high quality data during LHC Run 3. It confirms functionality and reliability of the upgraded electronics.

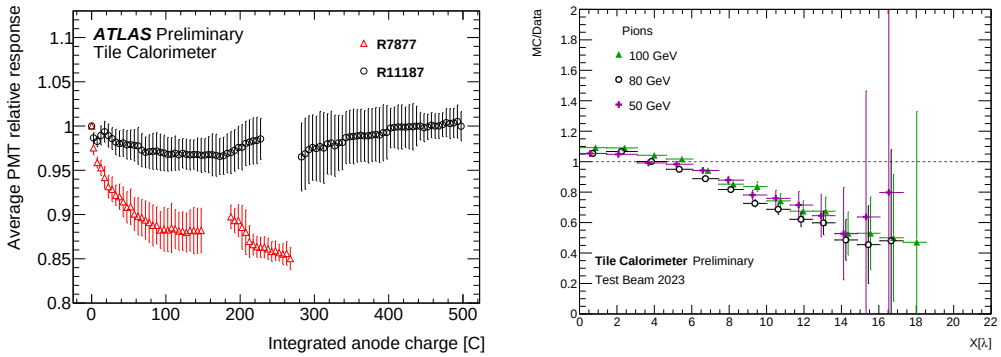


**Figure 5:** Average PMT gain variation dependence on the anode current for the current (red) and upgraded (black) PMTs [9] (left), normalised longitudinal profile for pion beams at various energies [9] (right).

## 5. Summary

The TileCal demonstrates excellent performance, with only approximately 1% of its cells unavailable for physics analyses. Its response is regularly calibrated to high precision using dedicated calibration systems. Performance studies with isolated muons from $pp$ collisions, as well as with isolated hadrons and jets, are ongoing with the latest LHC data. To meet the requirements of HL-LHC operation, TileCal is undergoing a complete redesign of both on-detector and off-detector electronics. The upgraded electronics have been successfully tested in beam tests and within ATLAS using the demonstrator module, confirming their good performance.



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