PROCEEDINGS OF SCIENCE

The ATLAS Tile Calorimeter performance in the LHC Run 2 and its upgrade towards the High-Luminosity LHC

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The Tile Calorimeter (TileCal) is a sampling hadronic calorimeter covering the central region of the ATLAS experiment. The TileCal uses steel as the absorber and plastic scintillators as the active medium. The scintillators are read out by wavelength shifting fibres coupled to 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 front-end electronics reads out the signals produced by about 10k 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. A summary of the performance results using proton-proton collisions from LHC Run 2 at 13 TeV is presented. The High-Luminosity phase of the LHC, delivering up to 7.5 times the LHC nominal instantaneous luminosity, is expected to begin in 2026. The TileCal will require new electronics to meet the requirements of a 1 MHz trigger, higher ambient radiation, and to ensure better performance under high pileup conditions. Both the on- and off-detector TileCal electronics will be replaced during the shutdown of 2024-2025. PMT signals from every TileCal cell 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 for calorimeter signals used by the trigger system and will allow the development of more complex trigger algorithms. Changes to the electronics will also contribute to the data integrity and reliability of the system. The ongoing developments for on- and off-detector systems, together with expected performance characteristics and recent results of test-beam campaigns with the electronics prototypes are discussed.

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1. Introduction

The ATLAS Tile Calorimeter (TileCal) is a sampling calorimeter covering the central region (pseudo-rapidity $|\eta| < 1.7$) of the ATLAS detector [1]. The TileCal is crucial in measuring jets, missing-energy, taus and muons. It is divided into 3 cylinders (barrels): one Long Barrel ($|\eta| < 1$) and two Extended Barrels ($0.8 < |\eta| < 1.7$). Each cylinder is composed of 64 wedge modules. Each module is segmented in η and in three radial layers (A,BC,D) composing the readout units: *cells*. The TileCal uses steel as the absorber and scintillating tiles as the active medium, as shown in Figure 1. Scintillating tiles in each cell are coupled to wavelength shifting fibers, read out by two photomultiplier tubes (PMTs). The analogue signals delivered by the PMTs are amplified with two gains ($\times 1$,$\times 64$), shaped and digitized by sampling the signal every 25 ns. The digitized samples are stored in a pipeline memory until a trigger decision is received. Once the trigger decision is received, the data of one of the gains are transferred, via optical links, to the back-end electronics (see Figure 2) where an optimal filtering is used to reconstruct the signal.

Each stage of the signal production from scintillation light to the signal reconstruction is monitored and calibrated (Figure 3): a charge injection system (CIS) is used to calibrate the response of the analogue-to-digital conversion, a laser calibration system to measure the gain stability of each PMT and a Cesium system (Cs) is used to calibrate the full optical chain. LHC proton-proton collisions are dominated by soft parton interactions, so-called Minimum Bias (MB) events. An MB monitoring system is used to monitor the TileCal response to signals induced by MB events.

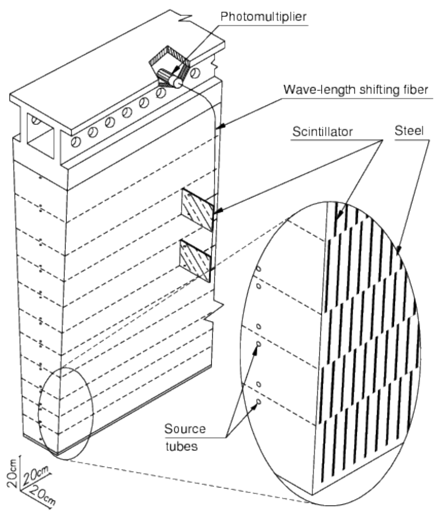

Figure 1: Tile Calorimeter module design [2].

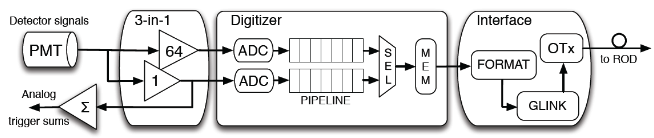

Figure 2: Tile Calorimeter readout scheme [2].

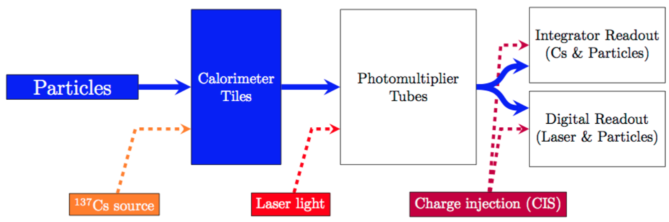

Figure 3: Tile Calorimeter calibration system chain [2].

2. LHC Run 2 performance

The performance of the TileCal is monitored using physics and calibration data. Problematic cells or readout channels that can affect the physics measurements are identified and masked. They are recovered during the maintenance periods before each data taking period. Figure 4 shows the evolution of masked cells and readout channels in the TileCal as a function of time, starting from 2010. The number of masked cells shown has negligible impact on physics measurements such as missing-energy. During LHC Run 2, the TileCal achieved 100% data quality efficiency in 2015, 99.3% in 2016, 99.4% in 2017 and 100% in 2018. Figure 5 shows the cell response variation (drift), obtained with Cs calibration, in the 3 layers as a function of cell position in η. Larger deviations are observed for cells closer to the beam line, caused by PMT gain variation and scintillator and fibre degradation due to exposure to the beam.

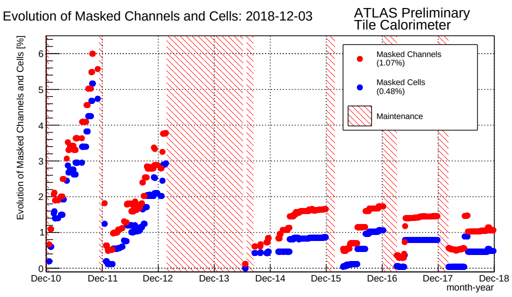

Figure 4: Percentage of all cells and channels in the detector that are masked as a function of time starting from December 2010 to December 2018. The shaded regions represent the maintenance period of the detector. The legend includes the percentage of masked cells (0.48%) and masked channels (1.07%) as of the end of December 2018 [2].

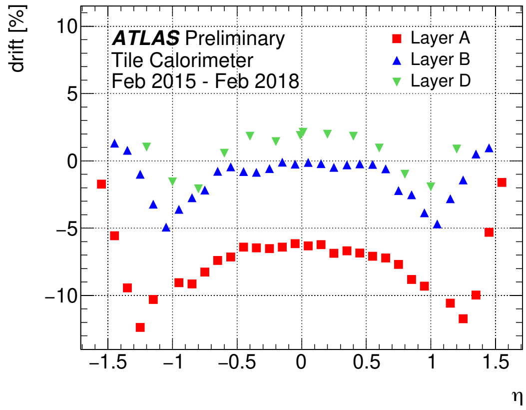

Figure 5: Cell response variation (drift) seen by the Cesium calibration system as a function of cell η [2]. This variation can be due to an instability of PMT high-voltage, PMT stress induced by high light flux, or scintillator ageing. The notation *Layer B* refers to Layer BC.

3. Upgrade towards the High-Luminosity LHC

The upgrade of the LHC to the High-Luminosity LHC (HL-LHC) foreseen in 2026 will provide invaluable opportunities to search for physics beyond the Standard Model, as well as detailed studies of the electroweak symmetry breaking mechanism and precise measurements of the properties of the recently discovered Higgs boson. To fully exploit the LHC potential, an upgrade to a luminosity of up to 7.5 times the nominal is planned, corresponding to an average of up to 200 simultaneous proton-proton interactions per bunch crossing ($\langle\mu\rangle$).

The current readout electronics of the TileCal must be upgraded to cope with the expected high trigger rate and intense radiation environment. In the current system the trigger decision signals have to be propagated from the back-end to the front-end electronics where digitized samples are stored in pipelines. In order to reduce the latency due to signal propagation delay, the pipeline buffers in the upgraded architecture will be placed closer to the trigger system. The upgraded readout scheme is illustrated in Figure 6. Its performance has been evaluated in simulation in terms of noise in the TileCal, cell occupancies, muon identification, high transverse momentum (p_{T}) jet reconstruction, as well as in data from test beam [3]. Figure 7 and Figure 8 show the dependence of the jet energy resolution for jets in the p_{T} range between 1.5 TeV and 2.5 TeV as a function

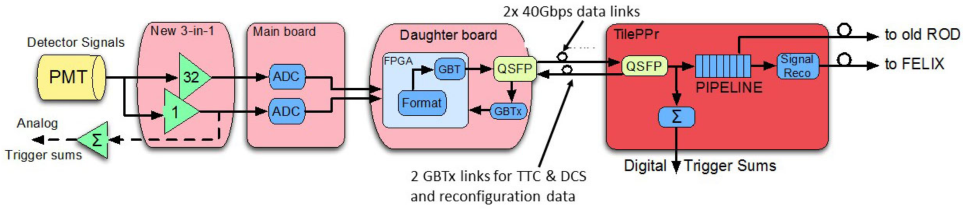

Figure 6: Phase-II architecture for the readout electronics [3].

of the fraction of the jet energy deposited in the first layer of the TileCal, f_{Tile0} for $|\eta| < 0.7$ and $1.0 < |\eta| < 1.7$, respectively. The jet energy resolution at the HL-LHC is 5–10% worse than in Run 2 simulations due to a much higher level of simultaneous proton-proton interactions per bunch crossing. Figure 9 shows the average jet energy resolution as a function of $\langle \mu \rangle$. This figure shows that the jet kinematics in very high pile-up conditions can be reconstructed at the HL-LHC with nearly equal precision as in Run 2. The jets used here are reconstructed from topo-clusters using the anti-kt algorithm [4] with a distance parameter of R=0.4. The jet calibration scheme used in the HL-LHC is simplified (i.e. no global sequential calibration (GSC)), in comparison to the nominal calibration used in Run 2 [6]. The pileup contribution is mitigated following the techniques described in [5].

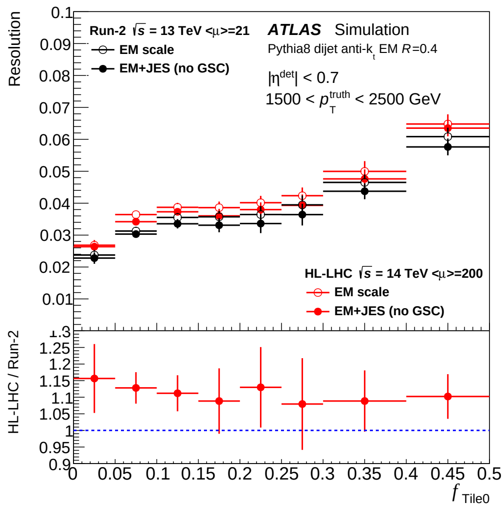

Figure 7: Jet energy resolution as a function of the jet energy fraction deposited in the A-layer of the TileCal for jets in the pseudo-rapidity range $|\eta| < 0.7$ [3]. EM and JES stand for Electromagnetic and jet energy scale [6].

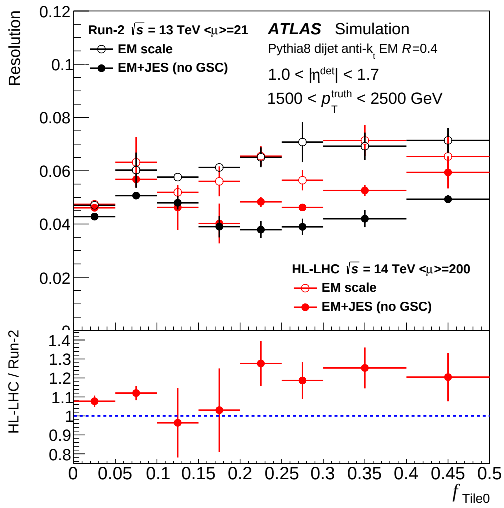

Figure 8: Jet energy resolution as a function of the jet energy fraction deposited in the A-layer of the TileCal for jets in the pseudo-rapidity range $1.0 < |\eta| < 1.7$ [3].

Extensive beam tests have been performed with the upgraded readout electronics [3]. The beams were produced by extracting 400 GeV protons from the Super Proton Synchrotron, where beams are directed to different targets, yielding beams composed of pions, protons, electrons, muons and kaons. Figure 10 shows the distributions obtained from simulated and test beam data using electron beams of 20, 50 and 100 GeV incident in the cell A4. These results show good performance of the new readout electronics and good agreement between data and simulation.

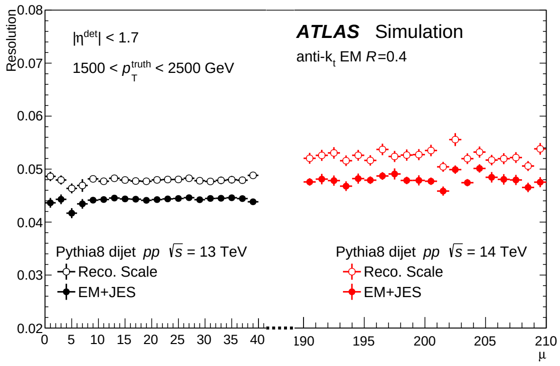

Figure 9: The average jet energy resolution as a function of the average number of simultaneous proton-proton interactions per bunch crossing $\langle\mu\rangle$. Black (red) markers denote the Run 2 (HL-LHC) MC simulation. Open (filled) markers indicate the EM (fully calibrated) jet energy scale [3].

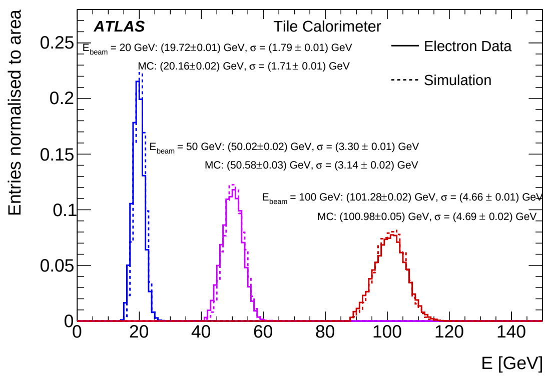

Figure 10: Distributions of the total energy deposited in the calorimeter obtained using electron beams of 20, 50 and 100 GeV incident in the cell A4 of the middle layer of the stack. The solid (dashed) distribution corresponds to experimental (simulated) data [3].

4. Conclusion

The ATLAS TileCal, its performance in Run 2, and the expected performance at the HL-LHC have been presented. A set of calibration and monitoring systems used in the TileCal led to a good performance in Run 2 of the LHC. The TileCal must be upgraded to comply with the new specifications aiming for the HL-LHC. The current electronics will be replaced with new ones that provide faster and more precise measurements, and high radiation tolerance. The performance of the new readout electronics has been evaluated in both simulation and test beam and the results are found to be promising.

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