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Upgrade of the ATLAS Hadronic Tile Calorimeter for the High Luminosity LHC

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The Tile Calorimeter (TileCal) is the hadronic calorimeter covering the central region of the ATLAS experiment. It is a sampling calorimeter with steel as absorber and scintillators as active medium. The scintillators are readout by wavelength shifting fibers coupled to photomultiplier tubes (PMTs). The TileCal response and its readout electronics are monitored to better than 1% using radioactive source, laser and charge injection systems. Both the on- and off-detector TileCal electronics will undergo significant upgrades in preparation for the high luminosity phase of the LHC (HL-LHC) expected to begin in 2029 so that the system can cope with the HL-LHC increased radiation levels and out-of-time pileup and can meet the requirements of a 1 MHz trigger. 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 improved readout architecture allows more complex trigger algorithms to be developed. The TileCal system design for the HL-LHC results from a long R&D program cross-validated by test beam studies and a demonstrator module. This module has reverse compatibility with the existing system and was inserted in ATLAS in August 2019 to test current detector conditions. The new design was tested with a beam of particles in 2021 at CERN SPS. The main features of the TileCal upgrade program and results obtained from the Demonstrator tests and test beam campaigns will be discussed.

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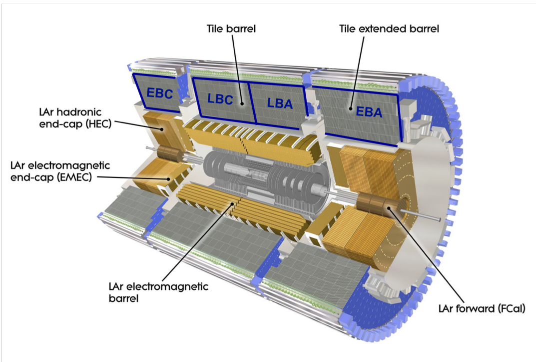
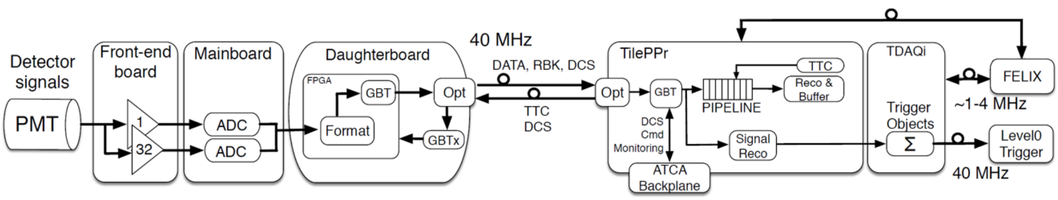
1. Introduction

The Tile Calorimeter (TileCal) [1] is the central hadronic calorimeter of the ATLAS experiment [2] at the CERN Large Hadron Collider (LHC) [3]. TileCal contributes to the measurement and reconstruction of hadrons, jets, τ-leptons hadronic decays and missing transverse momentum. It is also used for the muon identification and provides inputs to the Level 1 calorimeter trigger system. TileCal is a sampling calorimeter consisting of staggered steel plates and plastic scintillating tiles. It is divided into a central barrel and two extended barrels, as shown in Figure 1(a), covering the pseudo-rapidity range $|\eta| < 1.7$. Each barrel is segmented into 64 modules, with a 0.1 granularity in $\Delta\phi$. Each module is segmented in the radial direction into three layers. The granularity in $\Delta\eta$ in the two innermost layers is 0.1 and it is 0.2 in the outermost layer. In total there are 5182 cells in 256 TileCal modules. Charged particles produce light in scintillators, which is collected by wavelength shifting (WLS) fibres from the two sides of each plastic tile and transported to the photomultiplier tubes (PMTs). Each cell is readout by two PMTs to provide signal redundancy and to improve the energy resolution. The PMT signals are digitized at the 40 MHz frequency and the digital samples are stored in front-end pipeline memories.

The High Luminosity LHC (HL-LHC) [4] will provide an instantaneous luminosity that is at



(a)



(b)

Figure 1: (a) Cut-away view of the ATLAS calorimeter system. The Tile Calorimeter, consisting of one barrel and two extended barrels, is shown with grey color in the outermost part of the picture. (b) The TileCal electronics architecture for the HL-LHC [5]. The front-end electronics section (on the left side of the diagram) with the PMTs, FENICS, Main Board and Daughter Board is connected by long fibres to the back-end electronics section (right side of the diagram) with the TileCal PreProcessor. The TDAQi module is optically interfaced to the trigger and DAQ systems.

least five times larger than the nominal LHC one, with the goal of collecting 4000 fb^{-1} integrated luminosity by the end of the HL-LHC data-taking. This dataset will allow to probe with great precision the Standard Model (SM) of particle physics and opens unprecedented opportunities to study rare processes and probe for Beyond SM phenomena. However, the HL-LHC conditions impose significant challenges for the detector, trigger and data acquisition systems. Around 200 simultaneous proton–proton collisions will happen for every bunch crossing, leading to a significant increase of the particle flux in the detector. The whole TileCal readout system has to be replaced in order to cope with the increase in data rate, and to enhance radiation tolerance of the front-end electronics. In addition, the most exposed 10% of the TileCal PMTs will be replaced. The higher radiation levels require as well the redesign of the low-voltage (LV) and high-voltage (HV) power distribution and regulation systems. The HL-LHC will start proton–proton collisions in 2029. This document presents the ATLAS Tile Calorimeter upgrade program [5, 6] and discusses its current status.

2. Mechanics and power distribution

The current mechanical unit sharing common power supply and holding PMT blocks and readout electronics of each TileCal module is called Super-Drawer (SD). Currently, each SD is formed by Drawers hosting up to 24 PMTs. A more modular design of SDs is being implemented for the upgrade mechanics, where each SD is formed by four linked Mini-Drawers (MD), each one housing up to 12 PMTs and with separate power supply and readout architecture to facilitate its installation and maintenance. The HV distribution system provides HV from the bulk power supply to individual PMTs with good stability through one regulation board, which provides the required voltage values for up to 48 PMTs. Differently from the present system, the new HV system regulation will be placed away from the detector to avoid radiation issues. The LV distribution system is currently providing power to the front-end electronics in two stages. For the HL-LHC Upgrade, a new system with threes stages with improved reliability and robustness has been designed. The bulk 200 V DC voltage is distributed to split boxes (1 box per 32 SD), then DC-DC converters (2 per SD) supply 10 V DC to the front-end electronics. Finally, point-of-load regulators are mounted on the electronics Main Board (described in Section 3) to provide the required voltages to each component. All elements of the LV power supply system have passed radiation tests for large doses.

3. Electronics

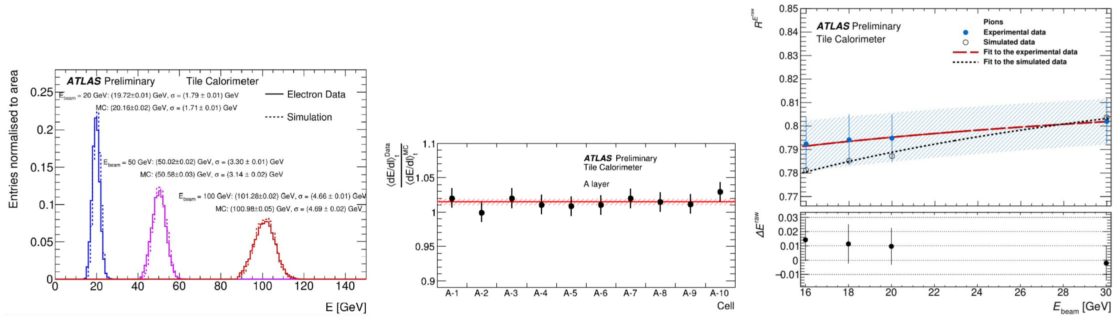
The scheme of the TileCal readout electronics is shown in Figure 1(b). The electronic is divided into front-end and back-end electronics. The new front-end electronic is designed to be radiation-hard for large doses. Electronics redundancy is increased as much as possible to minimize data loss during operations. The PMTs will be equipped with High Voltage Active Dividers to distribute power among the dynodes, improving the linearity in the response and, therefore, the accuracy on the energy scale calibration. The FENICS cards provide shaping and amplification of the PMT signals through two different readout paths: a fast readout for physics data-taking with two gains covers a dynamic range from 200 fC to 1000 pC; a slow readout with six gains integrates the PMT currents in order to calibrate the calorimeter response with a ^{137}Cs source. A Main Board (MB) is in charge of the digitisation of the low and high gain signals received from up to 12 FENICS cards. Each MB hosts a Daughter Board (DB), responsible for the high speed communication with the back-end electronics. Two 9.6 Gbps uplinks are responsible of the transmission of the digitised signals, while two 4.6 Gbps downlinks receive the LHC clock and configuration commands and distributes them to the front-end components. The TileCal PreProcessor (PPr) is the core of the back-end electronics. It is formed by an ATCA carrier board with four Compact Processing Modules (CPM). The CPM is designed as a double mid-size Advanced Mezzanine Card with Kintex Ultrascale FPGAs. Each CPM receives the data from the DBs of up to 2 modules, reconstructs online the amplitude and time of the pulses and buffers the data in pipeline memories until a trigger decision is received. A rear module, the TDAQ interface (TDAQi), receives the reconstructed amplitudes from the PPr, builds trigger objects for every bunch crossing and sends them to the first level of the ATLAS trigger. Moreover, a synchronous transmission of trigger objects copies is required to feed the different trigger systems designed for the ATLAS HL-LHC upgrade. If an event is accepted, the corresponding data is transmitted to the Front End LInk eXchange (FELIX) system.

4. Test-beam

Several test-beam campaigns have been carried out at CERN with the TileCal upgrade electronics for the HL-LHC. Recently, three Tile Calorimeter modules, two LBs and one EB, have been exposed to electron, muon and hadron beams of different energies and impact angles, at the H8 beam line of the Super Proton Synchrotron (SPS). The MDs were equipped with FENICS cards, Main Boards and Daughter Boards. The front-end electronics was powered with the pre-production version of the LV distribution system, and the latest prototypes of the HV system were used to operate the PMTs. The front-end electronic was configured through the TileCal PPr, used to take both physics and calibration data. In addition, one module was equipped with a combination of the upgrade and current electronics to compare the performance of the two systems. The good performance of the new electronics was demonstrated during these test beam campaigns. Figure 2(a) shows the distribution of the total energy deposited in the TileCal module for different electron beam energies (20 GeV, 50 GeV, and 100 GeV) and compared with simulation. The response to high energy muons has been studied using 165 GeV muons at an incident angle of $-90°$. The ratio between the energy deposited (dE) in a cell and the track path-length along the same cell (dl) was calculated in order to study the residual dependence of the muon energy on the path length. Figure 2(b) presents the ratio between the dE/dl values obtained for test-beam data and simulation, corresponding to the different cells of a the A layer of a module. The response to hadrons beams (pion, kaon and proton) with energies, E_{beam}, ranging from 16 to 30 GeV [7] is shown in Figure 2(c) and compared with simulated data.

5. Demonstrator

A Demonstrator module, equipped with upgrade electronics and offering backward compatibility with the analog trigger signal of the current modules, was inserted in the ATLAS detector at the end of July 2019. This module has shown stable performance and reduced noise with respect to the current electronics. The module is being operated during the Run 3 of the LHC to gain



(a) (b) (c)

Figure 2: (a) Distributions of the total energy deposited in the calorimeter obtained using electrons beams of 20, 50 and 100 GeV incident with an angle of 20° in the cell A-4 of the middle layer of the stack . The solid (dashed) distribution corresponds to experimental (simulated) data. The simulation is obtained using Geant 4.10.1 with FTFP_BERT physics list [8]. (b) Ratios of the energy deposited in the A layer cells per unit of path length between test-beam data and simulation, as a function of the cell number, obtained using a muon beam of 165 GeV with an impact angle of −90°. Results are obtained by analyzing Demonstrator data. The horizontal line corresponds to the mean value of the determinations and dashed red strips show uncertainty. (c) Energy response normalized to incident beam energy, $R^{<E_{\mathrm{raw}}>}$, measured (blue dots) and predicted by simulation (black circles) as a function of beam energy obtained in the case of pion beams. The experimental uncertainties include statistical and systematic effects combined in quadrature. Simulated results show only statistical uncertainty. The red dashed (black dot) curves are fits to the experimental (simulated) data points. In case of experimental determinations the dashed blue strips display the correlated systematic uncertainties. In the bottom of the histograms are shown the fractional differences $\Delta < E_{\mathrm{raw}} >$ defined in Ref. [7]. The uncertainties include statistical and systematic effects combined in quadrature.

experience with the new electronics before the start of the HL-LHC operations. The demonstrator module implements the clock and readout strategy for the HL-LHC. In the back-end electronics, the PPr receives digitized data from the Demonstrator module at the LHC frequency, and transmits triggered data to the ATLAS current readout system. During Run 3, the Demonstrator module is providing data for proton–proton collisions to the ATLAS TDAQ system in parallel with the rest of the TileCal modules.

6. Conclusions

The HL-LHC will provide unprecedented possibilities to search for new physics phenomena and test the Standard Model of particle physics, thanks to the large increase of instantaneous luminosity. ATLAS started an upgrade of the detector in order to withstand the tougher radiation environment and to provide excellent detector and data-taking performance. The upgrade requires a full replacement of TileCal front-end and back-end electronics. The design of the TileCal upgrade for the HL-LHC is close to be complete. Integration tests of the different parts of the TileCal upgrade project have been performed. The radiation tests of the prototypes of the active components have shown that the components are sufficiently radiation hard for the particle fluxes expected at the HL-LHC. Several parts of the front-end and back-end electronics are either close to the final production stage or in the pre-production phase. Tests for the low voltage distribution system and the high-voltage power supply system have been successfully completed. Several test-beam campaigns have been performed during the last years to test the prototypes of various TileCal subsystems in data-taking conditions. The acquired data have been used to validate the electromagnetic scale and constrain the modelling of hadron interactions in the calorimeter. A Demonstrator module of the upgrade TileCal electronics, offering compatibility with the current data readout paths, was inserted in the ATLAS detector at the end of July 2019. This module is being operated during the Run 3 of the LHC.

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