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Upgrade of ATLAS Hadronic Tile Calorimeter for the High Luminosity LHC

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Abstract

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 High-Luminosity phase of LHC, delivering five times the LHC nominal instantaneous luminosity, is expected to begin in 2029. TileCal will require new electronics to meet the requirements of a 1 MHz trigger, higher ambient radiation, and to ensure better performance under high pile-up conditions. Both the on- and off-detector TileCal electronics will be replaced during the shutdown of 2026-2028. 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 of the calorimeter signals used by the trigger system and will allow the development of more complex trigger algorithms. The modular front-end electronics feature radiation-tolerant commercial off-the-shelf components and redundant design to minimise single points of failure. The timing, control and communication interface with the off-detector electronics is implemented with modern Field Programmable Gate Arrays (FPGAs) and high speed fibre optic links running up to 9.6 Gb/s. The TileCal upgrade program has included extensive R&D and test beam studies. A Demonstrator module with reverse compatibility with the existing system was inserted in ATLAS in July 2019 for testing in actual detector conditions. The ongoing developments for on- and off-detector systems, together with expected performance characteristics and results of test-beam campaigns with the electronics prototypes will be discussed.

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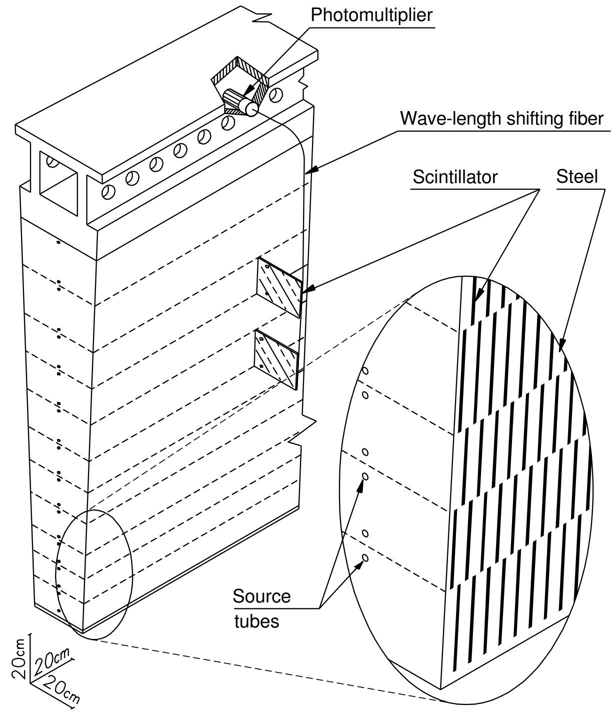

Figure 1: Components and mechanical structure of a TileCal module [2].

1 Introduction

The LHC (Large Hadron Collider) [1] was designed to collide bunches of accelerated particles (protons or heavy ions) at CERN (European Organization for Nuclear Research) with a period of 25 ns. Dedicated experiments were build at collision points. One of the general purpose experiments is the detector ATLAS (A Toroidal LHC ApparatuS) [2]. The experiments record signatures of the particles created in collisions such as their tracks, energies, and derive their identities.

The ATLAS contains 3 layers of detectors. The innermost layer is a track detector to measure tracks of charged particles. The next layer contains electromagnetic and hadron calorimeters to measure total energy of particles. The momenta of the most penetrating charged particles – muons – are measured in the muon spectrometer in the outer layer. The ATLAS is transparent for neutrinos. The central hadron calorimeter of the ATLAS is the Tile Calorimeter (TileCal) [3].

The TileCal is a sampling calorimeter built with steel plates as absorber and scintillating tiles interleaving the steel plates. The TileCal consists from three barrels. The central Long Barrel is divided into two partitions (LBA, LBC). The Extended Barrels (EBA, EBC) are located on each side of the Long Barrel. Each barrel is constructed from 64 modules. Each module contains 11 layers of scintillators placed perpendicular to the beam direction.

The light produced by each scintillating tile is collected by wavelenght shifting (WLS) fibers and transmitted to Photo-Multiplier Tubes (PMT) where a fast electric signal is produced (see Figure1). This electric signal is further conditioned in the on-detector electronics through a shaper circuit [4] before being digitized at a sampling frequency of 40 MHz with 10-bit Analog-to-Digital Converters (ADCs) [5]. In total, almost 10,000 readout signals are available at every collision.

The High-Luminosity Large Hadron Collider (HL-LHC) is a project to increase the potential for discoveries of the LHC [6]. The luminosity will increase by a factor of almost 10 beyond the LHC's design value, reaching an instantaneous luminosity of $7{,}5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The expected average number of collisions per bunch crossing is 200. The total integrated luminosity of $4000\,\mathrm{fb}^{-1}$ will reach in 2040. The new ATLAS trigger and data acquisition systems requires complete revision of the TileCal readout electronics [7].

2 Upgrade of the Tile Calorimeter for the HL-LHC

The TileCal digital data are stored in the on-detector pipeline memory until a first level trigger acceptance signal is received in the current electronics used at LHC (legacy). Then, the data of the accepted event are read out to the off-detector electronics at the maximum rate of 100 kHz. The TileCal readout electronics needs to be completely revised to cope with the unprecedented condition of the ATLAS at HL-LHC. Some TileCal components including the scintillating tiles and WLS are build in the detector and cannot be replaced. Both on- and off- detector TileCal electronics components will be replaced for the HL-LHC condition. The upgrade includes: new mechanical structure for the on-detector electronics, improved low voltage (LV) and high voltage (HV) systems, active dividers for all PMTs, replacement of 10% of PMTs (the most exposed ones), digital trigger output up to 40 MHz, increased detector read-out bandwidth to 40 Tbps for the entire TileCal.

The TileCal on-detector electronics and PMTs of each module are housed in three-meter long drawers called Super Drawers (SD). The legacy SD consists from two permanently jointed drawers with common components. Failure of the common components like power sources or interface cards can lead to loss of the full module. In the new configuration, the SD consists from four independent mechanically connected Mini Drawers (MD). SD for the extended barrel modules contain only three MD and two passive spacers. Each MD can contain up to 12 PMTs. The MD has independent parts for 6 up and 6 down PMTs. Failure of any component can lead to loss not more than 6 PMTs. Most of the TileCal cells have two PMTs and the loss of one of them allows to continue the operation. The new configuration simplifies installation and manipulation. The modularity, redundancy and robustness achieved by the new configuration improve the reliability of the on-detector acquisition system [8].

The new on-detector electronics transmits digitalised data at the rate of 40 MHz to off-detector units. Memory buffers (pipeline) are moved to the off-detector part. The on-detector parts contain two signal paths with the gain ratio 1 : 32. Each signal path has a 12-bit ADC. The off-detector part contains digital trigger output which allows more advanced trigger algorithms.

The HV regulation and distribution systems are moved off-detector. It allows to access and maintain the systems during the LHC operation. The on-detector part of the HV system contains only passive distribution boards.

The PMTs will operate at higher value of the direct current (DC), up to 40 μA. All PMTs will be equipped with active dividers with good linearity for currents up to 100 μA. 10% of PMTs will be replaced. These are the PMTs of the most exposed cells that are expected to have the highest level of degradation of the PMT gain with the high integrated anode charge during the HL-LHC operation.

The new LV system is designed to provide better reliability, lower noise, improved radiation tolerance and reduced single points of failure in comparison with the legacy. The system has three stages:

- Stage 1 is off-detector and provides 200 V DC.
- Stage 2 is on-detector located on the outer side of modules. There are eight DC bricks for each module with single level voltage of 10 V. Two bricks are connected to each MD, one for the up and one for the down half. The MD contains fuse and diode circuit which allows to power both MD parts using only one brick.
- Stage 3 is on-detector located on each half of the MD. It provides all required voltage levels for the MD components.

2.1 The Demonstrator Module

The Demonstrator Module was built to provide the backward-compatible upgraded electronics together with the legacy. The demonstrator was inserted to ATLAS in July 2019 and will be kept in ATLAS during the RUN 3 data taking period. The Demonstrator contains upgraded version of the electronics and analog adder cards for compatibility with the legacy ATLAS trigger.

The Demonstrator PreProcessor is a modified system to ensure compatibility with current TDAQ (Trigger & Data Acquisition) and TTC (Timing, Trigger and Control) system. The Demonstrator can be controlled and monitored by DCS (Detector Control System) like any other module.

The Demonstrator was tested at test-beam campaigns in CERN at the H8 SPS secondary beam during 2015 – 2018. The module with Demonstrator was exposed to particle beams with various particles and momenta. The acquired results show very good performance and good agreement between data and Monte Carlo predictions.

The Demonstrator is tested in ATLAS from July 2019. The Demonstrator is powered (HV and LV) and monitored using DCS and calibrated using the legacy TDAQ. The Demonstrator is also embedded into legacy calibration systems (pedestal, laser, charge injection system – CIS). The calibration data show stable performance, low noise and good CIS and laser signals. Also the analog trigger towers output was commissioned to the ATLAS level 1 trigger. First cosmic data and the LHC splash events were recorded. The Demonstrator performs as good or better compared to the legacy module.

3 Conclusions

The High-Luminosity LHC is expected to start its operation in 2029. The electronics of the TileCal was completely revised to cope with the expected conditions at the HL-LHC. The new configuration of the TileCal improves redundancy and robustness of the system and removes single points of failure. The digital trigger output allows more complex trigger algorithms.

A hybrid Demonstrator module is used to test the new components in the legacy environment. The Demonstrator was tested and validated in test-beam campaigns and integrated into current ATLAS systems. The results show good performance of the new electronics. The Demonstrator will be kept in ATLAS during the RUN 3 data taking period to gain more experience before installation of the new systems for the HL-LHC.

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