PROCEEDINGS OF SCIENCE

Upgrade of 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. The High-Luminosity phase of LHC, delivering five times the LHC nominal instantaneous luminosity, is expected to start 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. Approximately 10% of the PMTs, those reading out the most exposed cells, will be replaced. 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 40MHz. 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 components and redundant design to minimize 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 equipped with the new electronics but with reverse compatibility with the existing readout system was inserted in ATLAS in August 2019 for testing in actual detector conditions. The status of the various components and the results of test-beam campaigns with the electronics prototypes will be discussed.

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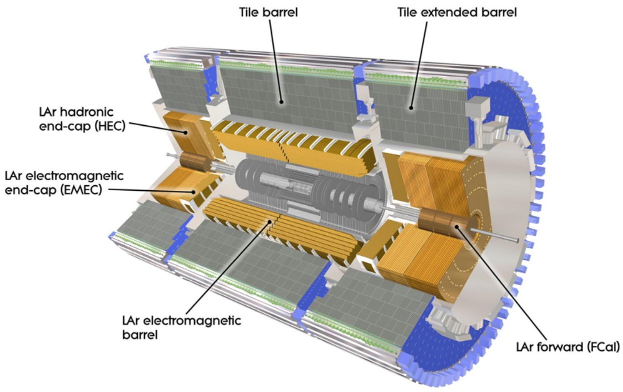

Figure 1: ATLAS calorimetry [1]

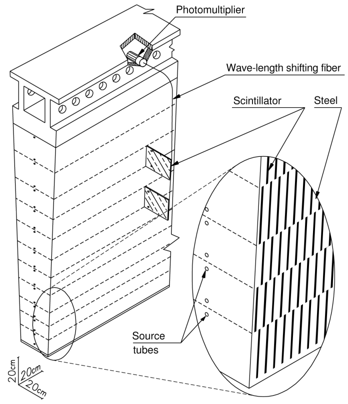

Figure 2: Tile module wedge [1]

1. Introduction

The ATLAS Tile Calorimeter (TileCal) [1] is the central hadronic calorimeter of the ATLAS experiment [2] in the Large Hadron Collider (LHC) at CERN. TileCal contribution is crucial for measuring and reconstructing jets, hadrons, tau-lepton hadronic decays and missing transverse energy. It also provides inputs to the calorimeter trigger system. TileCal is a non-compensating sampling calorimeter with low-carbon steel as an absorber and plastic scintillating tiles as an active medium, oriented perpendicular to the beam axis, with the design resolution for jets $\Delta E/E = 50\%/\sqrt{E} \oplus 3\%$. It is divided into a central long barrel (LB) and two extended barrels (EB) sections (figure 1), covering the pseudo-rapidity range $\eta < |1.7|$. Each barrel is segmented into 64 wedges (modules) in ϕ. Each module is further segmented in the radial direction into three layers, providing 7 nuclear interaction lengths λ in the central region. The segmentation in η, ϕ and radial direction defines the cell structure of TileCal. There are 5182 cells in 256 TileCal modules in total.

Charged particles produce light in the 3mm trapezoidal scintillating tiles made from polystyrene with dopants, wrapped in Tyvek® paper, which is then collected by the green wavelength shifting (WLS) fibers (Kuraray Y11(200)MSJ) from the two sides (redundancy) of each plastic tile and transported to the photomultiplier tubes (PMTs) (Hamamatsu R7877), located at the outer radius of the calorimeter inside the metallic girder (figure 2). The fibers are bundled to define readout cells in η and r in one module.

To cope with the new challenges from the high-luminosity, high pile-up and high-frequency trigger readout of the HL-LHC, TileCal will undergo an extensive upgrade [3], entirely replacing its on- and off-detector electronics to provide 40 MHz continuous data readout from all channels and a digital trigger output (figure 3). On-detector electronics must have improved radiation hardness and redundancy. New mechanical supports for the front-end electronics will enhance the maintainability thanks to a more modular design. About 10% of the PMTs will be replaced by a more robust and performing model. New low-voltage and high-voltage power supplies will provide necessary power with better granularity. Calibration systems will be updated to comply with the new data-taking architecture and offer an extended functionality.

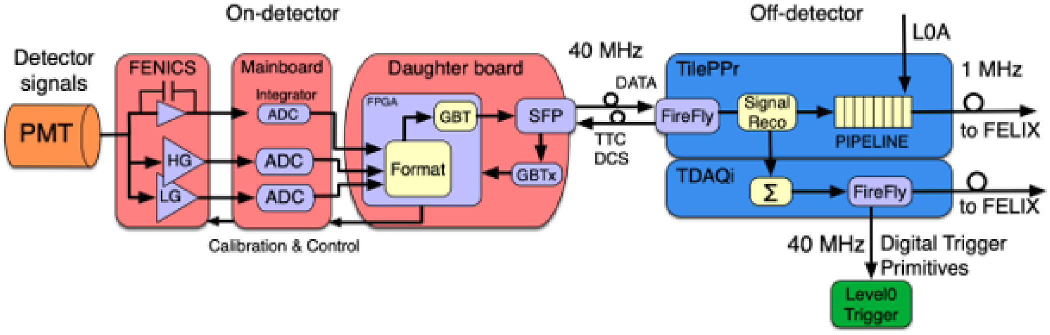

Figure 3: Schematic view of the new TileCal electronics architecture

2. Mechanics

The PMTs and on-detector electronics of TileCal are housed in super-drawers (SD), inserted into the girder on the outside radius of TileCal module, to shield them from magnetic field and radiation. To provide better modularity, serviceability and improved cooling, the new design consists of four mini-drawers (MD) (figure 4), connected in series, in the long barrel and 3 mini-drawers with two micro-drawers (μD) in the extended barrel sections. New mini-drawers provide robust mechanical and cooling links, allow finer modularity for the mechanics and its associated electronics, simplifying the installation and maintenance. A new services and tooling are also provided. The production is complete and delivered to CERN.

3. Electronics and power supplies

To cope with the large anode currents and charges during the HL-LHC, about 10% of the PMTs will be replaced with a more robust model (Hamamatsu R11187) in the most exposed cells, providing strong performance even after a significant charge accumulation (figure 5). To withstand the large anode currents, all PMTs will be equipped with active high-voltage dividers, providing stable high-voltage distribution for up to 100 μA anode currents. The PMTs are being produced, and the HV dividers are entirely produced and delivered to CERN.

The signals from the PMTs are shaped and amplified by the very-front-end board called FENICS. It has a 7-pole passive shaper to produce a unipolar pulse with 50 ns FWHM width with an amplitude proportional to the input charge of the PMT, two amplifiers with a 1:40 gain ratio and a slow integrating channel with six different gains for calibration and monitoring purposes, including luminosity measurements. It also has an embedded charge injection to calibrate fast and slow channels. The production is underway, including a lifetime test.

The shaped signals from FENICS are then digitized by fast 12-bit 40 Ms/s ADCs on the MainBoard that process and control up to 12 channels. Each board is split into two independent groups of 6 channels, providing additional robustness to communication and power supply failures. The MainBoard also digitizes the slow integrating channel by a 16-bit ADC. The digitization results are then collected by the DaughterBoard with large Kintex Ultrascale FPGA and sent out off-detector with GBT protocol via high-speed 9.6 Gb/s redundant optical links, using SFP+ transceivers. All MainBoards have been produced and delivered.

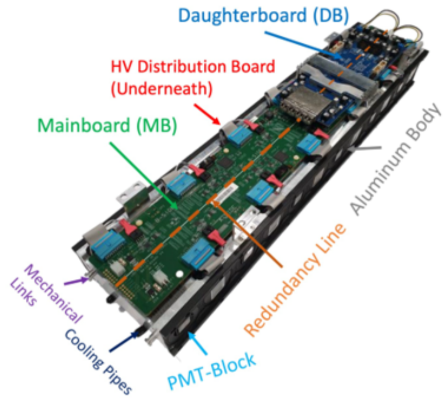

Figure 4: Fully equipped mini-drawer

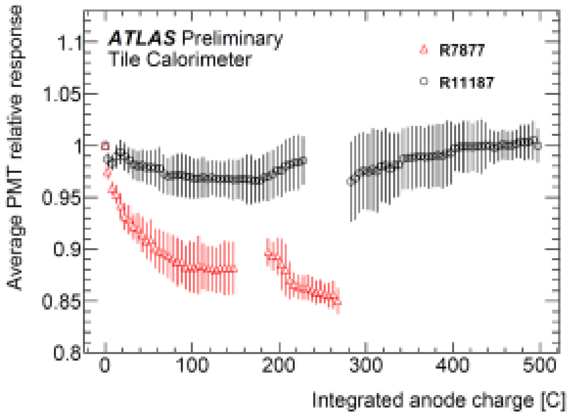

Figure 5: Response evolution comparison of PMT models [4].

The data from the detector is then processed by the off-detector electronics, the pre-processor boards (PPr) [5], installed in ATCA crates. The optical fibers are connected to the compact processing module (CPM). Four such modules, corresponding to 8 TileCal super-drawers, are housed on the ATCA carrier board. The CPM reconstruct the data using Kintex Ultrascale+ FPGAs, calculates energy and time for every 40 MHz bunch-crossing, and provides them to the ATCA RTM board called TDAQi. The trigger primitives are computed in TDAQi's FPGA, and data are then sent to the ATLAS trigger and DAQ system using optical links and the FELIX system. Several prototypes were tested and a final design is being prepared.

The new on-detector electronics require new, more radiation-hard low-voltage (LV) power supplies that are now using the three-level scheme, starting from 200 V AC-DC converters in the control room, 10 V DC-DC converters located in the TileCal modules and point-of-load regulators on the front-end boards themselves. Each mini-drawer now has its dedicated power brick that can be turned on and off independently, decreasing the amount of single-point failures. The pre-production of the bricks is underway.

The high-voltage (HV) system provides up to 1 kV for almost 10000 channels with individual settings and regulation. To simplify the design, reduce the radiation tolerance requirements, and ease the repair and maintenance, the new design uses remote regulation, with passive HV distribution boards on-detector and active regulation boards away from the high-radiation area. The design has been finalized and is moving to pre-production.

4. Calibration systems

Due to the change in the trigger and data acquisition architecture, and to survive harsher on-detector environment, the calibration systems of TileCal have to be upgraded as well.

The laser calibration system for the PMTs will have a new control and data interface, and the new functionality to add constant light to simulate the high pile-up conditions of HL-LHC during standalone calibration runs without collisions. This will be achieved by mixing the light from LED matrix and laser pulses using the integrating sphere.

The movable ^{137}Cs source calibration system will undergo a complete replacement of on- and off-detector electronics, with GBT optical links replacing the old CANbus lines. The hydraulic part that moves the source will also be upgraded, with the aim of reducing the operating pressure and reducing the stress on the system.

5. Integration, assembly, tests and installation

Before the final installation on the detector, the front-end electronics has to be assembled into the new mini-drawers and thoroughly tested. After the final installation it should be tested as well. A new Prometeo portable test-bench to certify the functionality and performance of the front-end electronics has been produced. The test results and board IDs will be saved in the installation database.

To validate the new electronics in more realistic conditions and to perform full slice tests of the complete chain of the on- and off-detector boards, many testing campaigns using the CERN SPS fixed target facility were performed with encouraging results. To gain more experience with collision data, a backward-compatible hydrid demonstrator was installed in TileCal detector in 2019 and is providing valuable data and training for future experts.

6. Summary

The HL-LHC upgrade challenges the detector and detector electronics in many aspects, including high radiation doses and high pile-up. The ATLAS Tile Calorimeter is significantly upgrading its on- and off-detector electronics to cope with these new challenges and new data-taking architecture. The project is on schedule, and many upgrade deliverables have already been produced. Multiple test beam campaigns help to validate the designs and involve new persons. An upgraded demonstrator module is already taking data in the ATLAS experiment, providing new information and training for future experts.

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