PROCEEDINGS OF SCIENCE

Upgrade of the ATLAS Tile Calorimeter for the High Luminosity LHC

Agostinho Gomes[a,b*] **on behalf of the ATLAS Tile Calorimeter**

a LIP - Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

b Faculdade de Ciências da Universidade de Lisboa, Lisboa, Portugal
E-mail: agomes@lip.pt

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 operation of High Luminosity LHC targets 4000 fb^{-1} of total integrated luminosity with an increase of a factor of five to the LHC nominal instantaneous luminosity. New electronics of the TileCal is needed 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 after the end of the LHC operation. 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 results of the extensive R&D programme for on- and off-detector systems, together with expected performance and results of beam tests with the electronics prototypes will be discussed. A demonstrator module which uses partly the upgrade electronics and is designed to be compatible with the current ATLAS read-out chain is in continuous operation since it was inserted in the TileCal in 2019.

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[*] Speaker

1. Introduction

The Tile Calorimeter [1] is a sampling hadronic calorimeter covering the central region of the ATLAS experiment [2] at the CERN Large Hadron Collider (LHC). TileCal is a key detector for measuring and reconstructing jets, hadrons, tau-lepton hadronic decays and missing transverse energy, with a design resolution of $\Delta E/E = 50\%/\sqrt{E} \oplus 3\%$ for jets. Additionally it also provides inputs to the ATLAS Level-1 calorimeter trigger system [2]. TileCal is a sampling calorimeter with steel as absorber and plastic scintillating tiles oriented perpendicular to the beam axis as active medium. It is composed by three cylindrical sections (figure 1, left), a central long barrel (LB) and two extended barrels (EB), covering the pseudo-rapidity range $|\eta| < 1.7$. Each of the three cylinders is made of 64 modules along ϕ. Each module (figure 1, right) is radially divided in three layers originated by selection of the scintillators that couple to each wavelength shifting (WLS) fibre. The cell structure of TileCal is defined by the segmentation in η, ϕ and radial directions, with 5182 cells in 256 modules in total.

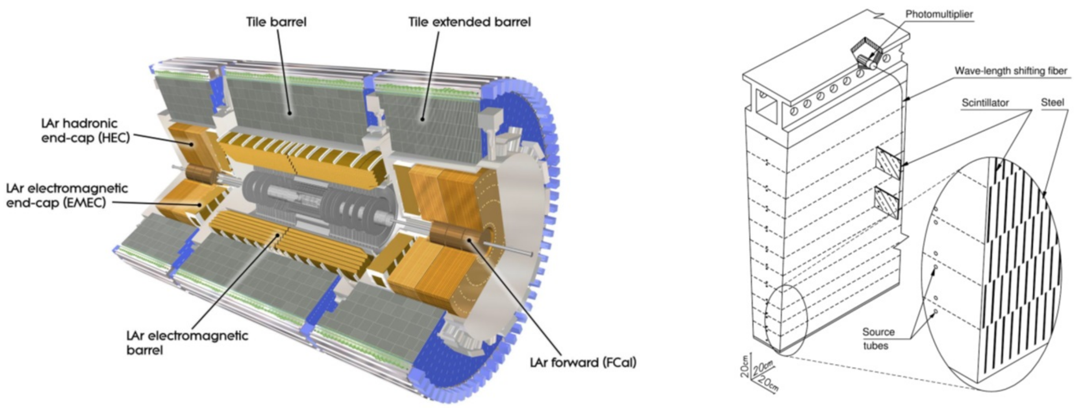

Figure 1 - The ATLAS calorimeters showing Tile calorimeter barrel and EB cylinders (left) and schematic view of a TileCal module (right).

The scintillators are made of polystyrene dopped with PTP and POPOP and light is produced when charged particles pass through them. They are wrapped in Tyvek for mechanical protection and light collection optimization and are coupled to two Kuraray Y11(200)MSJ WLS fibres that collect the light at both sides and transport it to the photomultiplier tubes (PMTs), located at the outer radius of the calorimeter inside the metallic girder. The WLS fibres are grouped in bundles according to the geometry of the cells of the calorimeter.

For the HL-LHC a major change in ATLAS is the replacement of the current analog trigger by a full digital trigger. To cope with the new challenges from the higher luminosity, pile-up and high-frequency trigger readout of the HL-LHC, TileCal will undergo an extensive upgrade [3], replacing its entire electronics to provide 40 MHz continuous data readout from all channels and a digital trigger output. On detector electronics must be more radiation tolerant and have increased redundancy and the respective new mechanical supports were redone with a more modular design for easier maintenance. While most of the PMTs will be re-used, about 10% in the most exposed cells will be replaced by a better performing model. New low voltage (LV) and high voltage (HV) power supplies will provide power with better granularity. The calibration systems will be updated to comply with the new data taking architecture.

2. Mechanics

The PMTs and on-detector electronics of TileCal are currently housed in super-drawers (SD), inserted into the girder on the outside radius of the TileCal modules, to shield them from magnetic field and radiation. A SD consists of two drawers, each one hosting up to 24 PMTs. Failure of the common components like power sources or interface cards can lead to loss of the full module. To provide better modularity, serviceability and improved cooling, the new design consists of four smaller mini drawers (MD) in the long barrel and 3 mini drawers with two micro drawers in the extended barrel sections. The new electronics modularity is designed in such a way that failure of any component will not result in a loss of more than 6 PMTs. The new MDs provide robust mechanical and cooling links, allow finer modularity for the mechanics and its associated electronics, simplifying the installation and maintenance. New services and tools were also built. The production of the mechanical components and tools is completed.

3. Replacement of the PMTs

Tilecal calibration systems including the laser and cesium systems are used to monitor the PMT response stability and degradation of the calorimeter signal. In general during collision periods there is a loss in a chanel response, followed by partial recovery during the long periods without collisions. Part of the response degradation is due to scintillator irradiation, that affects more the most exposed cells: the inner cells (layer A) and the cells in the gap region (layer E). An extreme example of light output degradation with the increase of integrated luminosity is shown in figure 2, left, for the A13 cells. The PMTs that readout these cells integrate also a larger amount of anode current. To cope with the large anode currents during the HL-LHC, about 10% of the PMTs will be replaced with a more robust model (Hamamatsu R11187) in the most exposed cells, keeping the initial performance even after a significant charge accumulation (figure 2, right) [4]. To withstand the large anode currents, all PMTs will be equipped with active high voltage dividers, providing a better linearity at high current than the current passive dividers. The PMTs are being produced and tested, and the HV dividers are entirely produced.

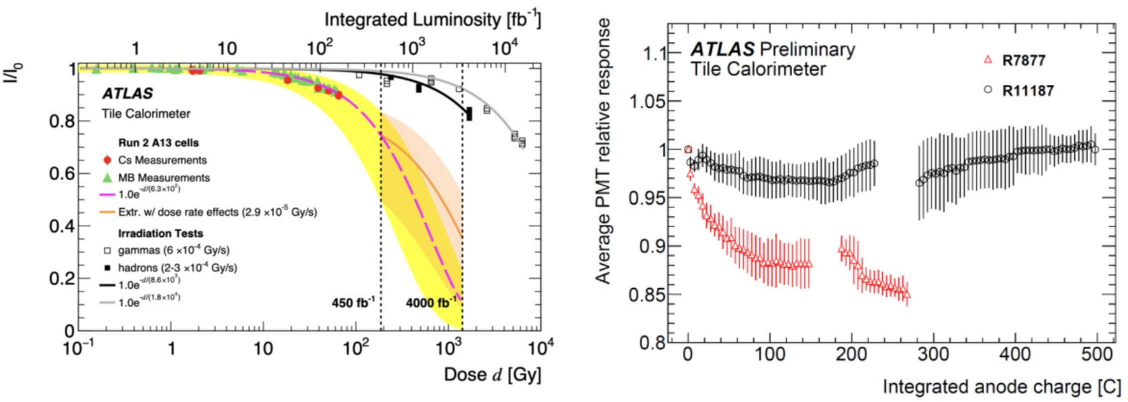

Figure 2 - Light output of cell A13 as a function of the dose with extrapolation for HL-LHC integrated luminosity (left) and response as a function of the integrated anode charge for old (red markers) and new (black markers) PMTs (right).

4. Readout electronics

The upgrade readout scheme is shown in figure 3. The front end board that shapes and amplifies the PMT signals is called FENICS. It produces an unipolar pulse with 50 ns FWHM width with an amplitude proportional to the output charge of the PMT, and has two amplifiers with a 1:40 gain ratio and a slow integrating channel for calibration and monitoring purposes, including luminosity measurements. It also has an embedded charge injection to calibrate fast and slow channels. Its production is ongoing.

The digitization of the signals shaped by FENICS is done on the MainBoard by fast 12-bit 40 Ms/s ADCs. A MainBoard processes and controls up to 12 channels. For additional robustness to failures in communication or power supply, each MainBoard is split into two independent groups of 6 channels. The MainBoard also digitizes the slow integrating channel using a 16-bit ADC. The digitization results are collected by a 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 already been produced. The DaughterBoard final prototype was successfully tested and pre-production is about to start.

Pre-processor boards (PPr), installed in ATCA crates are used to process the data transmitted by the DaughterBoards. Each PPr contains an ATCA Carrier Board and four Compact Processing Modules (CPM). The CPMs contain a Kintex UltraScale 115 FPGA and Samtec FireFly optical modules to receive 32 links at 9.6 Gb/s from eight DaughterBoards. The CPM reconstructs the data, calculates energy and time for every bunch-crossing, to be sent to TDAQi, an ATCA Rear Transition Module that produces primitives for the Level 0 trigger.

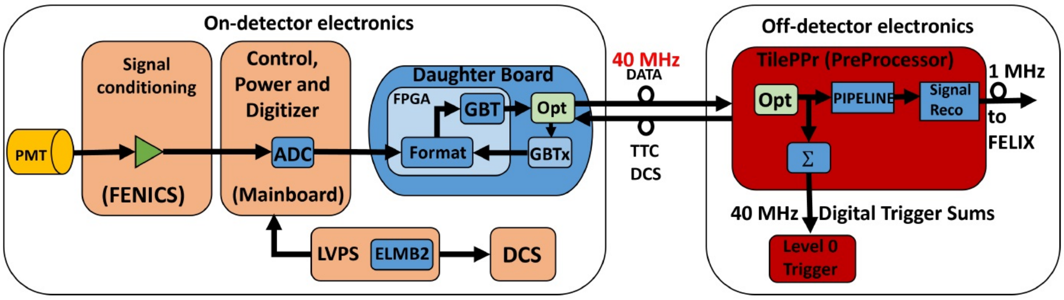

Figure 3 - Readout scheme for the upgrade, showing on- and off-detector electronics.

5. Power supplies

The new low voltage power supply is organized in a cascade with three levels starting from 200 V AC-DC converters in the electronics cavern, followed by bricks with 10 V DC-DC converters (figure 4, left) located in the TileCal modules and point-of-load regulators on the front-end boards. Each MD now has its dedicated power brick that can be turned on and off independently, decreasing the amount of single-point failures. The location of the last levels of conversion inside the detector required the development of more radiation hard power supplies. Currently the pre-production of the bricks is underway.

The current HV system is mostly located inside the detector, exposed to high levels of radiation. The new design moves the active regulation boards away from the high radiation area to the electronics cavern ~100 m far from the detector, keeping only fully passive boards inside the girder in the MDs to distribute the voltages to the PMTs. This strategy simplifies the design reducing the radiation tolerance requirements, and makes repair and maintenance easier. HV supply boards (figure 4, center) housed in custom crates generate voltages up to 1 kV that are then regulated individually for up to 48 PMTs per HVremote board (figure 4, right) located back to back in the same crates. A total of 256 sets of boards is used to produce the HVs used by ~10000 PMTs. The remote nature of the system requires a large number of wires, organized in 256 long cables, half of them with very demanding diameter limitations to be able to be installed in the existing flexible chains that serve the EB modules. The design of the cables and most of the boards has been finalized and some of them are in pre-production.

Figure 4: Low voltage brick (left). High voltage supply board (center) and HVremote board used for the individual regulation of the voltage for 48 PMTs (right).

6. Calibration systems

The calibration systems of TileCal have to be upgraded due to changes in the trigger and data acquisition architecture, and to operate in a more demanding detector environment. A new Charge Injection System is incorporated in the FENICS boards. The laser calibration system for the PMTs will have a new control and data interface (ILANA), and a new functionality to add constant light to mimic the continuous level of light from the high pile-up conditions of HL-LHC during standalone calibration runs without collisions. This will be achieved by mixing the light from a LED matrix and laser pulses using an integrating sphere.

The cesium calibration system that uses a movable ^{137}Cs source will undergo a complete replacement of the electronics, with GBT optical links replacing the old CANbus lines. The hydraulic part that moves the source will also be upgraded.

7. Testing, assembly and installation

To validate the new electronics in more realistic conditions, a set of TileCal modules including two new SDs have been tested for several years in a test beam setup using the CERN SPS fixed target facility. It is a full slice of the complete chain of the on- and off-detector boards where the powering system, back-end electronics and new SD front-end electronics are replaced every year with the most recent versions. It allows the testing of the detector with upgraded electronics using several types of particles and comparison with simulation. Results are shown in figure 5, right.

To gain experience with collision data, a backward-compatible hybrid demonstrator (figure 5, left) was installed in the TileCal detector in 2019. It is a full super-drawer equipped with new front-end electronics boards but also containing legacy boards to generate the analog trigger. It is readout by a new back-end system that can send data in both upgrade and legacy formats. Since its installation it has been successfully taking data, including physics collisions, and it is upgraded for the most recent versions of the boards in the winter technical stops.

The tools for the assembly of the new mini-drawers have been produced. Before installation on the detector, the front-end electronics has to be assembled into the new MDs and tested, and tested again after the final installation. A new portable test-bench (Prometeo) to certify the functionality and performance of the front-end electronics has been produced.

Both the test beam and the demonstrator module experience, as well as all the related SD assembly activities, are providing valuable data and training for future experts.

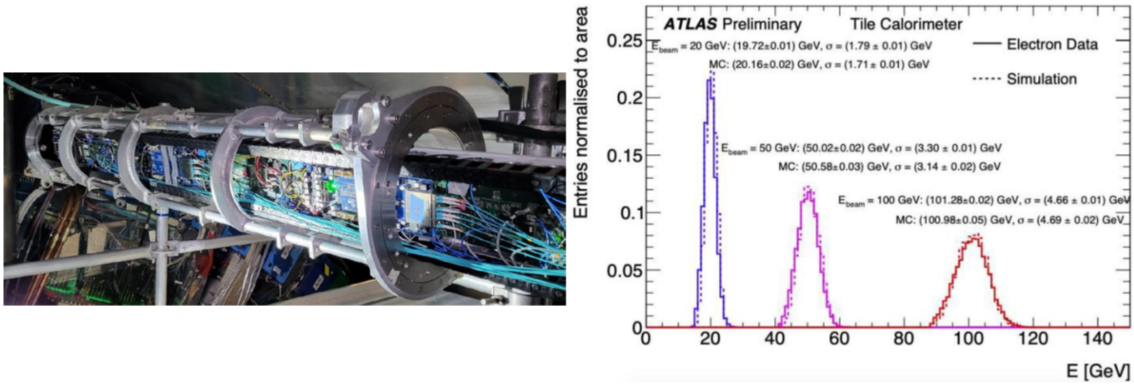

Figure 5: Demonstrator SD ready for installation in a TileCal module of ATLAS (left). Experimental data and simulation of the total energy deposited in a TileCal module by electrons in the test beam (right).

8. Summary

The ATLAS Tile Calorimeter will undergo an upgrade that will allow to operate in the challenging luminosity conditions of the HL-LHC. A new electronics system with full digital trigger, higher radiation tolerance and improved reliability will be in place for operation. The components of the new system are currently in production, after showing good performance in extensive testing in dedicated setups including test beam and the participation in the LHC collisions data taking in the demonstrator module installed in the ATLAS detector.

Acknowledgements

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References

[1] ATLAS Collaboration, *ATLAS tile calorimeter: Technical design report*, CERN-LHCC-96-42

[2] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008), S08003

[3] ATLAS Collaboration, *Technical Design Report for the Phase-II Upgrade of the ATLAS Tile Calorimeter*, CERN-LHCC-2017-019

[4] G. Chiarelli *et al*, *Long term aging test of the new PMTs for the HL-LHC ATLAS hadron calorimeter upgrade*, Nucl. Instrum. Meth. A 1045 (2023) 167595