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

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Abstract: The ATLAS hadronic Tile Calorimeter (TileCal) will undergo major upgrades to the on- and off-detector electronics in preparation for the high luminosity programme of the LHC (HL-LHC) in 2026. The system will cope with the HL-LHC increased radiation levels and out-of-time pileup. The on-detector electronics of the upgraded system will continuously digitize and transmit all photomultiplier signals to the off-detector systems at a 40 MHz rate. The off-detector electronics will store the data in pipeline buffers, reconstruct cell energy, produce digital hadronic cell sums of various granularity and send it to the Level-0 calorimeter trigger system, finally read out selected events. 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 using the beams from the Super Proton Synchrotron (SPS) accelerator at CERN. A Demonstrator module equipped with the novel electronics for the HL-LHC upgrade and compatible with the existing ATLAS read-out chain inserted in ATLAS in August 2019 for testing in actual detector conditions. We present the status of the upgrade program, the results using muon, electron and hadron beams at various incident energies and impact angles collected in 2015-2018, combined results of Demonstrator tests and calibration runs to evaluate the readiness of the new design.

Keywords: Calorimeters, Front-end electronics for detector readout

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Contents

1 Introduction

The ATLAS Tile Calorimeter (TileCal) is the central hadronic calorimeter section of the ATLAS experiment [1] at the Large Hadron Collider (LHC). The TileCal is a sampling calorimeter using plastic scintillator as the active material and iron as the absorber. It is divided into a long barrel, and two extended barrel cylinders, covering in total a pseudorapidity range of $|\eta| < 1.7$, each barrel is segmented into 64 modules along the azimuth angle ϕ. Each module consist of 11 tile rows which form 3 longitudinal layers. Wavelength shifting fibers collect the light generated in the tiles and carry it to photomultipliers (PMT). Each PMT receives signal from multiple tiles which are grouped into cells of different size depending on their pseudorapidity and depth.

The Phase-II upgrade will prepare the ATLAS experiment for the High Luminosity LHC (HL-LHC), which is planned to begin operation in 2027 and to deliver more than ten times the integrated luminosity (up to 4000 fb^{-1}) of the LHC Runs 1-3 combined. The TileCal will require a new electronics to provide a low-latency, high-frequency and fully digital input for ATLAS trigger system.

2 New TileCal electronics for the High-Luminosity LHC

The new readout architecture proposed for the Tile Calorimeter Phase-II Upgrade [2], provides a fully digital trigger system with full precision and granularity to improve the event selection. In order to operate in the higher radiation environment, the new readout electronics system will include redundant optical fibers between the front-end and back-end electronics, redundant radiation-tolerant electronics, redundant low voltage power supplies and for data transmission will use more reliable protocols with error correction.

Each module of the ATLAS Tile Calorimeter is housing a Super Drawer (SD). For the TileCal Phase-II Upgrade a Super Drawer is divided into 4 Minidrawers (MDs) each with independent readout and power supplies. In most cases the smaller units reduce the consequences of fatal failures to only affect 12 channels from one of the two sides of 12 calorimeter cells, i.e. not a complete loss of cell data. In the present system an entire superdrawer is affected. A MD hosts 12 PMTs and 12 Front-End Boards (FEBs) named FENICS (**F**ront-**E**nd electro**NICS**). The FENICS card performs signal shaping and amplification (2 gains, 1/32 ratio). A Mainboard (MB) digitizes the input from 12 FEBs with 2x12-bit ADCs at 40 Msps, resulting in a 17-bit dynamic range (0-800 pC). A Daughterboard (DB) transfers redundant bi-gain high-speed (4 x 9.6 Gbps) output data from 12 channels every 25 ns to the back-end electronics, distributes the LHC system clock and liaises the on- and off-detector electronics.

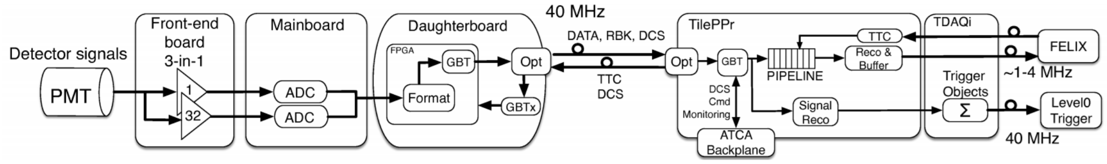


Figure 1. TileCal electronics layout for the HL-LHC [2].

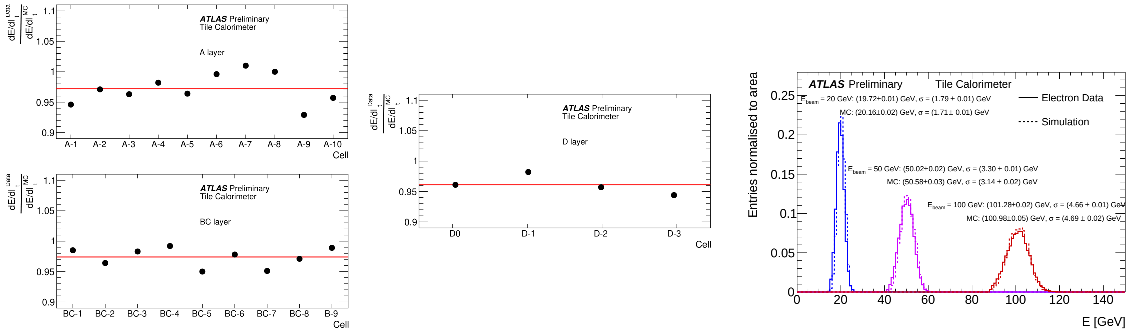
A Tile PPr (Preprocessor) which is located off-detector (Figure 1) buffers data from all MDs in pipelines, evaluates signal at the full 40 MHz rate, distributes the system clock and detector control and configuration information. It has to provide preprocessed trigger information for every bunch crossing. The **T**rigger and **D**ata **Acq**uisition **i**nterface (TDAQi) calculates trigger objects and interfaces with trigger and ATLAS TDAQ by sending accepted data via FELIX (**F**ront **E**nd **LI**nke**X**change). The TilePPr will transmit preprocessed data to the first level of trigger with improved precision and granularity for trigger decision. Table 1 shows a comparison between the data bandwidth of the current system and the Phase II architecture.

Table 1. Comparison between the Tile back-end read-out systems in the present (Read-Out Drivers - ROD) and Phase-II (Preprocessor - PPr) architectures.

Down-links	**Present**	**Phase II**
Number of fibers	512	2048
Link of bandwidth	80 Mbps	4.8 Gbps
Up-links	**Present**	**Phase II**
Number of fibres	512	4096
Link of bandwidth	800 Mbps	9.6 Gbps
Back-end read-out modules	32	32
Back-end crates	4 (VME)	4 (ATCA)
Back-end Input bandwidth	6.4 Gbps	625 Gbps
Back-end output bandwidth to DAQ	3.2 Gbps	40 Gbps
Back-end output bandwidth to Trigger	Analogue front-end	~500 Gbps

3 Test beams

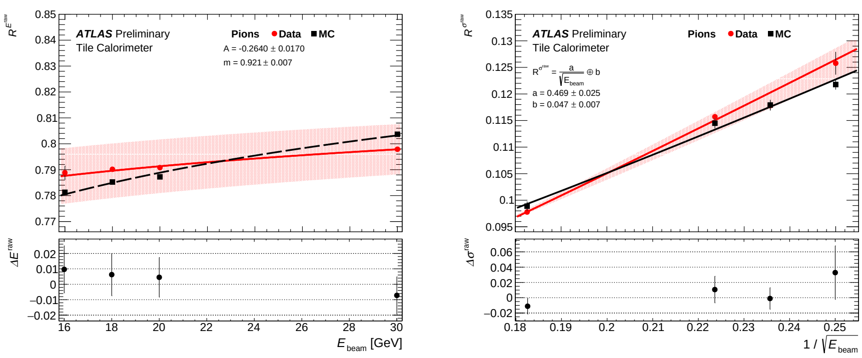
The TileCal modules equipped with Phase-II upgrade electronics together with modules equipped with the old electronics were exposed to different particles and energies in 7 test beam campaigns at CERN SPS North Area, during 2015-2018. A half-module has been equipped with the so-called Hybrid Demonstrator, which is a fully functional prototype of the new system, that can deliver analog trigger sums for backward compatibility. The extended barrel was equipped with new electronics in 2018 (latest generation of the front-end cards). Uniformity of the test module, that is segmented into three longitudinal layers (A, BC and D), was evelauted using muon beams (Figure 2(a)). Total energy deposited in the calorimeter obtained using electron beams was also studied (Figure 2(b)).



(a) (b)

Figure 2. (a) Ratios of the energy deposited in the A, BC and D layers' cells per unit of path length using experimental and simulated muon data as a function of the cell number. (b) Distributions of the total energy deposited in the calorimeter obtained using experimental and simulated electron data [2].

Detector energy response and resolution were studied using the hadron beams with different energies [3] (Figure 3). The results obtained using muons, electrons and hadrons are in agreement with the calibration settings obtained using the old electronics and with the expectations obtained using simulated data. They are consistent with the previous measurements [5].



(a) (b)

Figure 3. (a) Energy response ratios, measured experimentally (red circles) and predicted by simulation (black squares) as a function of beam energy obtained using pions [4]. (b) Fractional resolution, measured experimentally (red circles) and predicted by simulation (black quares) as a function of $\frac{1}{\sqrt{E_{\text{beam}}}}$ obtained using pions [4].

4 Summary

The Phase II Upgrade of the LHC plans to increase instantaneous luminosity by a factor of 5-10. Electronics will need to withstand a much higher radiation dose as well as an increased demand for data throughput. A stack of three modules of the hadronic calorimeter of the ATLAS experiment equipped with the updated front-end electronics has been exposed to the beams of the SPS at CERN. The results obtained using the different particle beams are in agreement with the calibration settings obtained using the old electronics and with the expectations obtained using simulated data. They are consistent with the previous measurements. All TileCal on- and off-detector electronics will be replaced in 2025-2027 during Phase II upgrade for the HL-LHC. R&D is done, initial tests demonstrate good performance. One Demonstrator super drawer with new electronics was inserted in the ATLAS detector and its performance is being evaluated.

Acknowledgments

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