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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 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 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 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 fiber 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 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.

KEYWORDS: Calorimeters; Front-end electronics for detector readout; Large detector systems for particle and astroparticle physics; Photon detectors for UV, visible and IR photons (vacuum)

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Contents

1 Introduction

The Tile Calorimeter (TileCal) [1] is the central hadronic calorimeter of the ATLAS experiment [2] in the Large Hadron Collider (LHC) [3] at CERN. TileCal contribution is crucial for the measurement and reconstruction of jets, hadrons, τ-lepton hadronic decays and missing transverse energy. It also provides inputs to the Level-1 calorimeter trigger system. TileCal is a sampling calorimeter using steel as absorber and plastic scintillating "*tiles*" as active medium. It is divided into a central long barrel (LB) and two extended barrels (EB) covering the pseudo-rapidity (η) range $|\eta| < 1.7$ (see figure 1 (left)). Each barrel is segmented into 64 wedges (modules) in ϕ, corresponding to a 0.1 granularity in $\Delta\phi$. Each module is further 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. The segmentation in η, ϕ and radial direction defines the cell structure of TileCal (see figure 1 (right)). In total, there are 5182 cells in 256 TileCal modules.

Charged particles produce light in the scintillating tiles, which is collected by wavelength shifting (WLS) fibers from the two sides of each plastic tile and transported to the photomultiplier tubes (PMTs). Fibers are grouped in bundles to define the unit readout cell. Each cell is readout by two PMTs to provide signal redundancy. In the present system the PMT signals are digitized at a frequency of 40 MHz. The digital samples are stored in front-end pipeline memories.

At the same time, the trigger analog boards sum the PMT pulses into pseudo-projective 0.1×0.1 in η, ϕ space trigger towers and send them to the Level-1 calorimeter trigger system. Once the event is accepted by the hardware-based Level-1 trigger system, it is extracted from pipelines and sent for further processing.

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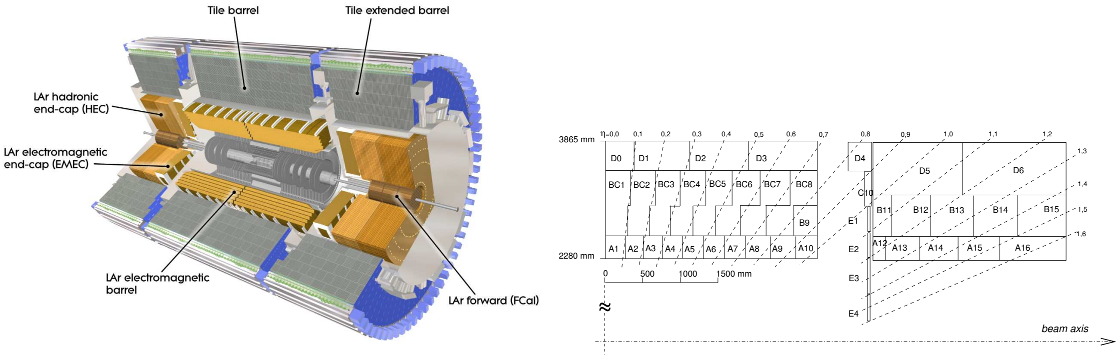

Figure 1. Left: a drawing of the ATLAS inner detector and calorimeters. TileCal consists of one central long barrel and two extended barrel sections and surrounds the LAr barrel electromagnetic and endcap hadronic calorimeters. Right: segmentation in depth and in η of the TileCal modules in the central and extended barrels. The bottom of the picture corresponds to the inner radius of the calorimeter. TileCal is symmetric with respect to the interaction point at the origin.

The High-Luminosity upgrade of the LHC (HL-LHC) [4] will provide an instantaneous luminosity that is at least five times larger than the nominal LHC one, with the goal to collect data corresponding to 4000 fb^{-1} of 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 will open up unique opportunities to study rare production processes and probe for beyond the SM physics with unprecedented sensitivity.

The high-luminosity conditions impose significant challenges for the detector, trigger, and data-acquisition systems. Up to 200 simultaneous proton-proton collisions are expected for every bunch crossing, leading to a significant increase of the particle flux in the detector. TileCal on-detector electronics will receive up to about 160 Gy of total ionizing dose (TID) during the full HL-LHC data taking, which is an order of magnitude larger than in Run-2 and Run-3 operations.

The HL-LHC phase of proton-proton collisions is expected to start in 2029 (Phase-II). In preparation, the ATLAS experiment is deeply committed into the design and construction of the upgraded detector [5], and the TileCal upgrade is part of this overall program. The full TileCal readout system has to be replaced in order to cope with the increase in the data rate, to enhance radiation tolerance of the on-detector electronics, and to be compatible with the fully digital ATLAS trigger and data-acquisition system for the HL-LHC [6]. In addition, about 10% of the PMTs, those reading out the most exposed cells, will be replaced by new PMTs, while the rest of the optics will be retained. The higher radiation levels require also the redesign of the low-voltage (LV) and high-voltage (HV) power distribution and regulation systems.

2 Mechanical structure

The current mechanical unit sharing common power supply and holding PMTs and readout electronics of each TileCal module is called Super-Drawer (SD). A SD consists of two joined drawers, each one hosting up to 24 PMTs with common components. Failure of the common components like power sources or interface cards can lead to loss of the full module.

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In the new upgrade calorimeter the mechanics has a modular design to facilitate accessibility and handling during the installation and maintenance. The new SD is made by mechanically linked Mini-Drawers (MD). Each MD forms an independent readout subsystem containing up to 12 PMTs and the required electronics for their operation, and is electrically independent from the adjacent MDs. The MD has two independent parts for reading 6 PMTs each. Failure of any component can lead to loose not more than 6 PMTs. Four MDs are linked to create one LB super-drawer, while three MDs form one EB super-drawer. In EB super-drawers there are two additional micro-drawers that hold the PMTs in the right position and do not include digital electronics. The modularity, redundancy and robustness achieved by the new configuration improve the reliability of the on-detector acquisition system. The production of all the SD mechanics is completed.

3 PMT's replacement

PMT response stability is monitored in TileCal with a laser calibration system which is part of the TileCal global calibration system [8]. PMT response variations were observed during collision and no-collision periods. As shown in figure 2 (left), a response loss occurs during collisions, followed by a partial response recovery in long no-collision periods (LHC machine shut-downs). Part of the response degradation is due to scintillator aging. The aging effects are more pronounced for the inner, most exposed cell layer A, whose readout PMTs integrate a larger amount of anode current.

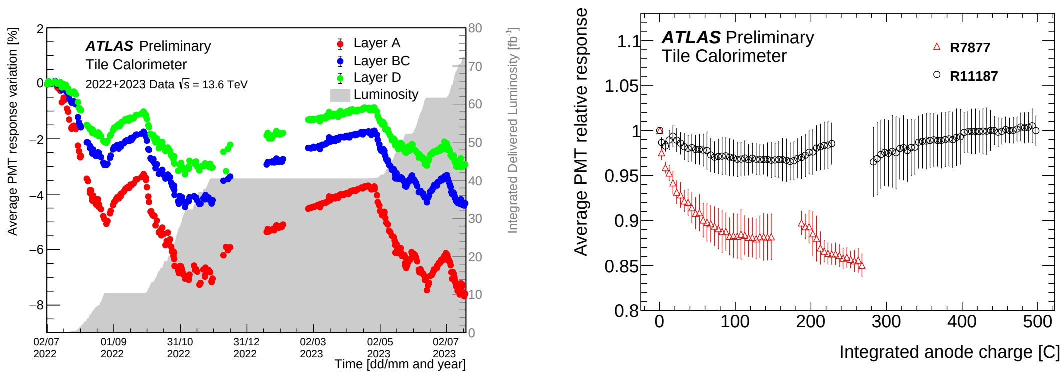

Figure 2. Left: the average relative response variation in the PMTs for each layer (A, BC, D) in TileCal as a function of time during LHC Run3. The LHC delivered luminosity is shown in grey. The down-drifts coincide with pp collision periods, while the response recovery occurs during heavy-ion collisions and technical stops. Down-drifts mostly affect PMTs reading out the most exposed cells (A-cells). Right: average PMT response as a function of integrated anode charge, in a dedicated test setup. The two different PMT types are shown separately. Each point is evaluated as the average of the response of the set of PMTs with the same integrated charge. The error bar corresponds to the RMS of the PMT response over the set.

Significant response variation (> 20%) is expected to occur for PMTs having integrated hundreds of Coulomb of anode charge, with a large spread of the response variation for different PMTs (an integrated charge of 600 C is expected at the end of HL-LHC, for the most exposed cells). Based on the results from laser calibration data and from a dedicated test setup, the TileCal Collaboration decided to replace before HL-LHC starts about 1,000 of the 9852 PMTs model Hamamatsu1 R7877, installed in the detector before start of LHC run 1 and reading out the most exposed cells, with the latest version of the same Hamamatsu PMT, labelled as R11187.

A recent production (2019) sample of PMTs model R11187 was tested in Pisa INFN Laboratory with a dedicated experimental setup. The main goal was to study the average PMT response stability and the spread in the sample of the response variation as a function of the integrated anode charge, with the goal of reaching the target 600 C in about 2 years. Studies on PMT aging effects during long period excitation were performed on a sample of 22 PMTs, including 3 old model R7877 PMTs and 19 new model R11187 PMTs. The 3 old model R7877 PMTs were dismounted in 2017 from the TileCal calorimeter after having integrated only a few Coulomb of anode charge. In the test setup, the PMTs are excited using laser light ($\lambda = 532$ nm) while a LED is used to generate a constant light to enhance the charge integrated by the PMTs. Figure 2 (right) shows the average PMT response as a function of the integrated anode charge for the two different PMT models [7]. The PMT response is normalized to the first day of data taking and to the signal of a reference PMT monitoring the laser light intensity. There is a clear separation between the old (R7877) and new (R11187) PMT models. New PMT model shows a smaller down-drift as a function of the integrated anode charge.

All PMTs needed for the replacement have been ordered. There are three dedicated test-benches in Bratislava, CERN and Pisa to test and qualify the new PMTs before installation in TileCal. The tests of the pre-production PMT batches (110 PMTs) were performed in the three sites. These new PMTs showed excellent quantum efficiency and overall good characteristics.

All PMTs will be equipped with active high-voltage dividers to distribute power among the dynodes, improving the linearity in the response at high anode currents (up to 100 µA) and, therefore, the accuracy on the energy scale calibration.

4 Read-out electronics

All TileCal readout electronics will be replaced for HL-LHC. The TileCal read-out electronics is divided into two main domains: on-detector electronics that is housed inside the SDs and must pass strict requirements on the radiation hardness, and off-detector electronics that is located in underground counting rooms about 100 m away from the ATLAS detector. There are no requirements on the radiation hardness for the off-detector electronics. Redundancy is increased as much as possible to minimize data loss during operations. The TileCal read-out scheme for the HL-LHC upgrade is shown in figure 3.

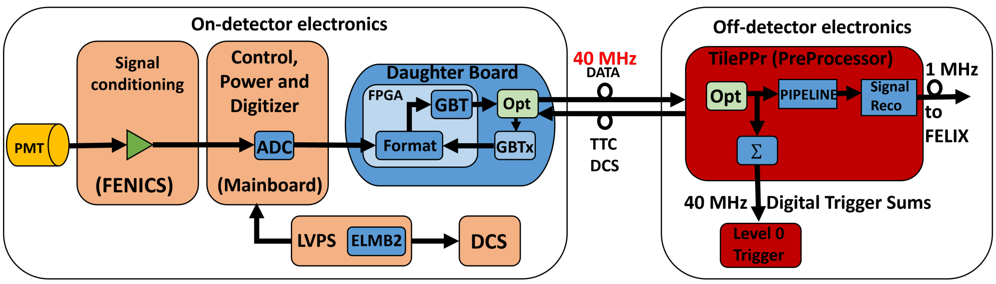

Figure 3. The TileCal Phase-II upgrade read-out scheme. On the left, the on-detector electronics section with the PMTs, FENICS, Main Board and Daughter Board, connected by long fibers to the off-detector electronics section with the Tile PreProcessor on the right part of the figure.

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4.1 On-detector electronics

The TileCal HL-LHC on-detector electronics chain is housed inside the mini-drawers (MD). Each MD contains up to 12 PMT blocks. Each PMT block is located inside a metal cylinder and includes a light mixer, a PMT, its active high-voltage divider base, and the Front End board for the New Infrastructure with Calibration and signal Shaping (FENICS) card. The FENICS boards shape and amplify the PMTs analog pulses. Two types of signal processing are implemented: the "fast readout" for physics data taking, which operates in two different gains in order to cover a dynamic range from 200 fC up to 1000 pC, to measure energies of a few hundreds MeV in a single particle or a multi-TeV hadronic jet; the "slow integrator read-out", which integrates the PMT current for the calibration of the calorimeter with a ^{137}Cs source and for luminosity measurements. The FENICS board is also able to inject a precise charge and to measure the conversion from pC to ADC counts. The production of FENICS boards is in progress. The PMT block is connected to a Main Board. There is one Main Board installed in each MD, which digitizes the low and high gain signals received from up to 12 FENICS cards. The fast readout uses 24 12-bit ADCs at 40 Msps, while the integrator readout uses 12 16-bit SAR ADCs. The Main Board provides also digital control of the FENICS to configure it for either a calibration run or for the physics data taking. The Main Board routes the data to the Daughter Board (there is one Daughter Board per MD) which is responsible for the high-speed communication with the off-detector electronics. Two 9.6 Gb/s uplinks are used for the transmission of the digitised signals, while two 4.6 Gb/s downlinks receive the LHC clock and configuration commands and distribute them to the on-detector components. For robustness and redundancy, both the Main Board and the Daughter Board have two electrically independent halves. As each calorimeter cell is read out by two PMTs, the two PMTs are connected to the two separate halves of the Main Board. Main Boards production is completed, while the Daughter Board design is going to be finalized by the end of 2023.

4.2 Off-detector electronics

During HL-LHC operation, the PMT digital samples for every bunch crossing will be transferred from the Daughter Board to the off-detector electronics, where the data will be reconstructed at 40 MHz frequency. The trigger primitives will be sent to the Level-1 trigger system, while up to 10 µs of consecutive data will be stored in pipeline buffers waiting for a trigger decision.

The TileCal off-detector electronics are hosted in four ATCA crates, with eight PreProcessor (PPr) blades per crate. The PPr is the core of the off-detector electronics. It is formed by an ATCA carrier board and four Compact Processing Modules (CPM), each being able to process the data from two TileCal modules. The interface with the front-end electronics, pipeline buffering and signal reconstruction are implemented in the CPM. The construction of the trigger primitives and the interfaces with the Level-0/Level-1 trigger system and Front End LInk eXchange (FELIX) systems are performed in the Trigger and DAQ interface (TDAQi). After the trigger decision, if an event is accepted the corresponding data is transmitted to the FELIX system.

5 Low voltage and high voltage systems

The TileCal low voltage (LV) system supplies power to all the front-end electronics. The new LV system is designed to provide better reliability, lower noise, improved radiation tolerance and reduced single points of failure, compared to the current system. A three-stage LV system, as shown in figure 4 (left), has been adopted. LV power supplies (LVPS) bricks are placed on-detector and they convert the input 200 V to 10 V as required for the on-detector electronics. Due to their position in a MD, the LVPS components are exposed to high level of radiation. For this reason, an extensive irradiation test program was performed to identify radiation hard components. Point-of-load regulators located directly on the Main Board and the Daughter Board make up the third stage of the LV system.

The high voltage (HV) distribution system supplies high voltage for each PMT. The TileCal upgrade HV system consists of HV-supply boards and custom remote regulation boards, located in the service cavern far from the detector to avoid radiation issues, in HV-crates connected to the on-detector components by 100 m long HV-cables (see figure 4 (right)). This choice allows to access and maintain the system during the LHC operation. Each regulation board serves one TileCal module. Inside the detector there are only passive distribution boards used to bring the HV individually to each PMT located in a MD.

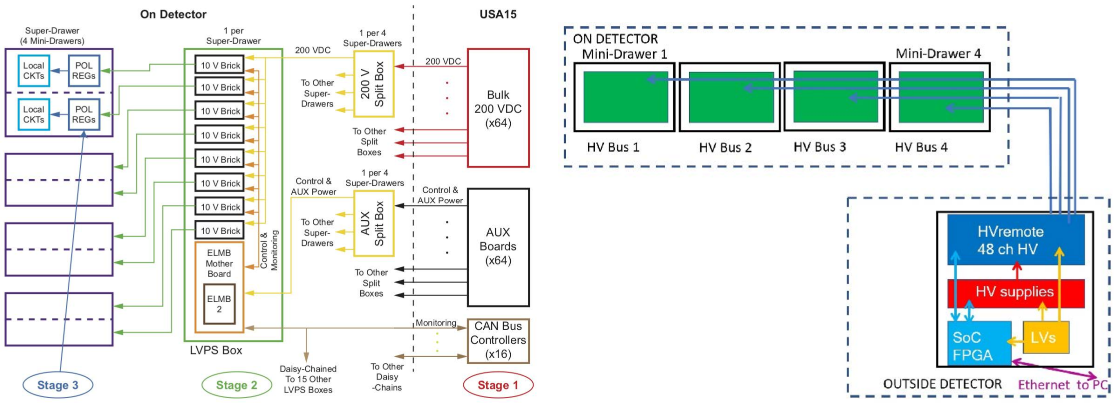

Figure 4. Left: the architecture of the low voltage system for the TileCal HL-LHC upgrade. The 10 V bricks represent the 200 V to 10 V converters. Stage 3 is located directly on the front-end electronics. Right: the high-voltage power supply system scheme for the upgrade. The regulation system is located far from the detector, and a large number of 100 m long cables bring the HV to the detector modules. Inside the detector, the HV is distributed to 4 (3) mini-drawers in the Long Barrel (Extended Barrel) modules.

6 Calibration systems

TileCal uses several calibration systems to ensure accurate and stable energy measurements. The Charge Injection System (CIS), implemented on each front-end card, injects the readout electronics with known charge, allowing constant monitoring but also mapping of the front-end response (ADC counts) to the input charge (pC). For the HL-LHC, the CIS will be updated to cover the input range of the new front-end electronics.

The Cesium (Cs) system allows calibration of the full optical chains (scintillating tiles, WLS fibers, PMTs) by means of a movable ^{137}Cs -source, hydraulically circulated through a system of tubes that traverses every tile-row. The upgrade plan foresees integration of the control data flow into the standard data readout electronics, optimization of the operation mode and replacement of aged hydraulic equipment. Design of all boards is ready: all prototypes were produced and are under test.

The Laser calibration system is used to monitor and measure the gain stability of each PMT by sending a controlled amount of laser light to the photocathode. The reliable architecture of the current

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laser system will be preserved, with substitution of aged components and adaptation of the interfacing card to comply with the ATCA format of the PPr. In Run 2 it was observed that response to laser pulses may vary as a function of the current induced by Minimum Bias events. To handle this, it was decided to add a tool for controlling the PMT response as a function of the anode current. The simplest way to mimic what happens during collisions is to add a continuous light component to laser pulses. The laser light mixer in the present system will be replaced with an integrating sphere which will allow to simultaneously inject pulsed laser light and LED-generated DC light and to mix them. The DC LED light component will be provided by a power LED array. The new optical line is being installed at CERN for testing (figure 5).

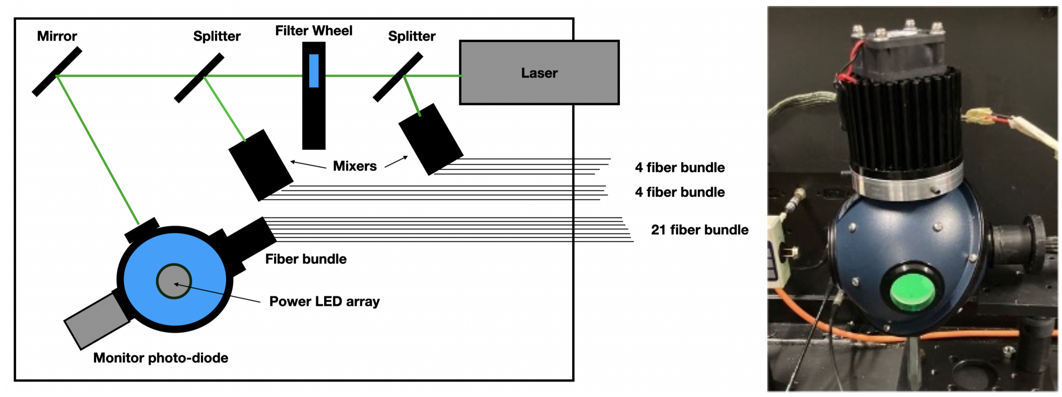

Figure 5. Left: preliminary layout of the new laser calibration system optical line under test at CERN. Right: detail of the power LED array positioned on top of the integrating sphere.

7 Test beam results

Several test-beam campaigns have been carried out at CERN SPS-H8 beam line between 2015 and 2023 to validate the performance of the different versions of the HL-LHC TileCal upgrade electronics and to get a direct comparison with the legacy system. Three TileCal modules, two LBs and one EB, have been exposed to electron, hadron and muon beams with different energies and incident angles. Figure 6 (left) shows the test beam experimental hall and the three TileCal modules positioned on a movable table. Figure 6 (right) shows the schematic layout of the test beam SPS-H8 beam-line and of the three TileCal modules under test. The MDs were equipped with FENICS cards, Main Boards and Daughter Boards. The front-end electronics was powered with various versions 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 7 (left) shows the distribution of the total energy deposited in the modules under test, for electron beams of 20, 50 and 100 GeV incident in the cell A-4 of the middle layer of the stack of modules, at an angle of 20^o. The response to pion beams with energies E_{beam} ranging from 16 to 30 GeV [9] is shown in figure 7 (right) and compared with simulated data.

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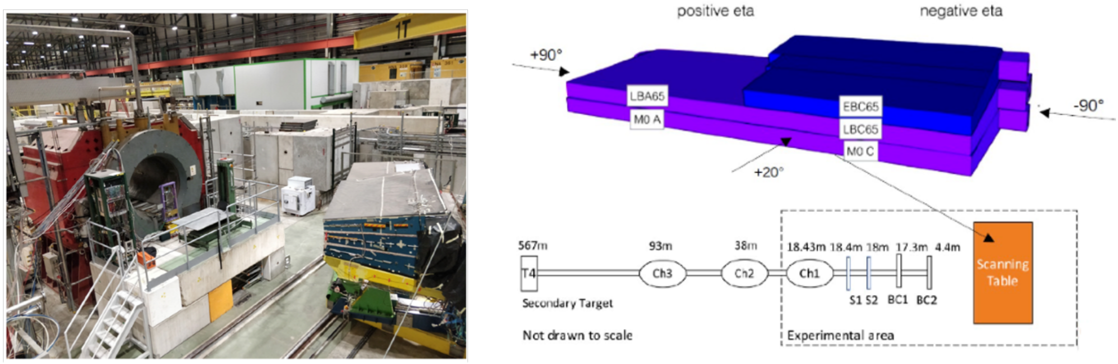

Figure 6. Left: TileCal setup in the SPS-H8 beam-line. Right: schematic layout of the SPS-H8 beam-line and of the three TileCal modules positioned on a movable table.

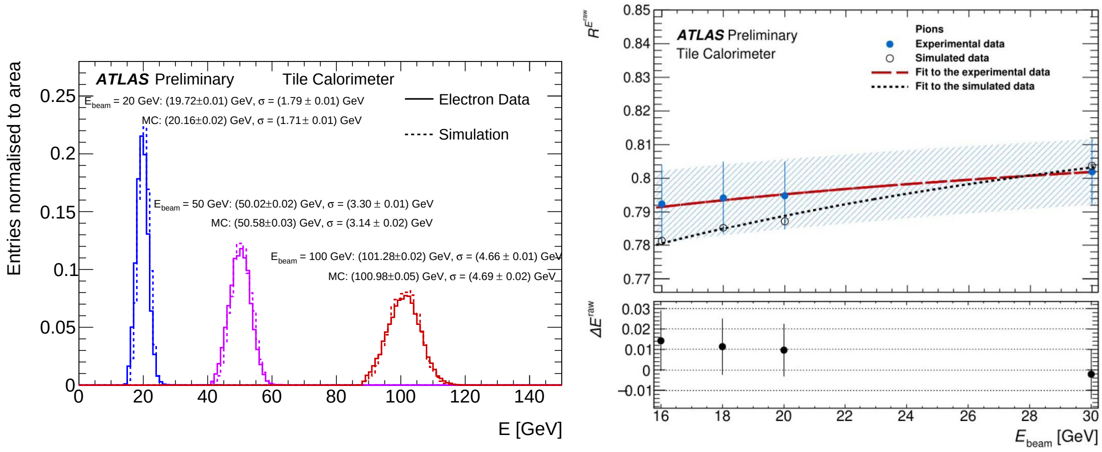

Figure 7. Left: distribution of the total energy deposited in the TileCal module for different electron beam energies (20, 50, and 100 GeV), for data and simulation. Right: energy response normalized to incident beam energy, $R^{<E_{\text{raw}}>}$, for pion beams. A comparison of data (blue dots) and simulation (black circles) as a function of pion beam energy is shown. The red dashed (black dot) curves are fits to the experimental (simulated) data points. In case of experimental data, the dashed blue strips display the correlated systematic uncertainties. In the bottom part the fractional differences $\Delta < E_{\text{raw}} >$ defined in ref. [9] is shown.

8 The Demonstrator module

After being evaluated during several test beam campaigns, finally a Demonstrator module, equipped with upgrade electronics but providing backward compatibility with the analog trigger signal of the current modules, was inserted in the ATLAS detector in July 2019 and it was successfully integrated into the legacy ATLAS DAQ system. This module has been operating during the Run 3 of the LHC to gain experience with the new electronics before the start of the HL-LHC operations and timely identify problems. It has shown stable performance and reduced noise with respect to the legacy electronics. Currently, the Demonstrator module provides physics data from proton-proton collisions with the rest of the TileCal modules and it is contributing to ATLAS Level-1 trigger. We are planning to install, before the end of Run 3, a second special module in the extended barrel. This EB module will be very close to final Phase-II design and it will allow to get a valuable experience with real collisions data.

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9 Conclusion

The HL-LHC will provide unique opportunities to test the SM of particle physics and probe for beyond the SM phenomena. In order to cope with the high radiation environment and to guarantee excellent detector and data-taking performance, the ATLAS experiment will undergo an ambitious upgrade program which requires, among other aspects, a full replacement of TileCal on-detector and off-detector electronics. Several test-beam campaigns were performed throughout the last decade, where prototypes of the various TileCal subsystems were simultaneously validated. A Demonstrator module of the upgrade TileCal electronics, offering compatibility with the current data readout paths, was successfully inserted in the ATLAS detector in July 2019. Overall the TileCal upgrade project is advancing well and is on schedule for installation in ATLAS and commissioning during the Long Shutdown 3 (2026–2028).

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