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P. TSOTSKOLAURI
ON BEHALF OF THE ATLAS TILE CALORIMETER SYSTEM
High Energy Physics Institute of Tbilisi State University
(3, Chavchavadze Ave., Tbilisi 0179, Georgia; e-mail: pavle.tsotskolauri@tsu.ge)

ATLAS TILE CALORIMETER PHASE-II UPGRADE: ELECTRONICS CERTIFICATION WITH THE PORTABLE READOUT MODULE "PROMETEO" [1]

The High-Luminosity LHC (HL-LHC) will extend the physics reach of the ATLAS experiment, bringing new opportunities for discovery and for measuring the properties of particles. To achieve this, the HL-LHC requires a complete upgrade of the ATLAS detector, including its Tile Calorimeter (TileCal). TileCal is a sampling hadronic calorimeter covering the central region of the ATLAS experiment in a pseudorapidity range of $|\eta| < 1.7$. It consists of thin steel plates and about 460000 scintillating tiles configured into 5182 cells, each viewed by two photomultipliers (PMTs). The Phase-II upgrade of TileCal will include a complete replacement of its on- and off-detector electronics, as well as 10% of the PMTs in the most exposed regions. PMT signals from every TileCal channel 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. This large-scale replacement presents a considerable challenge in terms of testing and certification of the new electronics. To address this, the Portable ReadOut ModulE for Tile Electronics (PROMETEO) system has been developed as a portable tool for testing and certifying both the on- and off-detector electronics. While PROMETEO was originally designed primarily for electronics certification, research and development efforts have revealed a clear need for fast and precise optical testing of both the current and new PMTs. As a result, future developments of PROMETEO will incorporate optical measurement capabilities, including the ability to measure relative quantum efficiency and dark current for all the PMTs. This article presents the current status of the TileCal Phase-II upgrade project, along with expected performance characteristics. In addition, the PROMETEO system for testing and certifying of new electronics and its future enhancements are discussed.

Keywords: ATLAS, Tile Calorimeter, TileCal, HL-LHC, Phase-II upgrade, PROMETEO, PMT-Block, Tile Electronics.

1. Introduction

The ATLAS experiment at the CERN Large Hadron Collider (LHC) is a general-purpose detector that studies proton–proton and heavy-ion collisions at en-

[1] This work is based on the results presented at the 2025 "New Trends in High-Energy Physics" Conference.

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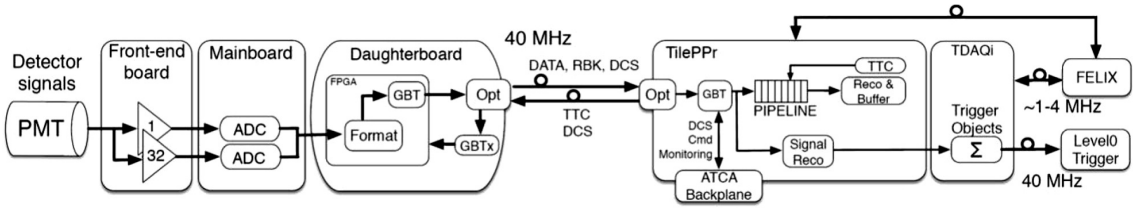

Fig. 1. TileCal Readout Chain

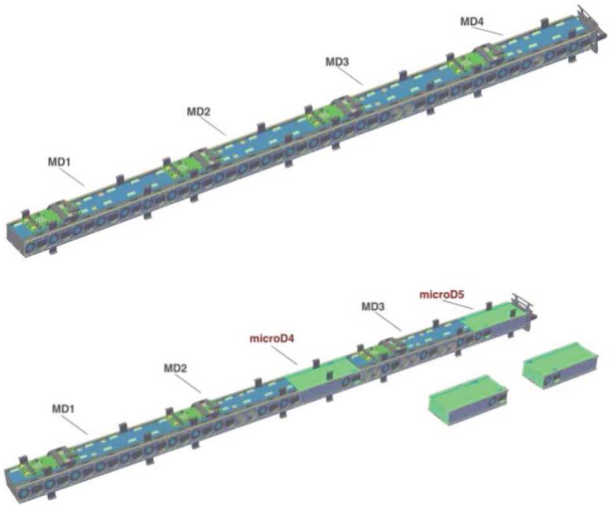

Fig. 2. TileCal Mechanics

ergies up to 14 TeV. It enables precision tests of the Standard Model, including the Higgs boson, and searches for new physics beyond it. The upcoming High-Luminosity LHC (HL-LHC), starting in 2026, will deliver 5–7.5 × more integrated luminosity and up to 200 interactions per bunch crossing, reaching about 4000 (fb^{-1}) by the late 2030s [1]. This demanding environment drives a comprehensive Phase-II upgrade of the ATLAS detector systems to ensure reliable operation under higher radiation levels and unprecedented data rates. In this article, the upgraded Tile Calorimeter readout chain, readout components, the Portable ReadOut ModulE for Tile Electronics (PROMETEO), and its future upgrades are presented.

2. Tile Calorimeter

The Tile Calorimeter (TileCal) is a sampling calorimeter constructed of steel and plastic scintillator plates, covering $|\eta| < 1.7$. It measures hadrons and hadronic decays of τ leptons, contributes to missing transverse energy reconstruction, provides trigger input to the Level-1 Calorimeter system, and assists in muon identification. To meet the demands of the HL-LHC, TileCal will undergo a full Phase-II electronics upgrade with a new readout chain, as shown in Fig. 1, replacing all on- and off-detector electronics for a fully digital trigger at 40 MHz with improved radiation tolerance and long-term reliability [2]. The upgrade also introduces new super-drawer mechanics, redesigned high- and low-voltage power supplies, enhanced Cesium and Laser calibration systems, redundant optical links, and the replacement of the most radiation-exposed photomultiplier tubes (PMTs).

3. TileCal Readout Chain

3.1. Mechanics

The upgraded TileCal mechanics, shown in Fig. 2, use a modular drawer concept to house the new on-detector electronics. Each super-drawer forms the main structural unit and is subdivided into smaller modules for easier installation and maintenance. In the long barrel region, a super-drawer contains four mini-drawers, while in the extended barrel it is assembled from three mini-drawers and two micro-drawers. Every mini-drawer hosts twelve PMT-Blocks together with their front-end boards, Mainboard, Daughterboard, and the high voltage distribution board. This modular design simplifies handling during assembly and replacement, improves accessibility for testing with PROMETEO [3].

3.2. PMT-blocks

Scintillator tiles in the TileCal are grouped, forming readout cells. When particles cross the scintillator tiles, produced light is transmitted by wavelength-shifting fibers (WLS). PMTs are responsible for converting this light coming from WLS fibers into analog signal and transferring it to the next stage of a readout chain. Every PMT is equipped with a High

Voltage Active Divider (HVAD) which divides high voltage coming from high voltage system to eight PMT dynodes, resulting in a linear PMT response. The high voltage for PMTs is in the range of 600–950 V. PMT-Block, shown in Fig. 3, consists of the PMT, light mixer, HVAD, upgraded front-end board, iron and μ-metal cylinders. Before implementation of an individual PMT-Block into super-drawer they are tested using the PROMETEO system, which ensures the correct functionality of PMT-Blocks as well as the rest of the readout chain components [3].

3.3. Front-End Board

The Front-End board for the New Infrastructure with Calibration and Signal Shaping (FENICS), shown in Fig. 4, processes the analog signals from each PMT by performing shaping, amplification, and integration. It provides a 17-bit dynamic range, two fast readout channels with different gains and one slow channel for charge integration, as well as a charge injection circuit for precise calibration [3].

3.4. Mainboard

The Mainboard, shown in Fig. 5, is responsible for digitizing the analog signals from the FENICS boards and transferring them to the Daughterboard. Each Mainboard connects to 12 PMT-Blocks and uses field-programmable gate arrays (FPGAs) to configure the analog-to-digital converters (ADCs) and provide clock and control signals. For PMT readout, it performs fast sampling at 40 MHz with 12-bit resolution and provides a 16-bit slow integration path for calibration and monitoring. The board is divided into two independent sections, A and B, each with its own low-voltage power supply, ensuring reliable operation in the high-radiation and high-rate conditions of the HL-LHC [3].

3.5. Daughterboard

The Daughterboard, shown in Fig. 6, interfaces the on-detector electronics with the off-detector readout system. It receives digitized data from the Mainboard, manages Detector Control System (DCS) communication, and transmits detector readout data to the Tile PreProcessor (PPr) via high-speed optical links. Each Daughterboard is split into two independent sides, A and B, each with its own power supply and redundant optical connections. It also distributes timing and control information from the back-end to the on-detector system and uses CERN-developed GBTx chips for remote configuration of

Fig. 3. PMT-Block Components

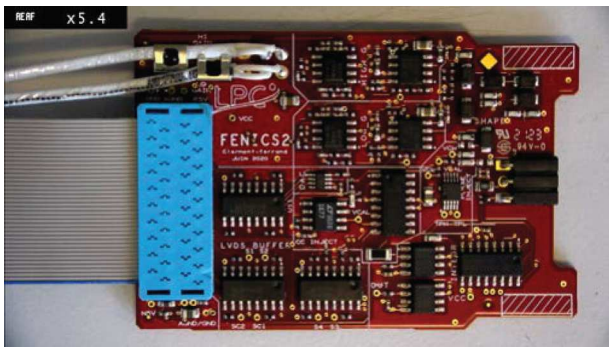

Fig. 4. FENICS Board

Fig. 5. Mainboard

Fig. 6. Daughterboard

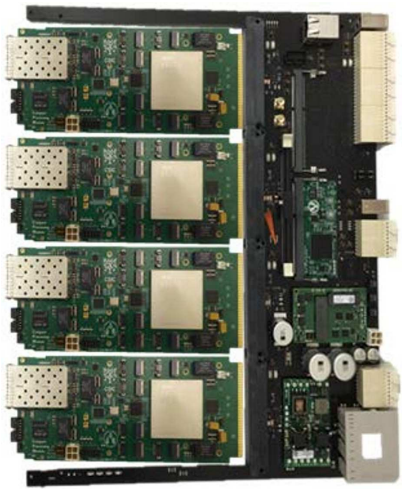

Fig. 7. Tile PreProcessor

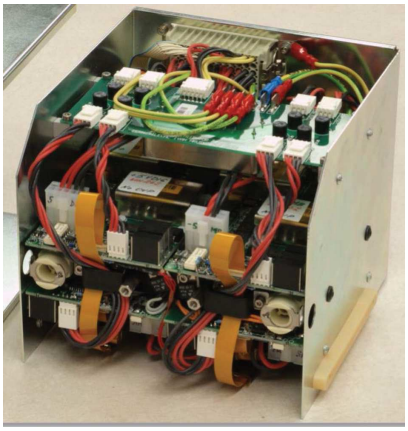

Fig. 8. LVPS Box

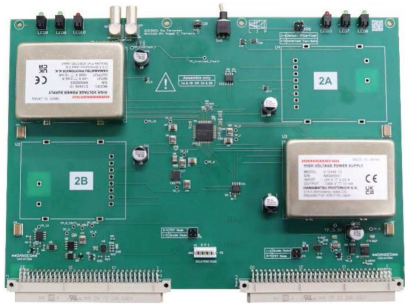

Fig. 9. HVPS Board

the FPGAs and on-board flash memory, while providing the global 40 MHz clock for synchronous data acquisition.

3.6. Tile preprocessor and trigger and data acquisition interface

The Tile PreProcessor, shown in Fig. 7, is the core element of the TileCal off-detector readout electronics. It consists of four Compact Processing Modules (CPMs) and a carrier board. It has bidirectional communication with the on-detector system, providing DCS commands, timing, trigger, and control information, and distributing the LHC clock to the front-end electronics. At every bunch crossing, the PPr receives digitized PMT data from the Daughterboards, stores it in pipeline buffers, and waits for the central trigger decision. Based on this decision, the data are either sent to permanent storage for further processing or discarded. In addition, the PPr connects to the Trigger and Data AcQuisition interface, which links TileCal to the trigger system by managing clock distribution and configuration, and by building trigger primitives for each bunch crossing [3].

3.7. Low voltage power supply

The Low Voltage Power Supply (LVPS), shown in Fig. 8, delivers power to all on-detector electronics and provides monitoring and control feedback to the DCS. In the Phase-II upgrade, each super-drawer is powered by a single LVPS module that supplies a unified 10 V input to all front-end components, replacing the earlier system that generated multiple voltages locally. In total, 256 LVPS units are installed in TileCal. Each module contains eight power bricks that convert the 200 V input to 10 V output, arranged in four redundant pairs to ensure reliable operation [3].

3.8. High voltage power supply

The High Voltage Power Supply (HVPS), shown in Fig. 9, provides high voltage, up to 950 V DC, to all PMTs in the TileCal system. In the Phase-II upgrade, the high voltage is supplied remotely and regulated by 256 HV remote boards, with distribution to individual PMTs handled by dedicated high-voltage distribution boards. The system is fully integrated with the DCS for monitoring and control [3].

3.9. Calibration Systems

The TileCal calibration systems ensure stable and precise response of the detector over time. There are

three main calibration systems: Charge Injection System (CIS), laser and cesium. The CIS is used to monitor the on-detector electronics and to extract the conversion factor from ADC counts to pC by injecting a known charge from a capacitor into the shaper circuit of the FENICS card. The Laser calibration system delivers light pulses through optical fibers to all PMTs, allowing accurate monitoring of PMT gain variations and linearity. The laser calibration runs are taken daily, while laser pulses are also emitted during physics runs in the empty bunch crossings. The Cesium calibration system uses a movable ^{137}Cs radioactive γ-source to provide an absolute calibration of the full readout chain, including scintillators, WLS, PMTs, and electronics. The Cesium electronics is shown in Fig. 10. The Cesium scan is taken monthly during an 8-hour gap between physics runs to equalize cell responses and monitor long-term stability [3].

4. Testing and Certification

4.1. PROMETEO System

The Portable ReadOut ModulE for Tile Electronics (PROMETEO), shown in Fig. 11, is a fully autonomous and mobile test bench developed to certify and verify the upgraded TileCal on-detector electronics during assembly, installation, and maintenance. It recreates the complete readout environment, enabling comprehensive checks of modules before they are installed in the detector. PROMETEO performs automated tests such as connectivity verification, pedestal measurements, ADC linearity checks, charge injection calibration, integrator response evaluation, and LED light injection, ensuring every module meets operational requirements. A PC-based graphical interface provides dedicated panels for each test type, allowing fast configuration and clear visualization of results. One of the key applications of PROMETEO is its use with the PMT-Block Test Stand, a light-tight setup that houses up to twelve PMT-Blocks together with a Mainboard, Daughterboard, and the necessary high- and low-voltage distribution, shown in Fig. 11. This configuration replicates the full readout chain, from optical stimulation to digitized data transmission. PROMETEO integrates all required subsystems, including an LED driver for controlled light injection, a portable HVPS delivering up to 950 V DC, a portable LVPS providing

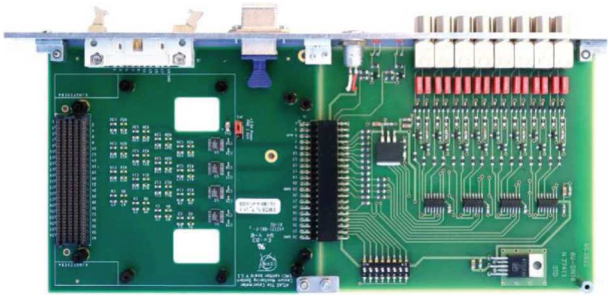

Fig. 10. Calibration Electronics Board

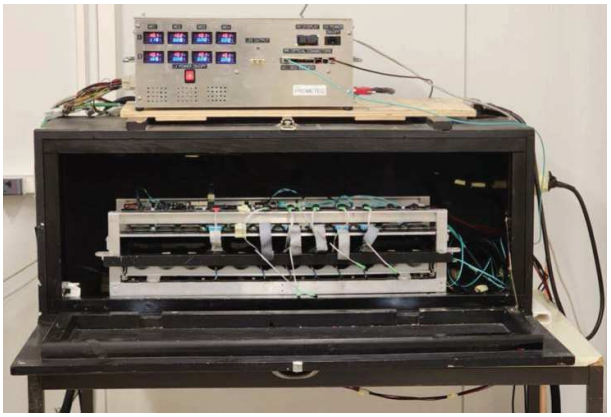

Fig. 11. PMT-Block Test Stand and PROMETEO System

10 V to on-detector electronics (with individual mini-drawer control), and a PPr/CPM that manages communication and data flow. Its flexible, portable design supports testing of super-drawers, mini-drawers, and PMT-Blocks in laboratories, assembly areas, or test beam environments, making it a key tool for reliable certification of the upgraded TileCal electronics [4].

4.2. Future enhancement: relative quantum efficiency

During the PROMETEO development, it became evident that, while only about 10% of PMTs will be replaced, monitoring the optical performance of the remaining PMTs is essential to ensure long-term stability. Existing test benches for PMT characterization can measure parameters such as quantum efficiency, relative quantum efficiency (RQE), and dark current, but these methods are slow and often require several days per PMT. To reduce testing time, PROMETEO and the PMT-Block Test Stand will be upgraded as

part of my PhD project to enable fast measurements of RQE. The concept uses a single optical fiber to simultaneously illuminate the PMT under test and a reference photodiode, with the light split by beam splitter cubes. This approach eliminates moving mechanical parts, allowing stable and efficient RQE measurements for large numbers of PMTs and enabling continuous monitoring of their optical response during the lifetime of the detector.

5. Summary

The ATLAS Tile Calorimeter Phase-II upgrade introduces a fully digital trigger readout operating at 40 MHz, along with radiation-tolerant on- and off-detector electronics, redesigned power distribution, and enhanced calibration systems to ensure reliable performance in the high-luminosity LHC environment. The PROMETEO system, together with the PMT-Block Test Stand, provides a comprehensive platform to certify upgraded modules before installation. Ongoing developments to integrate relative quantum efficiency measurements will further expand PROMETEO's capabilities, enabling fast optical performance checks of thousands of PMTs and supporting the long-term stability and precision of TileCal operation.

This work was performed in CERN on behalf of ATLAS collaboration.

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П. Цоцколаурі
від імені ATLAS Tile Calorimeter System

ДРУГА ФАЗА МОДЕРНІЗАЦІЇ КАЛОРИМЕТРА ATLAS Tile: СЕРТИФІКАЦІЯ ЕЛЕКТРОНІКИ З ПОРТАТИВНИМ МОДУЛЕМ ЗЧИТУВАННЯ "PROMETEO"

Великий гадронний колайдер з високою світністю (HL-LHC) розширить фізичні можливості експерименту ATLAS, створюючи нові можливості для відкриття та вимірювання властивостей частинок. Для досягнення цієї мети HL-LHC потребує повної модернізації детектора ATLAS включно з калориметром, складеним з плиток (TileCal). TileCal – це гадронний калориметр, що охоплює ценральну область експерименту ATLAS і працює у діапазоні псевдошвидкостей $|\eta| < 1{,}7$. Він складається з тонких сталевих пластин та близько 460000 сцинтиляційних плиток, сконфігурованих у 5182 комірки, кожна з яких забезпечена двома фотоелектронними помножувачами (ФЕП). Друга фаза модернізації TileCal включатиме повну заміну електроніки на детекторі та поза ним, а також 10% ФЕП у найбільш експонованих зонах. Сигнали ФЕП з кожного каналу TileCal будуть оцифровані та надходитимуть безпосередньо до відділеної від датчиків електроніки, яка ці сигнали реконструює, зберігає та надсилає до першого рівня системи відбору даних з частотою 40 МГц. Це забезпечить кращу точність сигналів від калориметра, які надходять до системи аналізу даних, та дозволить розробляти складніші алгоритми такого аналізу. Ця масштабна заміна створює значні труднощі з точки зору тестування та сертифікації нової електроніки. Для вирішення цієї проблеми було розроблено систему Portable ReadOut ModulE for Tile Electronics (PROMETEO) – портативний інструмент для тестування та сертифікації електроніки як на детекторі, так і поза ним. Хоча PROMETEO спочатку був розроблений в основному для сертифікації електроніки, дослідницькі та конструкторські роботи виявили явну потребу в швидкому та точному оптичному тестуванні як існуючих, так і нових ФЕП. Як результат, майбутні розробки PROMETEO передбачатимуть можливості оптичних вимірювань включно з можливістю вимірювання відносної квантової ефективності та темнового струму для всіх ФЕП. У даній роботі представлено поточний стан проєкту модернізації TileCal Phase-II, а також очікувані характеристики продуктивності. Крім того, обговорюється система PROMETEO для тестування та сертифікації нової електроніки і її майбутні вдосконалення.

Ключові слова: ATLAS, калориметр з плиток, TileCal, HL-LHC, друга фаза оновлення, PROMETEO, PMT-Block, електроніка для плиток.