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Performance of the ATLAS Tile Hadronic Calorimeter at LHC in Run 1 and planned upgrades

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ABSTRACT: The Tile Calorimeter (TileCal) is the central section of the ATLAS hadronic calorimeter at the Large Hadron Collider, a key detector for the measurements of hadrons, jets, tau leptons and missing transverse energy. Scintillation light produced in the tiles is transmitted by wavelength shifting fibres to photomultiplier tubes (PMTs). The resulting electronic signals from approximately 10000 PMTs are digitized before being transferred to off-detector data-acquisition systems. The data quality procedures used during the LHC data-taking and the evolution of the detector status are explained in the presentation. The energy and the time reconstruction performance of the digitized signals is presented and the noise behaviour and its improvement during the detector consolidation in maintenance periods are shown. A set of calibration systems allow monitoring and equalization of the calorimeter channels responses via signal sources that act at every stage of the signal path, from scintillation light to digitized signal. These partially overlapping systems are described in detail, their individual performance is discussed as well as the comparative results from measurements of the evolution of the calorimeter response with time during the full LHC data-taking period. The TileCal upgrade aims at replacing the majority of the on- and off-detector electronics so that all calorimeter signals will be directly digitized and sent to the off-detector electronics in the counting room. To achieve the required reliability, redundancy has been introduced at different levels. For the off-detector electronics a special pre-processor board is being developed, which will take care of the initial trigger processing while temporarily storing the main data in the pipeline and de-randomiser memories.

KEYWORDS: Calorimeters; Performance of High Energy Physics Detectors; Front-end electronics for detector readout.

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1. Introduction

The Tile Calorimeter (TileCal) [1] is the central section of the ATLAS [2] hadronic calorimeter at LHC [3], which plays a key role in the measurement of hadrons, jets, tau leptons and missing transverse energy. Superior performance and quality of data, together with low electronics noise, is vital for the precise measurements of ATLAS experiment [4]. A set of calibration systems is required to correctly follow the behaviour of the calorimeter during changing conditions. After the successful Run 1 data taking, the performance of the front-end electronics should be maintained to provide the same level of data quality for the next period. For the future high luminosity program, upgraded electronics is being designed to cope with new challenges. This paper describes the performance of the Tile Calorimeter during Run 1, maintenance activities, improvements for Run 2, and the planned upgrades to the front-end electronics for the future high luminosity LHC.

2. Tile Calorimeter

The ATLAS Tile Calorimeter is a hadron non-compensating sampling calorimeter with the steel as a radiator and plastic scintillating tiles as active medium, with the design resolution for the jets of $\Delta E/E = 50\%/\sqrt{E} \oplus 3\%$.The 3 mm thick scintillating tiles made from polystyrene base, inserted into the steel structure, are oriented in an unusual way, perpendicular to the beam axis, and are wrapped in Tyvek® paper for better light collection. The tiles are read out from two opposite edges via wavelength shifting fibres (WLS) that are delivering the light to the photomultipliers (PMT) in the module's girder. The calorimeter is divided into three cylinders (EBA, LB, EBC). Each cylinder consists of 64 wedge-shaped modules (figure 1). The long barrel (LB) covers the pseudorapidity region of $|\eta| < 1.0$ and the extended barrels cover the $0.8 < |\eta| < 1.7$. There are three longitudinal layers with total thickness of about 7.4λ at η=0. The cell geometry, shown in

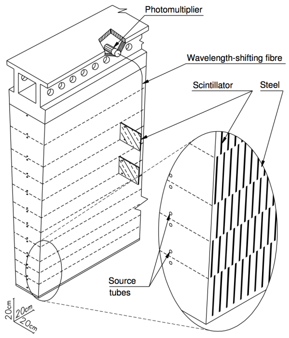

Figure 1. Tile Calorimeter module design [4].

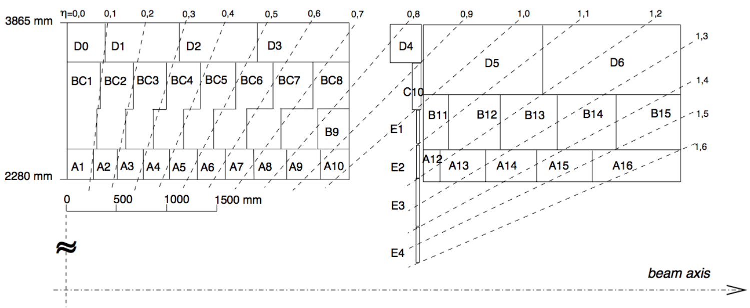

Figure 2. Tile Calorimeter cell layout [4].

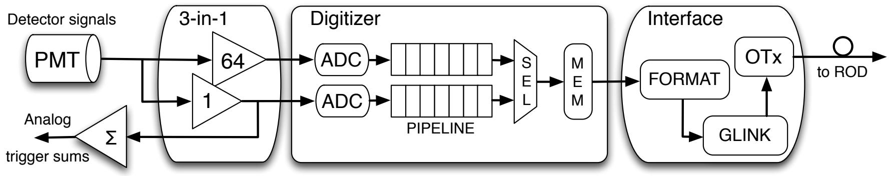

Figure 3. Tile Calorimeter front-end electronics data flow [5].

figure 2, is defined by the routing of WLS fibres. The cell granularity in $\Delta\eta \times \Delta\phi$ is 0.1×0.1 for the inner (A, BC) layers and 0.2×0.1 for the outer (D) layer.

The signals from the PMTs are shaped and amplified with two gains (1:64 ratio). Analogue sums of cell signals, forming pseudo-projective towers are provided for the first level trigger. Both gains are digitised in parallel by 40 MHz 10-bit sampling ADCs. The digitised samples are stored in a pipeline memory to allow for the trigger latency. Upon the first level trigger decision seven samples from one of the gains are transferred to the de-randomiser memory and then to the back-end electronics via readout fibres (figure 3). The signal from these seven samples is reconstructed using an optimal filtering algorithm, that extracts energy, time and quality factor.

3. Calibration systems

To provide correct energy and time for precise data reconstruction an elaborate and overlapping chain of calibration systems has been conceived [6]. It starts from the charge injection system (CIS) to calibrate the response of the ADCs, continues with the laser calibration system that is used to measure the performance of the PMTs, then the cesium moving radioactive source system to calibrate the full optical path from scintillating tiles and WLS fibres down to integrated current of the PMTs. Finally, it ends with the online minimum bias monitoring system (MBM) following the response of the calorimeter to the particles.

About 11% of 192 Tile calorimeter modules were calibrated at the test beams and the electromagnetic (EM) scale was transferred to the final detector with the help of the calibration systems.

The charge injection calibration system can inject a known charge into the shaper circuit. This pulse is then sampled by the 40 MHz ADC like a physics signal and the amplitude of the pulse

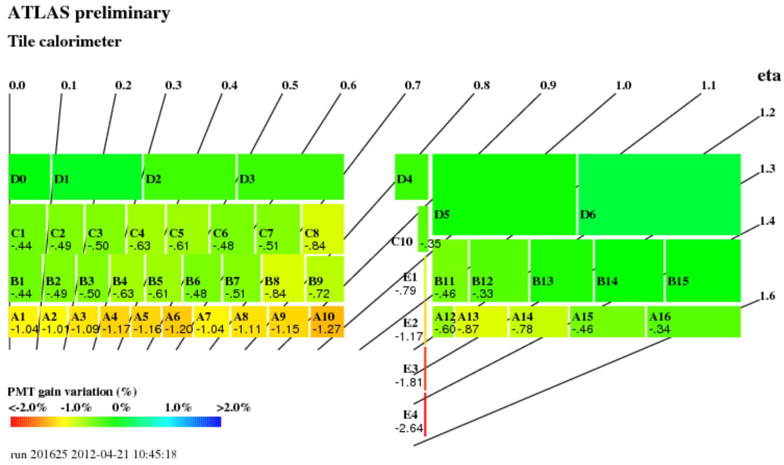

Figure 4. Variation of the cell response measured by laser calibration system [5].

is used to obtain the conversion constant from ADC counts to the charge in pico coulombs (pC). In the year 2012 the conversion factor was stable in time at the level of 0.02%. Charge injection calibration runs are taken twice per week for monitoring purposes. The CIS system can also be used to simulate jets for L1 trigger, by injecting the charge, simulated by Monte Carlo, into selected channels, that will look like a real jet from a collision.

The laser calibration system monitors the stability and the evolution of the PMT gain by sending calibrated laser pulses (532 nm) to all PMTs simultaneously via clear fibres. It follows the evolution of calorimeter response between cesium source scans, the PMT gain drifts due to large currents from collision events. The precision of this system is better than 0.5% of the gain variation, in a time period of one month. The largest drift in 2012 was observed in the A cells (up to 1.27%) and in the gap/crack scintillators (2.64% in E4 cells) (figure 4). The laser system is also used to adjust and verify front-end timing settings.

The cesium calibration system scans all scintillating tiles with a moving ^{137}Cs γ source (662 keV), while reading integrated currents from the PMTs. Usually 1-2 scans are taken per month, during beam-off time and short accelerator stops. The system was used to transport the calibration scale from the test beam measurements of several calorimeter modules to the running detector. Scan results from all modules were used to calculate and adjust the high voltage (HV) for individual PMTs, and to equalize cells responses for better uniformity of the calorimeter. The cesium calibration system follows the evolution of the response of the full optical path from scintillating tiles to PMTs, thus helping to disentangle the scintillator performance from the PMT, which is measured by the laser calibration system. The largest response deviation was found in the inner layer (A) cells, confirming the laser results (figure 5).

The minimum bias monitoring system (MBM) reads integrated PMT currents from all PMTs during physics runs to measure pile-up conditions and luminosity. It follows the response of the detector with time and confirms the detector response variation, with the stability of each channel better than 0.05%, and with average stability better than 0.01%.

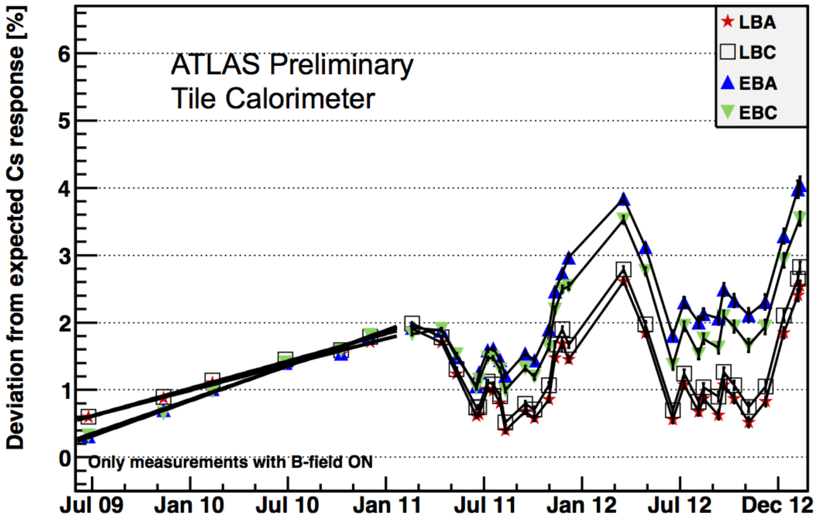

Figure 5. Deviation of the A-cells response in time measured by ^{137}Cs calibration system [5].

The plots detailing the performance of the calibration systems can be found in [5].

4. Run 1 performance

To provide the best quality of data for precision physics results, ATLAS employs data quality procedures at different levels. During the data taking period the data quality monitoring framework (DQMF) monitors and collects the information about the quality of the data, using automated quality checks based on expert provided test criteria applied to a number of dedicated performance histograms. These checks were visually controlled by the shifters during the data taking period. Thanks to all the efforts the resulting quality of the Tile Calorimeter data was 99.6%.

The number of "bad" channels was increasing during data taking periods, mainly due to the failures of the low voltage power supplies, affecting one full module. At the end of Run 1, the Tile Calorimeter had 2.89% of the cells masked due to various problems (figure 6). While six modules were off due to power supply failures, the non-working cell energy was interpolated from the neighbouring cells. For the four modules, that had high voltage control problem, the cells EM scale was restored with the help of cesium and laser calibrations.

Most of the broken channels were fixed during maintenance campaigns, thanks to the possibility to access front-end electronics during shutdowns. The low voltage power supplies were replaced with upgraded ones that are more reliable and have lower noise (figure 7) [7].

During a shutdown, when the ATLAS detector is open, the front-end electronics "drawers" can be extracted allowing bad components to be replaced or fixed by a dedicated team. These repairs allow operation with the minimum number of bad channels to maximize the quality of the data. The performance of consolidated modules were checked and the progress was tracked with web tools, which help to record all subtle problems and at the same time obtain a quick overview of the current status of the maintenance.

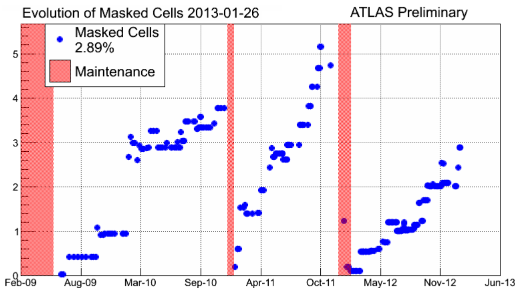

Figure 6. Evolution of the number of masked cells in Tile Calorimeter in Run 1 [7].

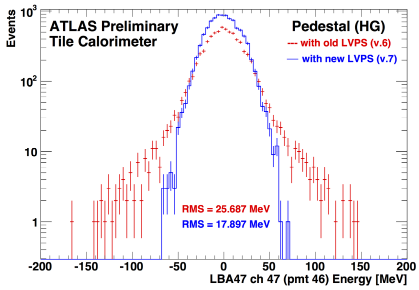

Figure 7. Pedestal distribution comparison between new and old power supply [7].

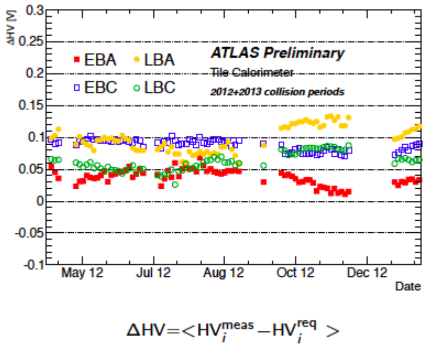

Figure 8. Stability of the high voltage system in time. [5].

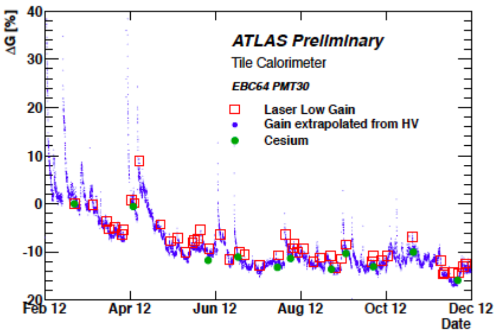

Figure 9. Evolution of the channel response with unstable high voltage [5].

As it was mentioned before, the on-detector front-end electronics power supplies happened to be quite sensitive and exhibited numerous trips, with the number of trips proportional to the integrated luminosity. Automatic procedures to recover the tripped module were introduced to reduce the module's unavailability to the bare minimum of a few minutes. As a consequence of the high failure rates of the low voltage power supply design was modified in order to improve the reliability. A pilot run of 40 new power supplies was installed in the course of Run 1 after which only one trip from one new power supply was observed, compared to thousands trips in the standard ones. Eventually, all low voltage power supplies were replaced with the new version during the long shutdown after the Run 1.

With the photomultiplier's gain highly dependent on the applied HV (ΔV=1V$\sim$1%ΔG), the stability of the high voltage system is crucial. Each channel's HV was monitored (figure 8) to spot unstable channels, and the response was corrected with the help of the laser and cesium systems (figure 9).

A full set of calibration systems allows a reliable and accurate description of the calorimeter, which is very important during fast changing conditions. The Tile Calorimeter response drifts down with increasing integrated luminosity but recovers during accelerator technical stops. Different calibration systems agree with each other and follow the calorimeter response behaviour with time (figure 10) [5].

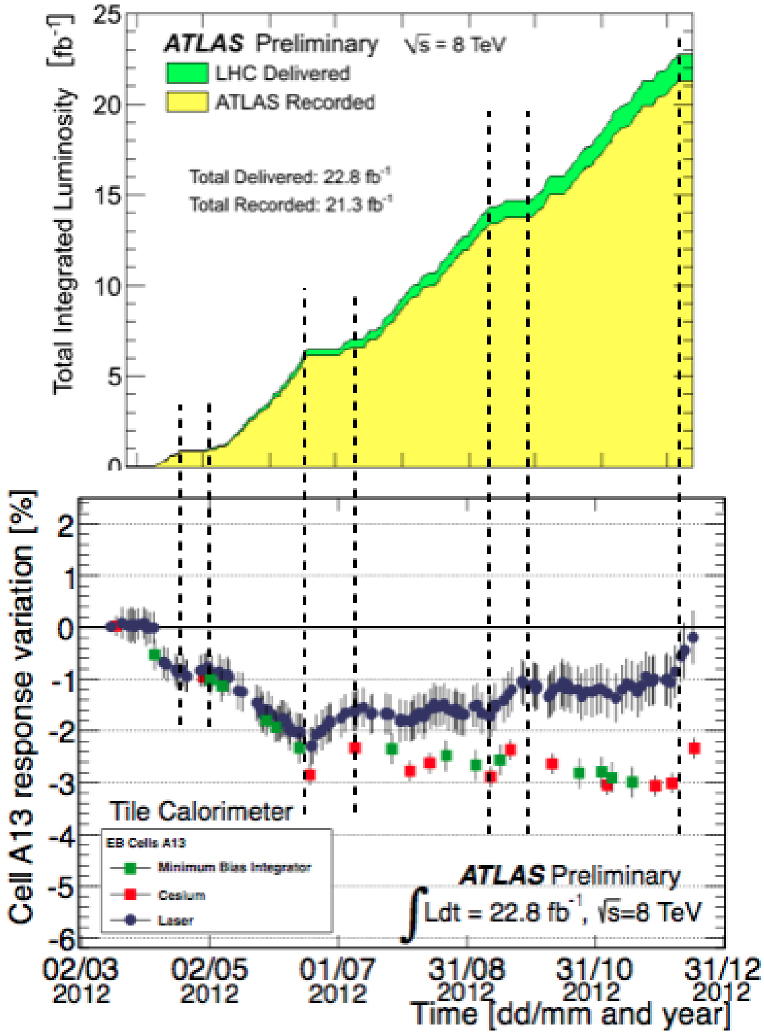

Figure 10. Evolution of A13 cell response in Run 1 tracked by several calibration systems [5].

The cell noise width was affected by the old power supplies and had to be modelled with two Gaussians. The new, improved power supplies have lower noise and a single-Gaussian shape (figure 7). The pile-up noise simulation is in good agreement with data.

The initial time calibration was done with the laser system, beam splashes and scraping beams. The calorimeter provides good cell time performance and a time resolution below 1 ns.

The energy reconstruction has shown good agreement between data and simulation. The energy is calculated online for the high level trigger with quite good correspondence between online and offline reconstruction. As the energy calculation depends on the phase of the signal, it can be and is corrected online.

For the non-compensating calorimeter, the E/p ratio from the data is correctly described by simulations. The jet energy resolution is quite good, following the simulation, and is under 20% in the entire range (figure 11) [8]. Another important characteristic of the calorimeter is the resolution of missing E_T measurements. With the help of robust pile-up suppression algorithms the

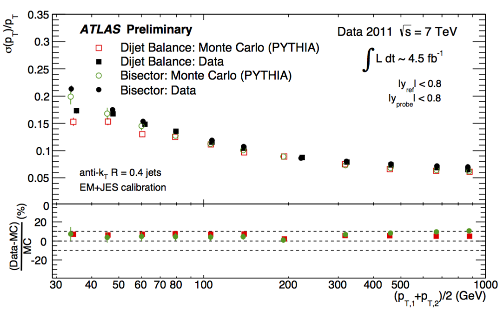

Figure 11. Jet energy resolution performance [8].

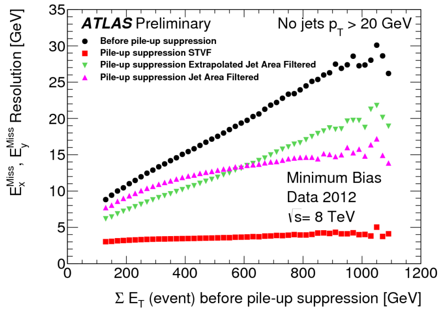

Figure 12. Performance of different pile-up suppression algorithms [9].

dependence on pile-up can be effectively suppressed (figure 12) [9].

5. Upgrade

The advanced physics goals and LHC upgrade plans create new challenges for the detectors. The LHC upgrade program aims at 5-10 fold luminosity increase that will result in more radiation, so better radiation tolerance is required. The ageing electronics that was originally planned for 10 years of operation needs attention. The higher event rates also require more efficient trigger algorithms.

To cope with these challenges a multi-phase upgrade program has been conceived: Phase-0, Phase-I and Phase-II. While the major Tile Calorimeter mechanics and optics will stay together with their PMTs, the front-end and back-end electronics and calibration systems will undergo major upgrades. There will be a complete redesign of the font-end and back-end electronics together with the new front-end drawer mechanics. A fully digital trigger with higher selectivity, better calibration and finer granularity will provide more detailed information. To discover and solve the unavoidable design and integration issues as quickly as possible, a "demonstrator" project has been set up.

In the Phase-0 stage of the upgrade, just before the Run 2, as discussed before, all Tile Calorimeter front-end electronics drawers were extracted to fix problematic channels and the new, stable, low-noise power supplies were installed. The upgraded laser calibration system, called "Laser-II", with the improved stability and precision, which is required to follow the evolution of the PMT response in a high luminosity environment, is being constructed and will be installed in the fall. The cesium calibration system will also be improved. Last, but not least, the Tile Calorimeter outer (D) layer muon data will be sent to the muon trigger to reduce the fake muon rate from the slow charged particles (protons) in a specific region of $1.0 < |\eta| < 1.3$ of pseudorapidity. The first level muon trigger rate will be cleaned up by taking a coincidence with the end-cap muon chambers and Tile D5 and D6 cells. The Tile muon digitizer board, which will process the calorimeter analogue signals from these cells and will provide the coincidence flags, is being developed to be installed before the Run 2.

The high luminosity LHC upgrade (HL-LHC) will require more performance from the detector electronics. The Tile Calorimeter will digitize shaped PMT signals and ship all the samples off

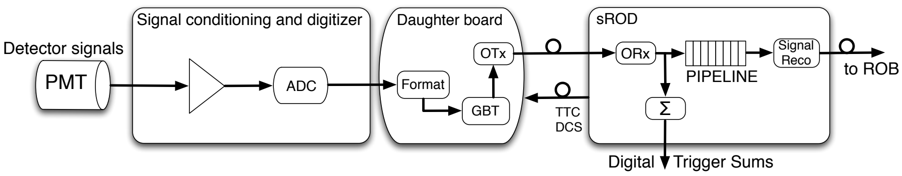

Figure 13. The upgraded front-end electronics data flow [10].

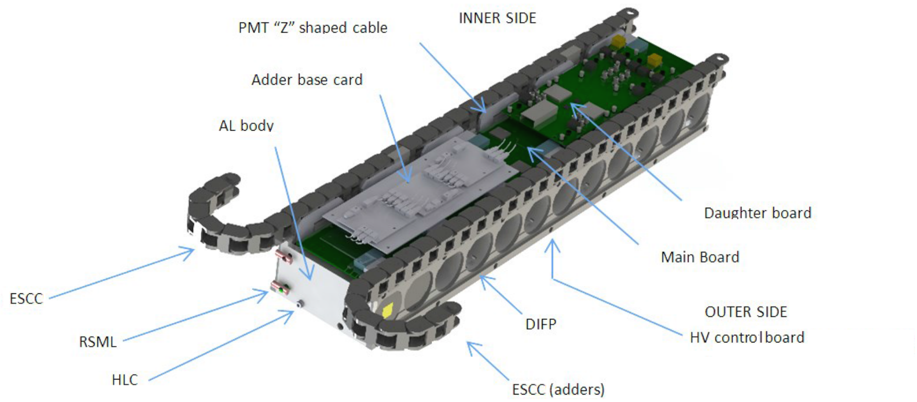

Figure 14. 3D rendering of the new mini-drawer design.

the detector to the back-end electronics for fast signal processing and digital triggering. As was mentioned before, the demonstrator project will allow to test new ideas and technologies already in Run 2 and to demonstrate the feasibility of the new design. This provides a good opportunity to explore new technologies, including high-performance FPGAs, fibre optics, and to improve the reliability of the system.

The front-end electronics will exhibit several architectural changes (figure 13) [10]. It will move from the old super-drawer mechanics to a new mechanics design with four mini-drawers, to improve operation, maintainability and handling. The mini-drawers system will have new rigid inter-drawer connections and internal cooling (as opposed to the external one) and new flexible cable trays (figure 14). To improve the reliability and redundancy, the electronics in the new design are made as independent as possible to reduce the number of single point failures, with the possibility to use dual power supply for power redundancy. Several design options are being followed for some key components, with up to three different alternatives. The best option will be chosen based on performance results from test beams and other dedicated tests. As the digitised samples will be sent outside the detector at full 40 MHz sampling rate, the digital trigger and data buffering will happen in the back-end electronics, called "Super-ROD" (sROD) that will be located in ATCA crates, each sROD will process data from eight Tile Calorimeter modules (32 mini-drawers).

It is to test and qualify these new designs the "demonstrator" electronics drawer will be installed in the detector during Run 2. Being installed before the planned upgrade point, this "demonstrator" has to be compatible with the previous design and to provide analogue trigger and standard data and calibration streams. The “demonstrator” boards prototypes are being tested to be ready for insertion during the scheduled stop before Run 2. Several dedicated expert integration weeks proved to be essential for the success of the project.

6. Summary

The Tile Calorimeter is a key detector for measuring jet energy and missing transverse energy in the ATLAS experiment. A complete and overlapping chain of calibration systems, ranging from simple charge injection to laser and cesium radioactive source monitoring, ensure correct energy reconstruction during the changing conditions of the running experiment. The PMTs’ gain drift is well monitored by calibration systems that follow the calorimeter response behaviour with time. During Run 1, thanks to the advanced online data quality systems, the performance was excellent, with minimal losses and high data quality. The long shutdown detector maintenance of the front-end electronics and associated power supplies, together with the software improvements for the next run, are under way. The upgrade R&D projects for electronics replacement for HL-LHC programs are progressing and to validate the performance of the new design a demonstrator electronics drawer will be installed during Run 2.

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