# Production and Commissioning Performance Tests of the Read-Out Driver Boards for the Hadronic Tile Calorimeter of the ATLAS Detector at the LHC

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***Abstract*–The ATLAS Hadronic Tile Calorimeter detector (TileCal) is an iron-scintillating tiles sampling calorimeter designed to operate at the Large Hadron Colloider (LHC) accelerator at CERN. The central element of the back-end system of the TileCal detector is a 9U VME Read-Out Driver (ROD) board. The operation of the TileCal calorimeter requires a total of 32 ROD boards. We report here on the overall electrical performance of the ROD boards during their production phase and during their first operation at the ATLAS commissioning setup at CERN. We report also on the real time operation and performance of the ROD Digital Signal Processors (DSPs) on the first cosmic data runs taken at the commissioning setup. The DSP operation is based on the use of optimal filtering algorithms for the signal amplitude, pedestal and time online reconstrucion and which, in addition, monitor the quality of the reconstructions.**

## I. Introduction

ATLAS is a general purpose experiment for the Large Hadron Collider (LHC), a proton-proton collider at a 14 TeV center of mass energy. Both ATLAS and LHC are under construction at CERN at the moment. The main goal of the ATLAS experiment is to explore the Physics at the multi-TeV scale, with special interest at the Higgs sector and the physics beyond the Standard Model. The trigger system in ATLAS is divided in three levels, which are responsible for selecting for storage only the events containing physical interesting information. This way, the 40 MHz interaction rate leads to only a 100 Hz data storage rate.

The Hadronic Tile Calorimeter (TileCal) is a sampling calorimeter made of iron and scintillating tiles. Fig. 1 shows simulation pictures of both ATLAS and TileCal. Longitudinally TileCal is divided in a long barrel (LB) and two extended barrels (EBs). Each barrel defines a detector partition, with its own trigger and dead-time logic, completely independent from the data acquisition point of view. In the $\phi$ direction, TileCal is divided in 64 modules for each barrel.

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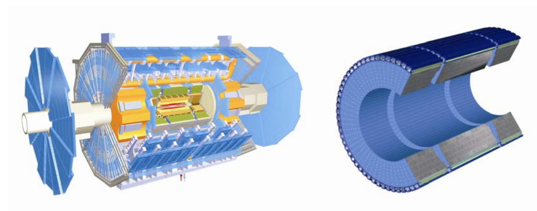

Fig. 1. Simulation of the ATLAS experiment (left) and its central hadronic calorimeter TileCal (right).

The energy deposited by the particles in the calorimeter produces light in the active medium. This light is routed to Photo Multiplier Tubes (PMTs), which are the first elements of the Front-End (FE) electronics. All FE electronics (shapers, amplifiers, digitizers, etc.) are integrated in a compact structure called superdrawer placed at the end of the modules. There are two superdrawers in each LB module and one superdrawer in each EB module.

The Read-Out Driver (ROD) electronic boards are the central element of the TileCal Back End (BE) electronics. Fig. 2 shows a picture of one ROD board.

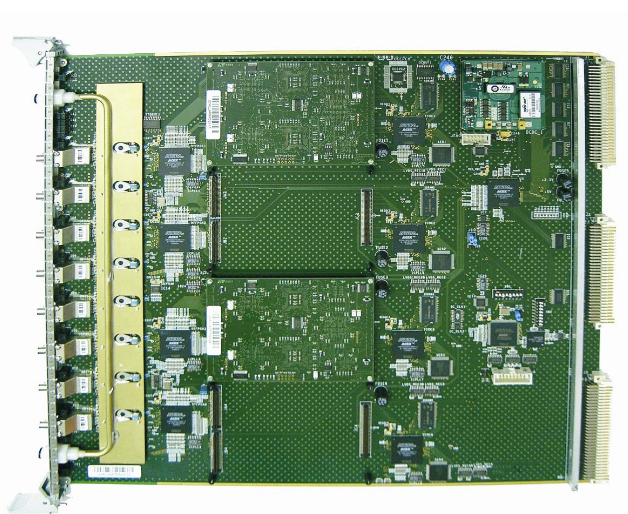

Fig. 2. Picture of the Read-Out Driver (ROD) electronic board. Note the two Processing Unit mezzanine boards.

The ROD is a 9U VME module which receives as input the fibers from the FE containing the digitized samples of the electronic pulse at a Level 1 trigger rate of 100 kHz. One ROD can handle 8 input fibers from 8 different superdrawers. Thus, 8 RODs are needed to read-out a TileCal partition (64 modules) and 32 RODs are needed to read-out the whole calorimeter.

The ROD has to process the data in real time, reconstruct the pulse and send information about the energy, timing and a quality factor (pile-up estimation) to Level 2 trigger. It is also responsible for the TTC synchronization, error detection, busy generation, etc.

## II. ROD PRODUCTION

TileCal ROD is based on the ATLAS Liquid Argon calorimeter ROD, with hardware and firmware modifications according to the TileCal FE requirements [1]. The TileCal-Valencia group is responsible for the design modifications, development, production, commissioning and future operation of the TileCal RODs.

During 2005 all the RODs and related modules are being produced at Valencia. To verify the integrity and functionality of the RODs, a set of tests have been prepared to be performed systematically on the boards in a controlled environment. These tests have been developed inside the ATLAS standard framework for online tasks: TDAQ (Trigger and Data Acquisition). The TDAQ framework is responsible for the experiment control, including run control, configuration of the trigger and data acquisition and the management of the data taking partitions. TDAQ also includes an online monitoring infrastructure and an Interactive Graphical User Interface (IGUI) for control and configuration of the system.

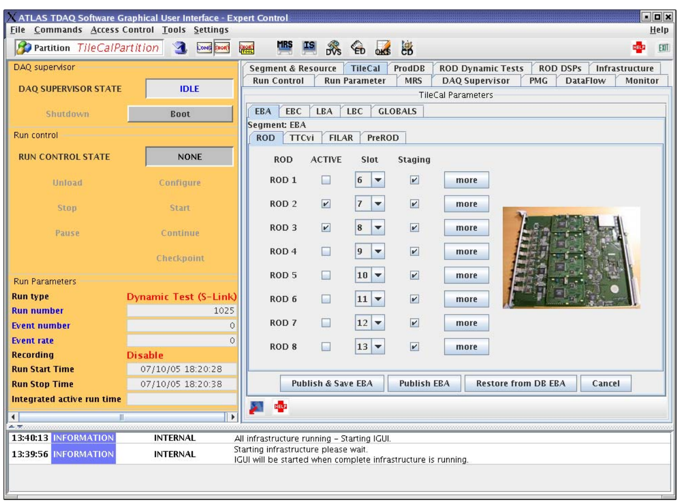


Fig. 3. TileCal ROD specific panel inside the main TDAQ IGUI window. From this panel, up to 8 RODs can be configured for tests and data taking.

Specific panels have been added to the TDAQ main IGUI for intuitive configuration of the ROD modules, as Fig. 3 shows. The following subsections are dedicated to the two kinds of tests prepared for the ROD Production.

### *A. Static Tests*

Their main purpose is to check the status and detect any malfunction in the boards. Basic functionalities are checked for all the devices and chips in the ROD: communication, VME register read/write operations, correct Processing Unit booting (see below), etc. For this, specific tests in the Diagnostics Verification System (DVS) inside TDAQ are used, as Fig. 4 shows.

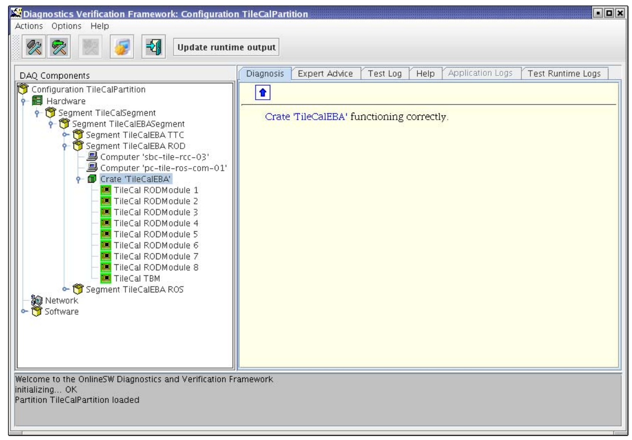


Fig. 4. DVS window where a test has been performed on all 8 RODs in the "TileCalEBA" crate. Note how the crate and all the RODs are displayed in green as they have passed all the tests.

### *B. Dynamic Tests*

Their main purpose is to validate the RODs from the data flow point of view. Data with a predefined format is injected to the ROD by dedicated electronic boards (PreROD prototypes [2], which are boards in development with double functionality: data multiplexers and injectors). Specific TDAQ ROD Crate DAQ (RCD) [3], [4] applications have been developed for transmitting the data through the RODs in short runs and burn-in tests.

To check the correct transmission of data a dedicated monitoring task inside TDAQ has been developed, which compare the acquired data with the injected data looking for transmission errors. This monitoring task also plots the number of events with errors versus the number of checked events in a graph inside TDAQ main IGUI window as Fig. 5 shows.

All the ROD modules produced together with the results of the tests performed on them are stored in a ROD Production mySQL data base accessible from the web.

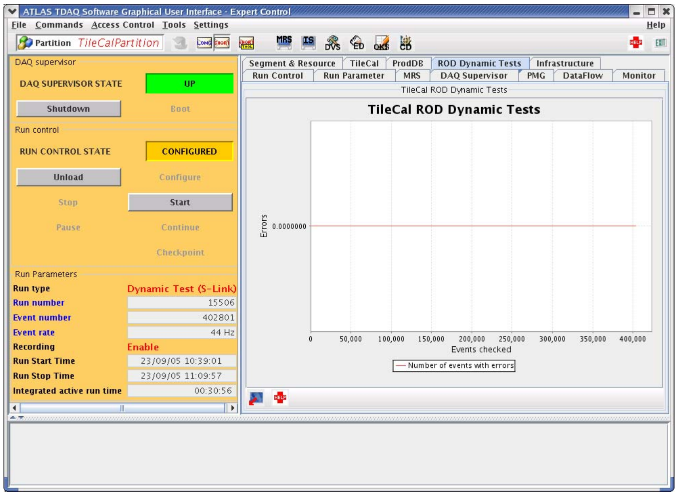


Fig. 5. TDAQ IGUI window after a dynamic test run with the custom TileCal ROD Dynamic Tests tab panel. It contains a single line graph which displays online the number of events containing data transmission errors in the run as a function of the events checked during the run.

## III. Commissioning

By summer 2005, the TileCal LB has been fully assembled in the ATLAS cavern. The main objectives of the commissioning phase of the experiment are the integration of all the hardware and software elements and the test the whole system in a setup close to the final one.

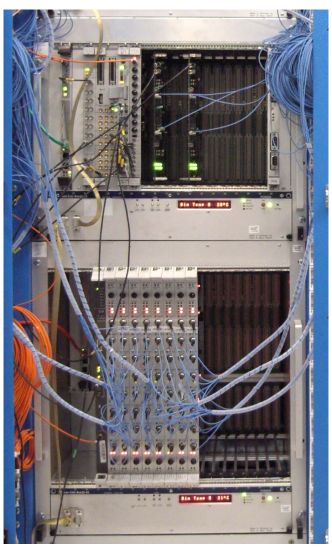

Fig. 6. Picture of the crates where the ROD boards and related modules are installed in USA15 for TileCal commissioning. The top 6U crate contains the boards dedicated to the trigger and timing control and the PreROD prototypes, used as data injectors. The bottom 9U crate contains 8 ROD boards.

One of the most important tests consists in verifying the whole data acquisition chain with final components. For this purpose, 8 RODs validated during production have been recently installed in the ATLAS electronics cavern (called USA15) and integrated in the general TDAQ environment together with the dedicated software for the FE configuration. Fig. 6 shows the crates used in USA15 for ROD boards and related modules installation and Fig.7 shows the ROD modules in detail.

We have been able to read-out data from the TileCal drawers using the RODs successfully during last month in Physics, Pedestal and Charge Injection Calibration runs. In the Physics runs, cosmic rays triggers based on the deposition of energy in a calorimeter single tower or in back-to-back towers are used.

The data acquired with the ROD for several runs have been analyzed in terms of pedestals, noise and energy deposited, as Fig. 8 shows. This represents a successful first step in the validation of the RODs in the final commissioning setup.

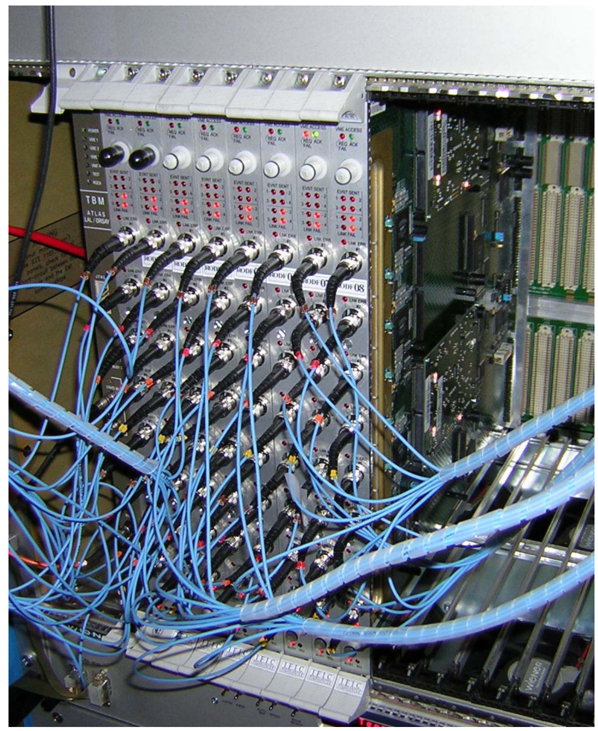

Fig. 7. Detail picture of the 8 ROD modules installed in USA15 for TileCal commissioning.

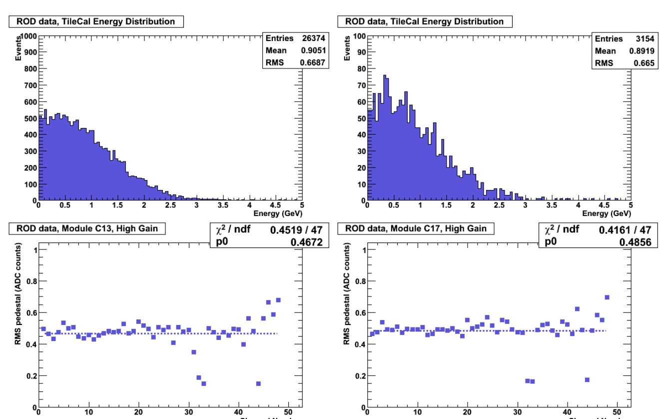


Fig. 8. Graphs obtained from the first TileCal data read-out with the RODs. Distributions for the total energy in the calorimeter in GeV for two different Physics runs (top) and noise value in ADC counts calculated as the RMS of the pedestal distribution for all channels in a superdrawer for two different modules during the same Pedestal run (bottom).

## IV. DSP PROCESSING UNITS

The TileCal ROD is equipped with 2 Processing Units (PUs). Each PU consists in a mezzanine board and contains 2 TMS320C6414 Digital Signal Processors (DSPs), as Fig. 9 shows. In ROD default operation mode (called *Staging Mode*), each DSP will process the data coming from 2 FE fibers with a maximum latency of 10 μs to avoid dead-time. Online energy reconstruction algorithms such as the Optimal Filtering (OF) can be implemented in the DSPs.

The OF algorithm [6] reconstructs the amplitude of the pulse (which is proportional to the energy deposition) as a weighted sum of the digitized samples in such a way that the contribution of the noise is minimized. It also computes the time of the signal and a quality factor of the reconstruction. The equations used in this algorithm for amplitude and time calculation are the following:

$$A = \sum_{i=1}^{n} a_i (S_i - p),$$

$$\tau = \frac{1}{A} \sum_{i=1}^{n} b_i (S_i - p)$$

where $A$ is the reconstructed amplitude of the signal, $\tau$ is the reconstructed time of the signal, $n$ is the number of samples, $S_i$ are the digital samples, $p$ is the value of the pedestal, $a_i$ are the weights for the amplitude and $b_i$ are the weights for the time. The quality factor $Q$ is obtained as:

$$Q = \frac{1}{A} \sum_{i=0}^{n} \left| A g_i - S_i + p \right|$$

where $g_i$ is the shape form factor for the sample $i$.

The weights $a_i$ and $b_i$ used in the OF are calculated from the signal shape (obtained from charge injection calibration runs) and the noise autocorrelation function (obtained from pedestal runs) so that the sigma of the energy and time distribution is minimized. Further developments in the OF have been done in order to obtain also the value of the pedestal with a similar procedure.

Fig. 9. Picture of the back side of the Processing Unit used in the ROD with two Digital Signal Processors.

OF is being implemented in the core of the DSPs using C and assembler for different types of run (Physics, calibration, etc.) and different number of samples.

The DSP can be configured to transmit the raw data without applying online reconstruction (*Copy Mode*) or transmit the raw data together with the online reconstruction. DSP Copy Mode has been extensively tested in laboratory and in the commissioning for different data formats. A first version of the OF algorithm (not with the final weights) has just being implemented and successfully tested with calibration FE data in the commissioning setup. In the final version an iterative procedure will be implemented so that the weights applied correspond to the right timing of the signal. For the moment, the weights applied correspond only to time equal to zero.

Fig. 10 and Fig. 11 show the results of the energy and time reconstructed online in the DSP compared with the offline reconstruction of the same data in a normal PC for a charge injection run. Though the DSPs are fixed-point processors, decimal precision is obtained by scaling the value of the energy, time and quality factor during the computation. A good agreement is found with small differences between online and offline calculations, although the distributions are wider than expected due to the use of non optimized weights.

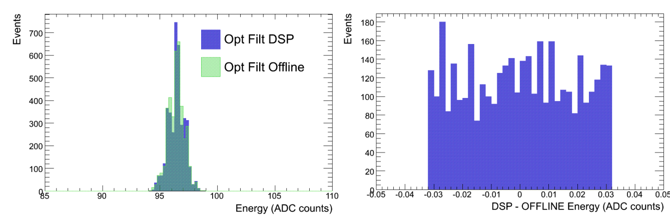


Fig. 10. On the left, energy distribution for a given TileCal channel obtained from TileCal charge injection data using the Optimal Filtering algorithm. In blue, the results obtained with online energy reconstruction in the DSPs and in green, the results obtained offline in a normal PC. On the right, the distribution of the difference between the energy reconstructed online and offline event by event.

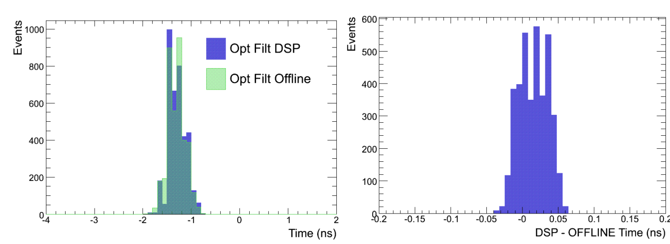


Fig. 11. On the left, time distribution for a given TileCal channel obtained from TileCal charge injection data using the Optimal Filtering algorithm. In blue, the results obtained with online time reconstruction in the DSPs and in green, the results obtained offline in a normal PC. Note that the mean value is around -1.5 ns. On the right, the distribution of the difference between the time reconstructed online and offline event by event.

The DSPs will also be used for online monitoring and histogramming of the data at the ROD level. Furthermore to exploit the online processing capabilities of the DSPs, the computation of the Missing Transverse Energy and a low $p_T$ muon tagging algorithm.

The ATLAS muon system has low efficiency in identifying and triggering muons with low momentum. A muon tagging algorithm in the calorimeter could give robustness to the overall muon trigger system. This algorithm is based in the distinctive energy deposition signature for these particles taking advantage of the projective geometry and longitudinal segmentation of the TileCal read-out cells. First implementations of this algorithm are being tested in the commissioning setup with cosmic rays at the moment.

## V. CONCLUSIONS

This paper summarizes the activities we are developing inside the ATLAS TileCal Collaboration. In the first place, the production of 32 ROD boards and related modules, full responsibility of our group, is taking place during 2005. We have reported about the software developments inside TDAQ for ROD production static tests in DVS and dynamic tests including specific monitoring tasks for data transmission checking and visualization. All the hardware and the test results are stored in a data base.

In parallel to their production, the RODs have been installed in the commissioning setup at CERN and integrated in the general TDAQ structure for data taking. Real data from the TileCal drawers have been taken with the RODs and analyzed offline successfully.

The OF algorithm for online energy and time reconstruction is being implemented in the ROD DSPs and tested with good results in the commissioning. Further developments in DSP monitoring and histograming as well as online missing transverse energy computation and muon tagging algorithm are foreseen to be implemented in the near future.

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## REFERENCES

[1] J. Castelo *et al.*, " TileCal ROD Hardware and Software Requirements," *ATLAS Internal Note ATL-TILECAL-2005-003*, Feb. 2005.

[2] V. González *et al.*, "Data Acquisition in TileCal/ATLAS Experiment. Design of the Optical Multiplexer Board Prototype," *IEEE NSS MIC 2005 Conference Record,* Oct. 2005.

[3] G.Crone, S.Gameiro, B.Gorini, M.Joos, E.Pasqualucci and J.Petersen, "ROD Crate DAQ User's Guide," *ATLAS EDMS Document ATL-DQ-EN-0020*, Sep. 2005.

[4] ATLAS ROS group, "Configuration of the ROS for test beam and ROD Crate DAQ applications," *ATLAS EDMS Document ATL-DQ-ES-006*, June 2004.

[5] J. Prast, "The TMS320C6414 DSP Mezzanine board," *ATLAS EDMS Document ATL-AL-EN-0051*, Aug. 2004.

[6] E. Fullana *et al.*, "Optimal Filtering in the ATLAS Hadronic Tile Calorimeter," *ATLAS Internal Note ATL-TILECAL-2005-001*, Jan. 2005.