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Upgrade of the ATLAS Tile Calorimeter High Voltage System

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Abstract. In the preparation for the new high luminosity phase of the Large Hadron Collider at CERN, many systems are undergoing improvement research and electronics upgrades. This is a report on the development of the high voltage system upgrade for the ATLAS's Tile Calorimeter. Prototype boards underwent testing under various situations, comparing results obtained by several measuring methods. Result analysis is presented for stability testing and board voltage limits testing. Methods for calibrating the system and program updates are also presented.

Keywords: Tilecal, LHC, PMT, High Voltage

1 Introduction

The ATLAS detector

The LHC (Large Hadron Collider) located at CERN is a complex experimental structure designed to uncover the true nature of particles and their interactions. In order to achieve this, several detectors are installed throughout the accelerator and its surroundings. ATLAS, one of the four largest detectors, has a cylindrical shape and a set of layers allowing to measure different properties of particles. The Tile Calorimeter (TileCal), located at the central region of this detector, is used to detect the passage of ionizing particles which lose energy going through plastic scintillating tiles supported by iron plates. The tiles respond to the energy deposition with a proportional emission of light that reaches photomultiplier tubes (PMTs) using optical fibers, where it is converted to an electrical signal. PMTs have an associated gain that is highly sensitive to its bias high voltage. Consequently, it is crucial to have a precise power source to have reliable data.

Presently, the preparation of the upgrades for the HL-LHC (High Luminosity Large Hadron Collider) is underway and it is projected to start operation by 2030. For this run, there is a target luminosity of 5× that of the last LHC run, which introduces many challenges. To avoid the great exposure to radiation, it was decided that the HVS (High Voltage System) that powers the PMTs of TileCal will be located outside the detector (as opposed to inside, where it has been placed until now) and it will be connected to it by 100 m long cables, which will bring its own challenges.

High Voltage System

In order to provide the adequate voltage to each PMT, prototype boards were designed. Each set of boards is composed of two boards, one HVSupply board [1] (Fig. 1) that generates a primary voltage and one HVRemote board [1] (Fig. 2) that divides and controls its output voltage for each of its 48 channels (each channel connected by the 100 m cable to a PMT). These cables are divided in groups of 12, each group using a connector to the HVRemote board. A Crate [2] is a metal box that can have 16 sets of boards simultaneously connected, and has an interface that allows the communication between both boards of a set as well as the communication for the control system, as seen in Fig. 1. With these Crates the approximately 10^4 PMTs of TileCal will be powered and controlled to ensure their correct operation.

Figure 1. Crate with two connected HVSupply boards on slot 2 and 13.

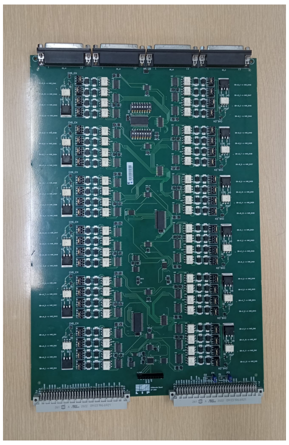

Figure 2. Prototype HVRemote board with two connector ports to the Crate interface and four connectors to the cables that will bring HV to the PMTs.

2 Measuring Systems

The prototype boards that were available at the lab were tested using different measurement systems: an internal HVRemote system, a voltmeter associated with a relay board and an external board. The stability of the output voltage of each channel of the HVRemote was tested, as well as the calibration of the internal measurements with

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the other methods, the range of voltages that could be controlled effectively at the HVRemote and the effect of different primary voltages for a chosen value for the output of the HVRemote.

HVRemote control

Each of the 48 channels of the HVRemote board is controlled by setting a value in the respective DAC (Digital-to-Analog Converter) channel. It also has its own internal measurement system which outputs DAC values per channel.

Throughout this paper, DAC Count values refer to the defined output for each channel on the HVRemote board. The full range of 12 bit DACs is adjusted to the HV range, so a DAC value of 4095 corresponds to 1000 V.

Voltmeter

A digital voltmeter connected to a relay board (Fig. 3) working as a mechanical multiplexer is also used as a measurement system. This is assumed to be the most accurate measuring method in use for the average voltage values, since a sampling time of 400 ms is used in the digital voltmeter for each of the readings.

External

An external measuring board was designed with a measuring circuit similar to the internal one of the HVRemote board (Fig. 4). Even though both this board and the voltmeter are external to the HVRemote board, this custom-made board is referred here as the External board (EB). It also possesses the capability to measure 48 channels at once and permits much faster readings than the set of voltmeter with the mechanically-operated relay board, although its accuracy must also be tested.

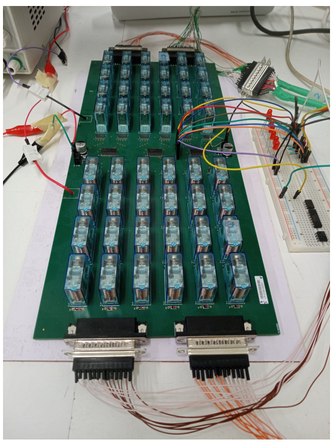

Figure 3. Relay board with four connectors of 12 channels, two on each side.

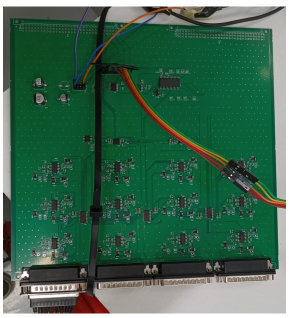

Figure 4. External board with the four connectors on the same side.

3 Experimental Procedure and Results

Stability Tests

The most important test made to the prototype boards was the stability test. When in use, it is imperative to ensure that the power supply voltage of the PMTs has as small as possible deviations from the expected value. In order to have reliable data, it was defined that the precision of the output must be within 0.5 V rms [2]. During a run at LHC, the detectors can be acquiring data for months; however, with the limited time for prototype testing, the maximum time used for stability testing was approximately 70 h (during the weekend in order to have stable conditions of temperature and humidity at the laboratory that are difficult to achieve during normal working hours). In Fig. 5 the normal behaviour of an output voltage for a channel in the HVRemote board is shown and it is possible to verify its stability.

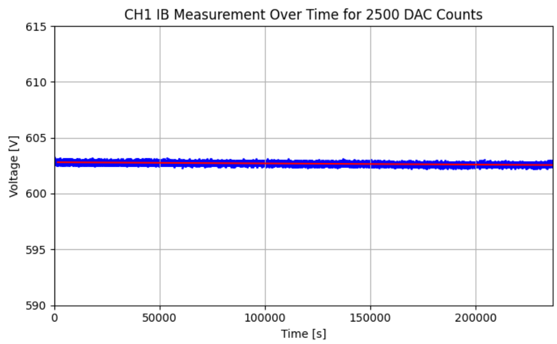

Figure 5. Stability testing started at July 26th for channel 1 of the HVRemote with the HVSupply set to 800 V and the HVRemote to 2500 DAC counts (aprox 610 V) representing the typical behaviour of an output voltage value over time for normal conditions of operation.

High voltage systems usually require some time of operation until they stabilize and reach normal operating conditions. So, after turning on, it is expected that the system takes some time to arrive to the stable target voltages, where the fluctuations of output values should remain within 0.5 V rms.

Departing from a state in which the Crate has been turned on for a long period of time and the HV has been active for previous brief tests, for the presented stability test the HV was switched on and values of the voltages for the 48 channels were recorded. The time required to get a stability with rms within 0.5 V was of the order of 1600 s. The time required for stabilization when the crate is turned on was not measured, but it is expected to be slightly longer.

A linear fit was applied to the collected data for each of the 48 channels, from which the rms was calculated (Fig. 6). For all the channels, negligible slope values of the order of 10^{-7} were obtained. The summary of the data is seen in Fig. 6, where it is shown the initial stable voltage value for each channel (shown to be approximately constant over time), with the rms given by the color scale.

From Fig. 6 it can be seen that, despite having the same DAC value, each channel has a different offset, resulting in a different output voltage. To have the correct value of the voltage for each PMT, it will be important to calibrate each channel and take into account the offsets and slopes obtained in the calibration procedure.

During that stability test the EB was also acquiring data, which presented similar behavior, as seen in Fig. 7. The different voltage values for the same channels (all with a positive offset when compared to the IB measurements) indicate that there is still a calibration to be made. Despite all channels measured with both boards having rms values below 0.5 V, there is a difference between the measurement systems. The main factor that can lead to this outcome is the number of measurements taken during a run, namely the number of consecutive ADC measurements that are averaged to give a single final measurement.

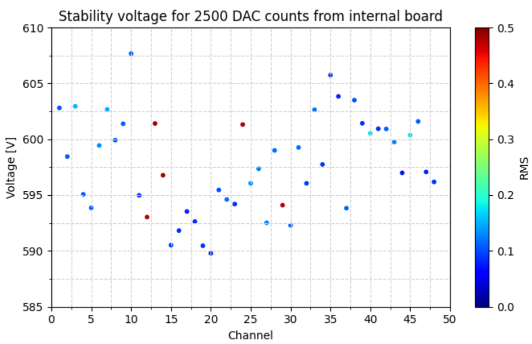

Figure 6. With a rms value calculated from a linear fitting that presented almost 0 slope, it can be observed that every channel measured from the HVRemote board had a rms value within the required parameter.

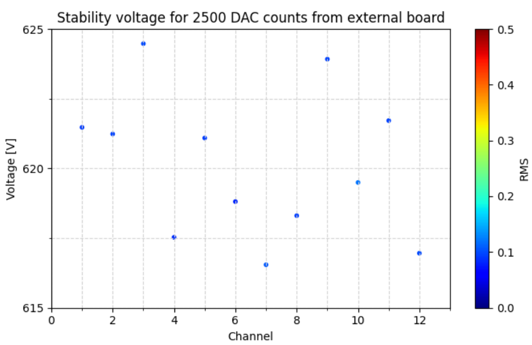

Figure 7. All the 12 channels connected to the left connector of the EB board presented rms values below the maximum allowed. Despite receiving the same DAC value, each channel gives a different output voltage.

For this particular test, the total number of measurements used by the IB for a channel was approximately 66 000, whereas for the EB it was only 24 000. The higher sampling for the IB is obtained averaging 5 consecutive readings of the ADC while the EB averages 10 consecutive readings at a lower rate, resulting in a higher rms for the IB.

Calibration

When comparing measured values across different measurement systems, slight differences were found.

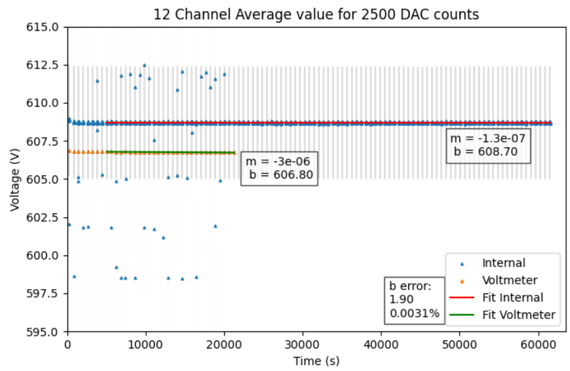

Figure 8. Average value across 12 channels with the HVRemote settings at 2500 DAC counts.

In Fig. 8, two important facts may be observed: first, for as long as the voltmeter is active, internal measurements have several outlying points. The reason for this behaviour is not yet known, however it is observed across several measurements. This is not relevant to regular operation, as it will not have an external voltmeter board attached past prototype testing. Second, it can be observed that b, the y-axis intersect value when performing a linear regression of all measured points, is different when using the internal measurement system and the voltmeter relay board. While the percentile error is low, an average difference of 1.9 V is still significant to the required precision in ATLAS measurements. As such, and assuming the voltmeter values as the correct ones, a correction factor can be determined for each channel and applied.

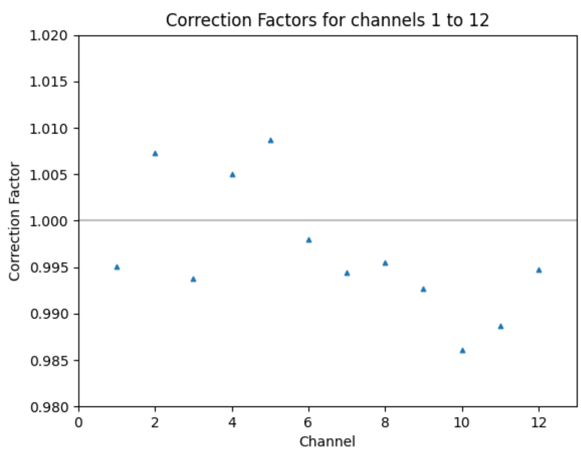

Figure 9. Calculated calibration factors per channel.

In Fig. 9, calibration factors for the first 12 channels are shown, all of them distributed very close to 1. These values were obtained from the average of the ratio $b_{\text{Int}}/b_{\text{Volt}}$ for each DAC count setting for each channel.

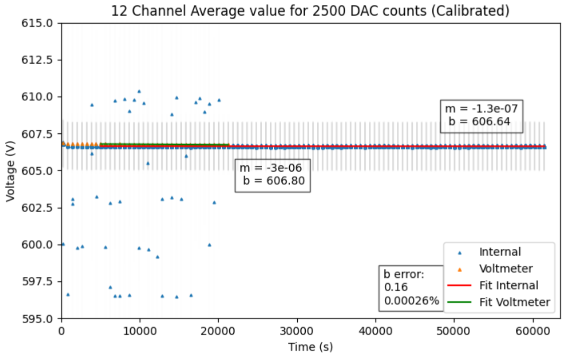

Figure 10. Average value across 12 channels with the HVRemote settings at 2500 DAC counts after multiplying by Calibration Factors.

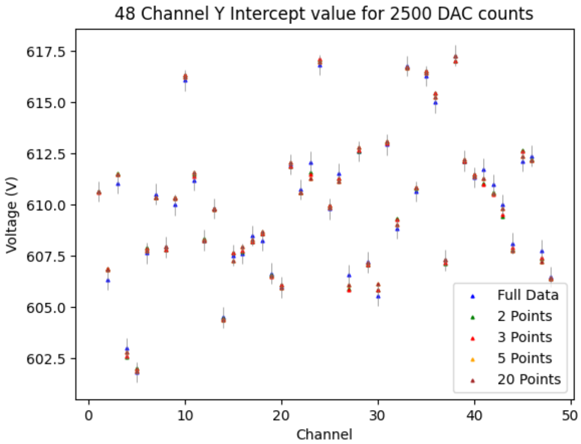

Figure 11. *b* value for 48 channels taken from internal measurements over night, calculated from different amounts of points.

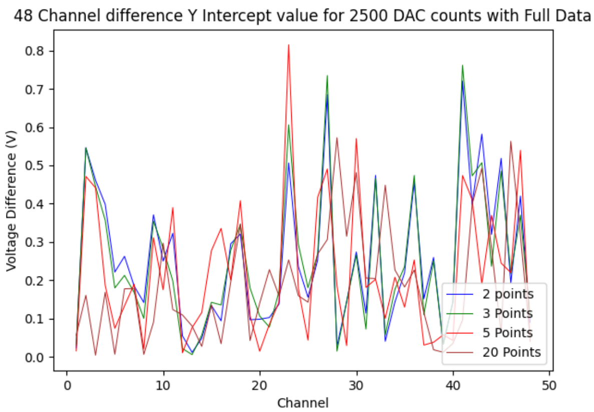

Figure 12. Difference between each set of calculated values to values obtained with all data points.

After applying the calibration, the obtained values for *b* were much closer, as can be observed in Fig. 10, reducing the error to 0.16 V on average. These factors may then be applied directly onto the internal voltage measurement software, providing it with higher accuracy.

In the future, several hundred of the HVRemote boards will require calibration. In order to optimize this process, Correction Factors were determined with data sets composed of different number of points along the voltage range of interest.

Linear regression y-axis intercept values calculated from all data points, 20, 5, 3 and 2 points for each channel are presented in Fig. 11. Variation between different amounts of points used to calculate this value goes up to 0.8 V. It can be observed that for most channels calibration with as little as 2 points were close to the real value; however, to be applied to all channels, it is recommended to use 20 or more points, as represented in Fig. 12.

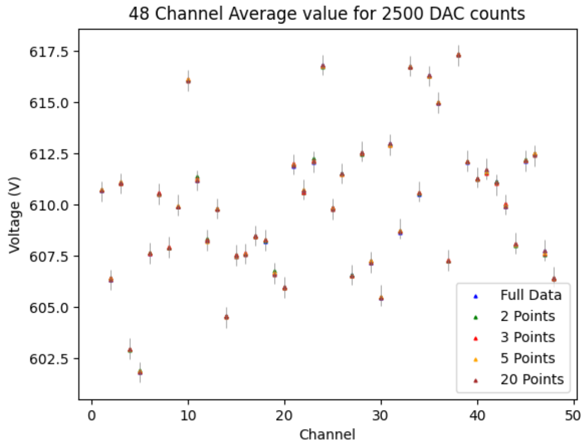

Figure 13. Average value for 48 channels taken from internal measurements over night, calculated from different amounts of points.

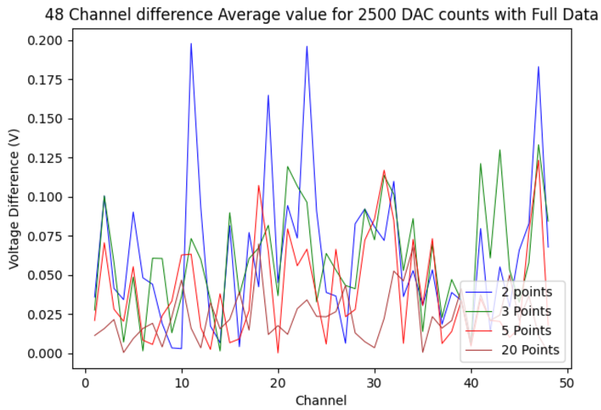

Figure 14. Difference between each set of calculated values to values obtained with all data points.

Average values calculated from all data points, 20, 5, 3 and 2 points for each channel are presented in Fig. 13. Variation between different amounts of points used to calculate this value is always lower than 0.2 V, as can be seen in Fig. 14. As such, this may be the preferred method to calculate Calibration Factors.

Interval of voltage control

The HVRemote voltage control is designed to be effective in a range of 360 V below the input voltage. Tests were conducted to find the experimental limits for the HVRemote output values depending on the primary voltage provided by the HVSupply along with output differences within the same HVRemote's settings.

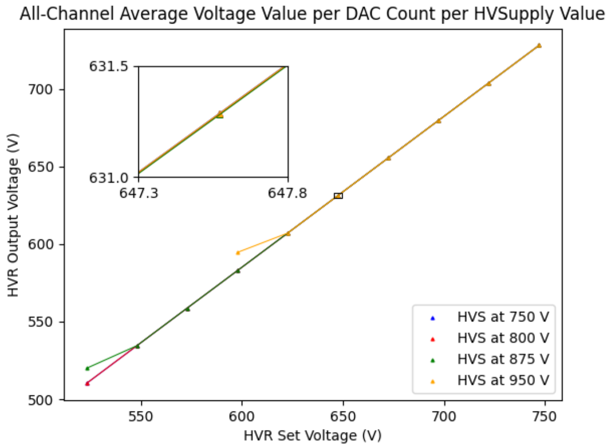

Figure 15. Averaged output value across all channels for each HVRemote DAC count setting for 4 HVSupply DAC count settings.

In Fig. 15, it can be observed that within a range for each HVSupply voltage, output on the HVRemote will be consistent, however it can also be concluded that each HVSupply setting also has a lower limit from which output linearity starts to change.

It was already known that for the HVRemote it was only possible to control values within 360 V below a given HVSupply primary voltage. It can be seen in Fig. 15 that with higher primary voltages the output voltages start to deviate from the desired values (the lower 3 values were taken out at 950 V because they no longer responded correctly).

To test more accurate limit control voltages, near the expected regions DAC count values were increased by 20 units (around 5 V of difference), which is the minimum DAC interval considered useable to detect this effect unambiguously. For the HVSupply voltages of 750 V, 800 V, 875 V and 950 V the DAC values at which the system had already control were 1640 (400.5 V), 1880 (459.1 V), 2180 (532.4 V), and 2480 (605.6 V), all values slightly higher than the previous reference (-360 V for each primary voltage). For DAC counts closer to the primary voltage, control was always observed, but tests with lower DAC count steps shall be done to verify how large the deviations from linearity are near the limits of the controlled region.

4 Program Improvements

Several custom programs were made in *Python* to allow an easy configuration of the measurements of each measuring system. Since each measuring board is accessed through a different interface, each one has its own custom program. This poses challenges as some testing requires varying input voltages in both the HVSupply and HVRemote boards,

which means any measurement method must be synchronized in order to allow the correlation of the measurements in both measuring methods and to keep track of the parameters that are changed for each measurement. As such, each program has a synchronization timer which will delay measurements by a margin after input voltages have changed and a margin before the new value is set. Each timer is measured locally but with respect to the program initialization time. This allows for the measurements to be synchronized across different platforms without active communication between them, as long as they are configured for the same set of measurements.

For the purpose of measurement configuration, a series of variables have been prepared, including timer settings, measurement types, order of DAC count inputs and combinations for both HVSupply boards and HVRemote boards, board channel mapping for the HVRemote board, channel-by-channel calibration factors and other similar details.

5 Conclusions

Considering that stability tests have shown stability to have a deviation within 0.5 V rms, this requirement has been met and current circuits may be used and possibly even further improved on. In regards to calibration, further studies will be required to correctly evaluate how to implement it in the long term, but initial implementation for short-term testing is already prepared. HVSupply voltage control intervals are wide and allow for fine control through the HVRemote, making this board nearly ready for use.

With some further testing and finer tuning, along with the implementation of a more user-friendly interface, this improvement needs only a bit more work before being in a use-ready state.

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References

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