Installation and Commissioning of the On-Detector Electronics of the CMS Electromagnetic Calorimeter

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Abstract

The CMS electromagnetic barrel calorimeter is composed of 76,000 $PbWO_4$ scintillating crystals. The scintillating light is captured by photodiodes, amplified and digitized. The conversion is performed inside the detector volume and data are transported through optical fibers to the off-detector electronics. About 25,000 Printed Circuit Boards of 5 different types and 5,500 Gigabit-Optical-Links and fibers should be installed and tested. The integration of electronics, cooling system, mechanical supports, low and high voltage distribution, synchronization and controls are discussed. Each step of the assembly sequence is followed by extensive test and quality control. Installation, commissioning strategy and the achieved system performance results are presented.

I. INTRODUCTION

A very high performance and homogeneous electromagnetic calorimeter [1] is an essential part of the CMS experiment [2]. It is designed to operate in a 4 Tesla magnetic field, in a ~ 2 kGy/year radiation environment and at the LHC bunch crossing rate of 40 MHz. This challenging requests and the energy resolution needed to detect the postulated two photons decay of the Higgs Boson have driven the design of ECAL. Lead tungstate scintillating crystals [3] have been chosen because of fast scintillation, short radiation length and small Moliere radius. The scintillating light from a crystal is detected by two avalanche photo-diodes (APDs). In order to achieve the design energy resolution, the crystal and APD temperature has to be kept constant to a high precision, and the crystal transparency, which varies with irradiation, has to be monitored and corrected. The signal amplification and digitization, including the formation of Trigger Tower sums on each group of 25 crystals, is performed inside the detector volume and transported through high speed links (optical fibers) to the counting room. Lower speed links are used to transport timing and control information to and from the detector. This scheme requires a large quantity of radiation hard electronics installed on the detector. Moreover the electronics must be highly reliable since it will not be accessible during data taking. For these reasons all the chips are manufactured in 0.25µm CMOS technology to guarantee radiation hardness and low power consumption.

A. The ECAL Barrel OnDetector Electronics

The CMS electromagnetic barrel calorimeter is composed of scintillating crystals grouped in 36 independent supermodules of 1,700 crystals each. The basic block of the electronics is a Trigger Tower made of 5x5 crystals [4]. It contains one Motherboard, five Very-Front-End (VFE) boards, one Front-End (FE) board, one Low Voltage Regulator (LVR) board and two Gigabit Optical Hybrids (GOH) (see Figure 1).

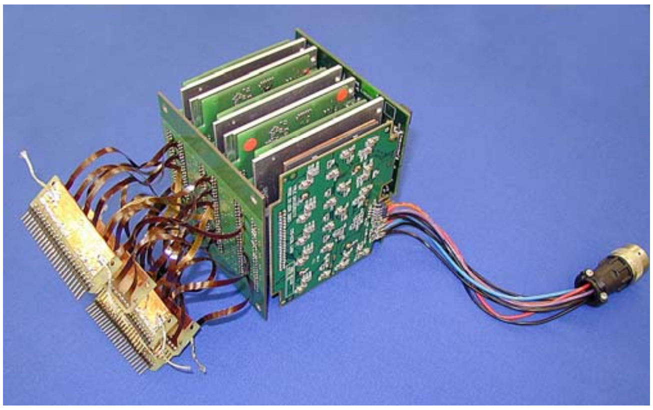

Figure 1: The readout electronics of a trigger tower, the basic electronics serving 25 crystals.

The Motherboard is connected to the avalanche photo-detectors by flexible kapton ribbons and distributes the bias voltage to the APDs and the low voltage from LVR to the VFEs. The LVR stabilizes the low voltage and contains three Detector Control Units (DCU) to monitor input and output voltages and cards temperatures. The VFE consists of five identical readout channels, each one consisting of a multiple gain preamplifier (MGPA) [5] with gains 1, 6 and 12. The three analogue outputs are digitized in parallel by three of the four channels of a 12-bit 40MHz Analog to Digital Converter [6]. The highest, non saturated signal is selected by the ADC integrated logic and stored in a buffer. On the FE board, the data are stored during the 3 µs latency of the trigger Level-1 Accept signal, while the trigger-primitives are calculated and transmitted. For these purpose two GOH boards, one for data and one for trigger, are used. They house a data serializer, a laser driver chip (GOL) and a laser diode with an attached fiber pigtail, 2 m long. Each FE hosts a Clock and Control Unit (CCU) integrated circuit which serves a I^2C interface to control the 68 trigger towers of the supermodule through a system of 8 token rings. A redundancy path guarantees the functionality of a token ring in case of non-operational FEs, provided that they are not consecutive. Each supermodule contains about 600 PCBs (340 VFE, 68 FE, 68 LVR, 68 MB and 8 token-ring link-boards TRLB), 138 Gigabit Optical Links, 17 LV distributors and 12 distributed fiber patch-panels. Each PCB element arrives fully qualified and labelled with bar codes.

For each supermodule a total amount of about 4.6 kW of heat has to be removed by the cooling system in order to keep the crystal temperature within the specified tolerance of ± 0.1º K.

B. The ECAL Barrel Off-Detector Electronics

The off-detector electronics has a modularity of one supermodule served by three 9U, VME64x compliant boards. A Clock and Control System (CCS) board initializes and controls the on-detector electronics. It also receives the LHC clock, the control signals and the trigger L1A and distributes them to the on-detector electronics and the other off-detector boards. A Trigger Concentrator Card (TCC) encodes the trigger primitives, transmit them at 40 MHz to the Regional Calorimeter Trigger (RCT), and stores them awaiting for a L1A signal. Then, upon receipt of a L1A signal, it transmits to a Selective Read-out Process (SRP) a classification of the trigger towers according to their energy deposits. A Data Concentrator Card (DCC) receives the supermodule data at the trigger L1A rate, performs integrity controls, reduces the data size via zero suppression and selective read-out, formats the data including the trigger primitives retrieved from the TCC, and transmits them to the central data acquisition.

C. Installation Sequence

The on-detector electronics is installed and tested at an integration area at CERN, Prevessin site (see Figure 2).

Figure 2: The electronics integration area at CERN. Installation can proceed in parallel on up to four supermodules.

This center is located in a huge assembly hall where trucks can enter and overhead cranes are available to load and unload supermodules. To cope with the construction schedule we have prepared three completely independent assembly stands. Each one consists of: a support stand; a cooling unit; a CAEN HV system powering the 34 channels; a Wiener LV system to power the 17 low voltage channels of one supermodule and 3 additional low voltage channels used to temporarily power trigger towers during tests; a readout system for single trigger towers; a database and shared services as the detector control system and the laser. Some extra stands with partial assembly components are also available. Beside the integration and test zone there are several areas to prepare and test electronics components and mechanical parts and an air-conditioned storage room for up to 20 supermodules.

After a supermodule arrives in the electronics integration area it is installed in a support stand and connected to services. The correct HV settings are retrieved from the database and all connections of the motherboards to the APS's and temperature sensors are tested. Then the integration sequence proceeds in steps, by installing:

- Trigger Tower electronics (first VFEs and LVRs, then FEs).
- Token-rings including TRLB.
- GOHs, optical fibers and fiber patch-panels.
- LV distribution cables and patch panels.
- Commissioning: one week operation and test of the completed supermodule using the standard CMS DAQ and control systems identical to the one that will be used in CMS.

At each step the bar code of installed components and their locations are registered into a dedicated database (CRYSTAL). The program verifies that each card has been previously registered in the database as good for installation and adds the location.

Installation sequence is optimized but still each phase covers the previously installed items so, given the complexity of the system, a full validation of each step is necessary. Extensive testing is part of each installation step to evaluate the full functionality and performance.

VFE cards are prepared by mounting an aluminium front cover, but first we apply a thermally conducting gap filling paste on the components side to ensure a good heat transfer. On the outside of the cover, we put 5 strips of 1mm thick gap pad to provide an efficient thermal contact to the cooling bars. The cover is alodined and connected to the ground plane of the VFE cards. Three captive stainless steel screws are mounted on the front covers to be used later to fix the cards to the cooling bars. The LVRBs are prepared similarly but their front cover is electrically isolated from the cards. FEs are prepared by gluing 3 strips of 1.5 mm thick gap pad in the places where they will touch the cooling bars.

The installation starts with the mounting of the VFE and LVR cards. Five VFEs and one LVRB are inserted on motherboard connectors and then fixed to the cooling bars. The procedure is repeated for all 68 trigger towers. Next the FE is mounted on top of each trigger tower. They have different CCU-IDs soldered so they need to be sorted to match the numbering scheme. In a supermodule the numbers from 1 to 68 are used for the trigger towers.

As a trigger tower is completed, it is connected to a dedicated VME read-out and its full functionality is tested as explained in a dedicated section.

Once all trigger towers are checked completely functional, the token rings are installed. First the four TRLB, each serving two token rings are installed and fixed to the cooling bars. Starting with rings 7 and 8, the token ring cables are installed on the FE cards and the TRLB (see Figure 3). The control fiber ribbon is connected to the PCI PEC in the test stand and all towers in a token ring plus the TRLB are powered. Default and redundancy path are tested to check the functionality of the TRLB and the correct cabling.

Figure 3: A supermodule after Trigger Towers and Token Rings installation.

Then, the GOHs (see Figure 4) for data and trigger links are installed together with the distributed fiber patch panels (DFPP), one each 12 channels of data and one for 12 channels of trigger. The DFPP contains a single fiber to a 12-way ribbon adapter. The extra-length of the GOH pigtail is stored in the DFPP. The routing of these optical fibers should be done rather carefully since they are fragile and a bending radius of ~ 4 cm should be respected. The correct operation of each individual GOH is verified by connecting the single fiber coming out from each box to the in-line patch panel. Every trigger tower is then tested again using the same software but now each tower is using its final links.

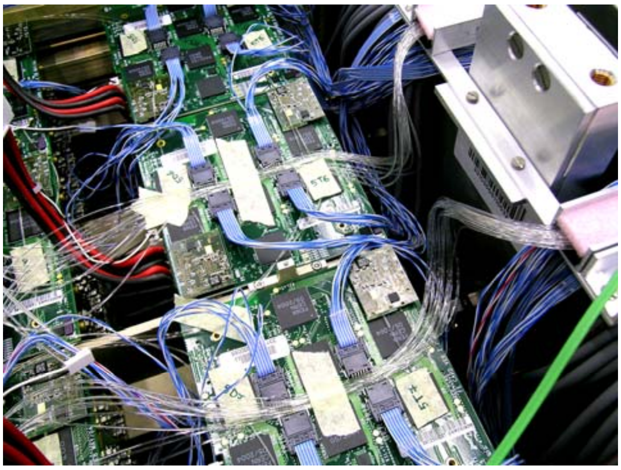

Figure 4: GOHs , optical fibers and Token Rings installation.

At this point the final low voltage distribution [7], made of 17 low voltage bus-bar, is installed together with their support plates, covering completely the on-detector electronics as shown in Figure 5. Each of the bus-bar connects to 4 trigger towers and to the corresponding TRLB. The power inputs connectors are fixed at the supermodule patch panel. A remote sense cable with 17 twisted pairs of wires terminated with a 37-pin connector at the supermodule patch panel is connected to the input of the 17 LVDs. Three inhibit cables terminated with 50-pin connectors are installed at the supermodule patch panel to control the LVDB. The voltages and correct assignment of the inhibit channels is verified.

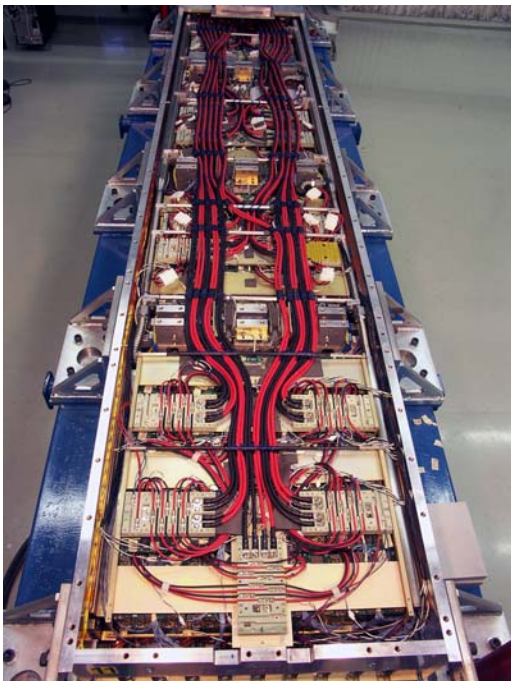

Figure 5: Overview of a completed supermodule. The low voltage distribution layer on top, is visible.

D. *Single Trigger Tower Testing*

The testing of individual trigger towers explores the full functionality of the corresponding channels and assesses their performance. It uses a dedicated VME read-out and a graphic data analysis interface.

The test sequence is the following:

- The communication of the CCU of the TT is verified by reading the CCU-ID on the FE, which should match the trigger tower location number in the supermodule.
- All devices connected to the 16 I^2C interfaces of the CCU are checked by scanning their addresses.
- The registers of FE and of the MGPA of the 5 connected VFEs are initialized, read back and their correctness is verified. For the FE case this insures the accessibility of all important registers. It includes setting the enabled channels, the power of GOHs, the transmission mode of optical links, the pipeline delay, the number of samples per trigger, the peak finding status, the filter parameters for the trigger and loading the pedestal values. In the MGPA case the registers are read for each individual channel. These registers are the calibration pulse enable, the pedestal DAC value for each gain and the test pulse amplitude, for each gain.
- A pedestal DAC values scan followed by a line fit is performed for each channel and each gain. Values are set to give pedestal mean values (200 ± 15) ADC counts A

typical distribution of pedestal averages is shown in Figure 6.

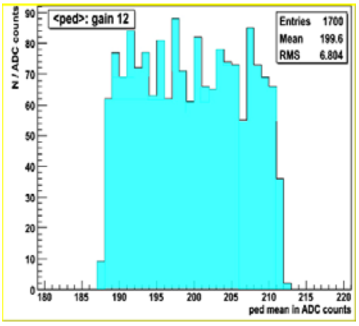

Figure 6: Pedestals mean value distribution for gain=12, all channels.

Using the obtained pedestal DAC settings the pedestals are measured. A total of 100 events, 10 samples each, are collected. The total noise is calculated as the r.m.s. value of all 1,000 samples. A low frequency contribution is estimated from the r.m.s. of averages per event. These measurements establish the performance of the readout and at the same time verify the correct operation of the full readout chain. A typical distribution of pedestal r.m.s. is shown in Figure 7.

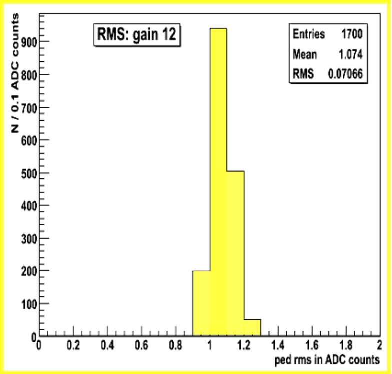

Figure 7: Pedestals noise distribution for gain=12, all channels.

The measure is repeated with HV on and off to check the correct connection and biasing of the APD, since the noise (r.m.s. of the pedestal) depends on the capacitance connected to the MGPA.

- For each channel and gain, mean amplitudes and r.m.s. of 10 test-pulses, injected using the generator internal to MGPAs, are measured and compared with the expectations (as shown in Figure 8). The same is done for the trigger channel. This test pulses are used to calibrate the electronics.

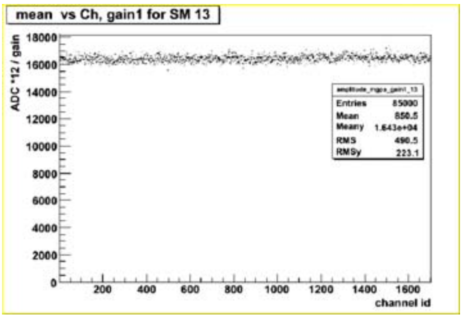

Figure 8: Test pulse amplitude distribution for gain=1, all channels

- Finally, using the DCU chips installed on the LVRB and VFEs, the low voltages and temperatures of the electronic cards , the APD leakage currents and their temperatures are measured.

A pulsed laser is available to test the full chain from crystal to optical fibers outputs (Figure 9). The same trigger tower test system is also used to read the signals of laser light injected into the front face of the crystals. This allows a validation of the full readout chain including crystals and APDs.

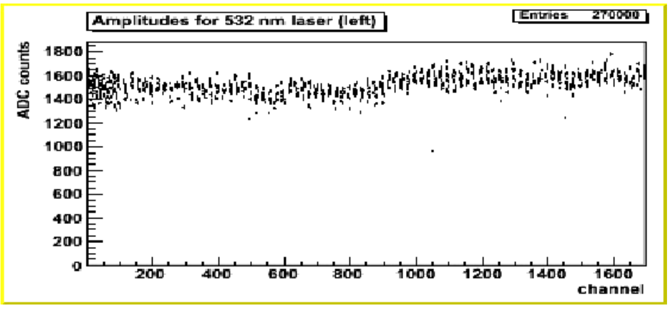

Figure 9: Laser signal amplitude distribution, for half a supermodule.

E. *Commissioning of a Supermodule*

Once a supermodule is completed it is operated at the electronic integration center for at least seven days. All problems discovered during this period are corrected, if possible. The standard CMS off-detector electronics system is used and it is controlled by the latest stable version available of the CMS-ECAL data acquisition software. Four different types of running mode are used in the data taking sequence:

PEDESTAL SCAN - to determine the DAC setting for pedestals mean values ~ 200 ADC counts.

PEDESTAL RUN - to measure with the above setting pedestal mean values, r.m.s. for all channels and all gains.

TEST PULSE RUN - to measure the amplitudes, for all channels and all gains, of the pulses injected by MGPAs at the input of the amplification chain.

LASER RUN - to measure the amplitudes of laser pulses injected in each channel.

At the end of each run a monitoring program is launched automatically to execute a series of control tasks, including a check of data integrity, pedestals and r.m.s., laser and test pulse amplitudes. Summary plots and reports containing detailed information are stored into web pages. They are easily accessible through browser application and provide immediate feedback for possible intervention.

The CMS Detector Control System (DCS) and ECAL Safety System (ESS) are used to monitor at all times low and high voltage, temperature and cooling system, allowing safe and unattended operation of the supermodule.

F. *Results*

23 supermodules have been assembled until now. As estimated it takes about 4-5 weeks to complete a supermodule achieving a very good quality and excellent performance.

For the first 19 supermodules assembled, corresponding to 32,300 channels, 278 problems were found and interventions done corresponding to 8.6 per-mills of the channels. 63% of the interventions were done during the installation of electronics components, 36% during the commissioning. Several types of typical problems (noisy channels, one or more gains not functioning, bit 11 problem, HV capacitor problem) have been classified and are found and solved systematically. In 78% of the cases the problem was solved by changing a component. Problems still remain in 62 channels corresponding to ~ 0.2%. Of these 32 channels are not working and 30 channels expose problems, i.e. showed a lower response to the laser pulse that seems related rather to bad optical connection of the laser fiber. The response can be verified with cosmic muons or with the test beam data.

G. Status and Plans

The integration and commissioning of the supermodules of ECAL barrel is proceeding well despite a slow down during the summer months due to MB problems related to some deliveries of bad quality kapton (bubbles and badly controlled etching). Figure 10 shows the commissioned supermodules and the planned schedule.

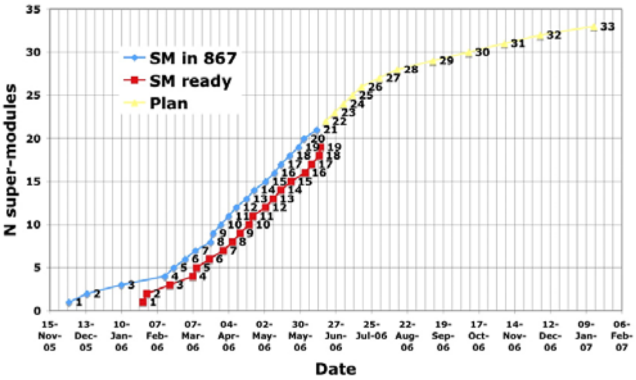

Figure 10: The integration progress in time showing the number of supermodule arrived so far to the integration center, the number completed and the schedule for the future months.

Until now 23 supermodules are completely commissioned, 20 have gone through cosmic data taking and 4 have been calibrated with an electron beam (see next paragraph).

The installation and commissioning of the 37 (36 + 1 spare) barrel supermodules shall be completed by early spring 2007.

H. Cosmic Ray, Calibration on a Test Beam and Other Data Taking

After the week of commissioning in the electronic integration center the supermodule is transported to a cosmic calibration stand. Ten days of cosmic ray data are collected. The supermodule is operated in stable environmental condition for 24 hours a day with no shifters, supervised by the already mentioned DCS and ESS. Besides the normal cosmic ray data taking, a sequence of pedestal, test pulse and laser runs is recorded regularly. Each run is analyzed automatically by the monitoring program immediately after completion of a run and re-analyzed later to extract crystal inter-calibration constants. The main goal is to achieve a further calibration of the crystals [8] in addition to laboratory and test-beam calibrations. But an important added value is the addition of a period of continuous running.

In this months different supermodule operations are ongoing at CERN. A subset of commissioned supermodules is calibrated with an electron beam at the H4 beam line in the North Area. Up to now four supermodules have been calibrated. Another supermodule is taking part in a combined hadronic and electromagnetic calorimeter test beam at the H2 beam line. At the CMS surface global integration area, two other supermodules together with sectors of the CMS detector are participating in the CMS magnet test and cosmic challenge (see Figure 11).

Figure 11: Two supermodules installed in CMS and the proud installation team.

I. Conclusions

The on-detector electronics installation sequence, test strategy and procedure are described and results of the system performance achieved are presented. The procedure for integration is well established and has improved with the accumulated experience. The commissioning of CMS ECAL barrel is proceeding steadily in compliance with the CMS installation schedule. The standard CMS-ECAL off-detector electronics, acquisition software and detector control and safety system are continuously used during commissioning, cosmic ray calibration, test beam calibration and CMS magnet test facility. The supermodules functionality and performance is tested both in standalone and in concert with other CMS subdetectors. A very good quality standard has been achieved with a level of channel failure down to a few per mills.

II. REFERENCES

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