Available on CMS information server **CMS CR -2012/189**

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

14 August 2012 (v2, 16 August 2012)

Upgrade of the CMS Hadron Outer Calorimeter with SiPM sensors

Benjamin Lutz for the CMS Collaboration

Abstract

The CMS Hadron Outer Calorimeter (HO) is undergoing an upgrade to replace the existing photodetectors (HPDs) with Silicon Photo Multipliers (SiPMs). The chosen device is the Hamamatsu $3 \times 3\,\mathrm{mm}^2$, $50\,\mu$m pitch Multi Pixel Photon Counter (MPPC). A complete control system of bias voltage generation, leakage current monitoring, temperature monitoring, and temperature control using solid state Peltier coolers has been developed. The system is design to be a ”drop-in” replacement of the HPDs. The complete system of more than 2800 channels has been produced and is currently burned-in. The installation of the SiPM based readout will be performed during the first LHC long shutdown scheduled for 2013.

Presented at *CALOR 2012: 15th International Conference on Calorimetry in High Energy Physics*

Upgrade of the CMS Hadron Outer Calorimeter with SiPM sensors

Benjamin Lutz for the CMS collaboration

DESY, Notkestrasse 85, D-22603 Hamburg, Germany

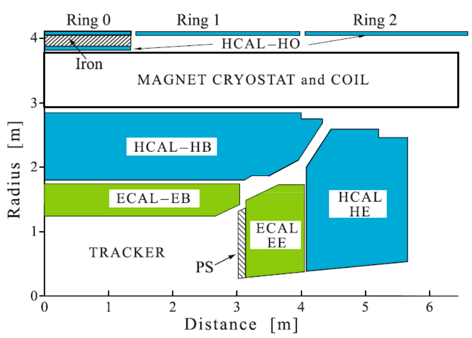
E-mail: Benjamin.Lutz@desy.de

Abstract. The CMS Hadron Outer Calorimeter (HO) is undergoing an upgrade to replace the existing photo-detectors (HPDs) with Silicon Photo Multipliers (SiPMs). The chosen device is the Hamamatsu $3 \times 3\,\mathrm{mm}^2$, $50\,\mu$m pitch Multi Pixel Photon Counter (MPPC). A complete control system of bias voltage generation, leakage current monitoring, temperature monitoring, and temperature control using solid state Peltier coolers has been developed. The system is design to be a "drop-in" replacement of the HPDs. The complete system of more than 2800 channels has been produced and is currently burned-in. The installation of the SiPM based readout will be performed during the first LHC long shutdown scheduled for 2013.

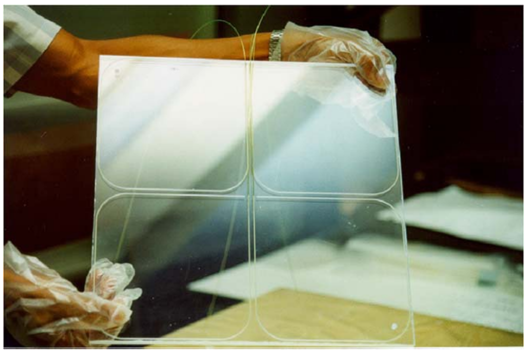
1. Overview

The CMS central hadron calorimeter is composed of barrel (HB), end-cap (HE), and outer (HO) regions. While the barrel calorimeter is located inside the magnet bore, the Hadron Outer [1] component is installed just behind the magnet coil inside the magnet flux return yoke. It provides and additional calorimeter coverage of about 3λ thickness. The outer calorimeter is composed of two layers of scintillator in the central section of the detector and one layer otherwise. The scintillation light is collected with wavelength shifting fibers and transmitted over clear fibers to front end electronics placed close to the layers. Figure 1a shows the schematic layout of the calorimeters in CMS and shows the location of the HO scintillator layers. Figure 1b shows a photograph of the scintillator tiles with embedded wavelength shifting fibers. The tile size is chosen to match projective towers in the HB. Currently, hybrid photo diodes (HPD) are used as photo-sensors, but for performance and operational reasons it is desired to upgrade these with SiPMs.

The CMS HCAL group has developed a drop-in replacement for the current front end based on SiPMs as photo-sensor [2, 3]. The choice of SiPMs is driven by several properties beneficial for this application: They are inherently magnetic field insensitive which allows a straight-forward design of the front-end considering that it has to operate in the 0.2 T return magnetic field. The SiPMs have a relatively high photon-detection efficiency and high gain. Finally, the devices are available as SMD mounts and can easily fit into the limited available space. The possible limitations of SiPMs like radiation hardness, limited dynamic range, and limited aperture don't pose a problem in this case: The radiation levels are modest with a lifetime expected flux of less than 10^{11} neutrons/cm^2 (E $>$ 100 KeV, 3 ab^{-1} LHC integrated luminosity). The energy flux into HO is small and the rate of larger energy depositions is low. The needed cross-sectional area is small due to the fiber based readout technique.



(a) Diagram of a quarter section of CMS showing the location of the HCAL HO



(b) An HO scintillator tile

Figure 1

2. SiPM choice

Following requirements have been chosen to select the right SiPM model for this application:

- Radiation tolerance up to 10^{11} neutrons ($> 100\,\mathrm{KeV}$)/cm^2
- Dynamic range sufficient for HO (2500 photo-electrons)
- Pulse recovery time short enough to accommodate HO rate-occupancy needs.
- Leakage current after radiation damage less than 40 μA
- Photon detection efficiency at least as good as the HPD (15% at 500 nm)
- Temperature dependence of gain small enough
- Source capacitance small enough not to significantly distort the pulse shape

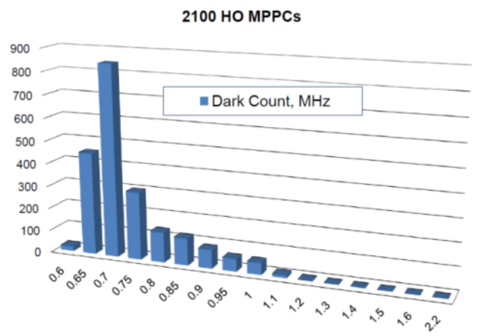
The evaluation [4, 5] of different SiPM candidates lead to the choice of the Hamamatsu $3 \times 3\,\mathrm{mm}^2$ 50 μm pitch MPPC as the appropriate device. These devices have 3600 micro-pixels which is a good match for our required dynamic range of 2500 photo-electrons (pe). At the wavelength of interest, 500 nm, the MPPC has a photon detection efficiency (PDE) between 25% and 30%. The capacitance of the MPPC (at operating voltage) is about 300 pF. The gain of the MPPC is about 6×10^5 when operated at 1 volt over-voltage (voltage difference to the point where the gain becomes zero). For 2500 pe this corresponds to 240 pC of charge. The MPPC pulse width for our signal is roughly 50 ns with a recovery time of less than 50 ns.

The MPPC gain depends linearly on the temperature. At the foreseen operation point this corresponds to a maximal relative dependence of 8% gain shift per degree C. This temperature dependence requires to actively control the temperature of the SiPM. Therefore, we require the temperature of the SiPMs to be regulated better than 0.1° C.

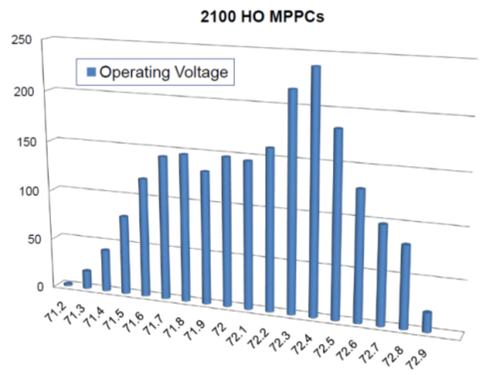
Figure 2 shows properties of 2100 MPPCs from the total order of 2900. Figure 2a is the dark count in photo-electrons and Figure 2b is the variation in operating voltage.

3. System design

The photo-detector and front end electronics are housed in crates (RBX) that are installed inside the magnet return yoke. Electronics and photo-detectors are arranged inside the RBX into independent Readout Modules (RMs) currently containing one HPD each. The original HPD [6] has 18 optical pixels with individual readouts. The drop-in replacement needs to match this physical layout as well as the existing front end ADC. Additionally, the drop-in system has



(a) Variation in dark count for 2100 MPPCs



(b) Variation in operating voltage for 2100 MPPCs

Figure 2

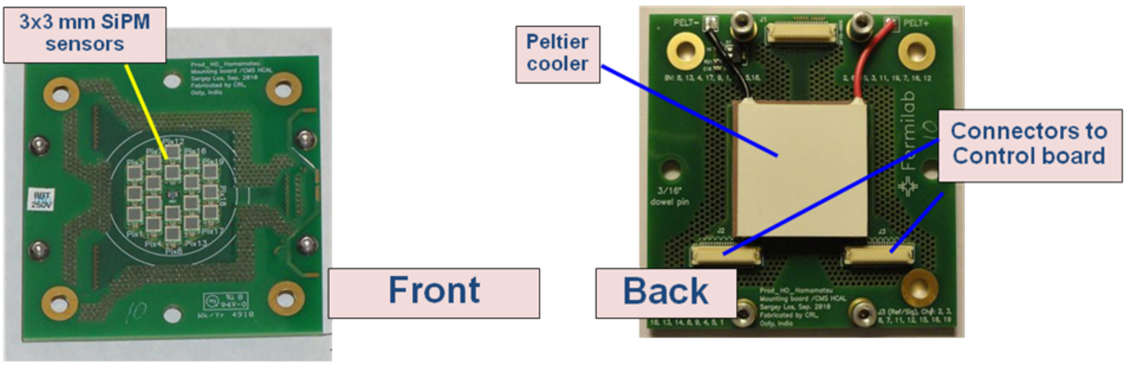


Figure 3: Photographs of the two sides of the Mounting Board (MB).

to supply a self-contained operating environment for the SiPM as only already existing supplies can be used.

The new system is designed to provide following functionality:

- Bias generation and regulation
- SiPM current monitoring
- SiPM temperature stabilization and monitoring
- Gain and shape matching to the existing ADC
- Matching of the detector optics

It consists of 3 circuit boards, the Mounting Board (MB), the Control Board (CB), and the Bias Board (BB). The array of 18 SiPMs is mounted on one side of the MB. On the other side a Peltier cooler is placed to regulate a constant temperature of the SiPM. The CB is connected on the Peltier side to the MB. The Both sides of the MB are shown in Figure 3. The BB is sitting as a piggy-back on the CB. Figure 4 shows details of the placement of the CB, MB, and BB in the RM unit of the RBX. To set the scale, the CB and MB are about 6.5 cm $\times$ 6.5 cm.

The control board shapes the SiPM signals and sends them to the 40 MHz flash front end ADC (QIE) [7, 8]. It also regulates the bias voltages, reads out the leakage currents, measures the

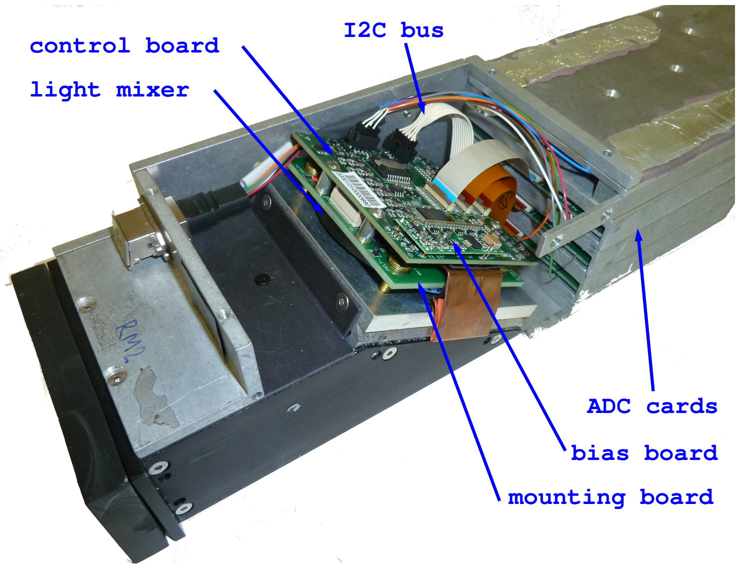


Figure 4: View of an opened readout-module where the mounting board, control board, and bias board can be seen. The ADCs (QIE) in the back are connected with three flat band cables. The optical system is coupled with a light mixer to the SiPMs.

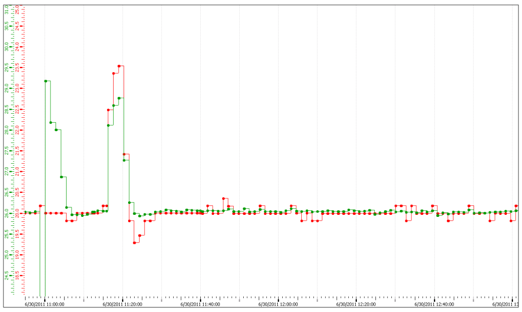
temperatures and voltages of the system, and supplies the Peltier with power. Communication to the outside is done via pre-existing paths using the I2C protocol.

The SiPM is AC coupled through a 22 nF capacitor to the QIEs. The coupling network achieves signal charge attenuation through capacitive splitting with the resulting gain of 50,000. For the largest anticipated pulse this corresponds to about 20 pC, split approximately into 1/2 in one 25 ns sample, and the remaining 1/2 split into 2 trailing samples. The maximum charge measurement for the QIE is 10 pC which matches the attenuated maximum anticipated signal of 200 MIPs.

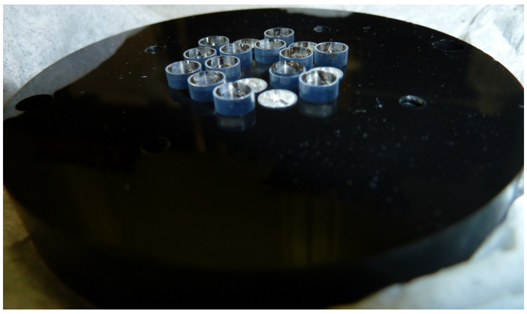
The SiPM bias voltage (BV) is generated on the BB from 6.5 V LV using a Cockcroft-Walton multiplier. The CB can regulate the 18 independent channels from 0 V to 100 V and supply 100 μA per channel. The BV is adjustable with a least count of 25 mV and is stable to about 5 mV. The SiPM leakage current can be read back for each channel, with a precision of 10 nA.

The temperature is stabilized using a Peltier cooler. About 1 watt of thermal power can be removed per RM. The mounting board has arrays of perforations around the SiPM area (Fig. 3) to provide a better thermal isolation. The temperature of the SiPM area is read out using a precision platinum resistor. The CMS slow control system reads out the temperature (through the CB) and generates a correction voltage to apply to the Peltier cooler. The control loop is executed about once per minute. Figure 5a shows a typical measurement of temperature vs time for the SiPM area. The least count of the readout is 0.018° C. We see that the temperature is stable to about 1 least count over a period of hours. The 2 transients are forced temperature excursions to demonstrate the temperature settling time. A hardware protection circuit is set to prevent the Peltier from driving the temperature below the local dew point. The trip temperature is 15° C and clamps off the Peltier power.

In order to ensure uniform illumination of the $3 \times 3\,\mathrm{mm}^2$ SiPM surface, a light mixer of a few millimeters thickness is placed between the input fiber bundle and the SiPM. These mixers prevent local SiPM saturation from light coming from the 1 mm diameter fibers from the scintillator tiles. Several different mixer designs have been tested to identify the optimal solution: Air-core mixers with cylindrical or conical reflective inner sides and mixers using optical fiber



(a) Temperature measurement of the SiPM area vs time (Green curve)



(b) Light mixer to distribute the light homogeneously over the SiPM surface. The fiber stubs responsible for the mixing have been elevated for better display.

Figure 5

inserts. Several metallic reflectors (Al, Au, and Cr) have been compared in the tests of the air-core mixers. The mixer based on optical fibers was chosen due to its superior performance in light transmission and homogeneity. Figure 5b shows such a mixer which is a black plastic disk with fiber stubs inserted.

The different parameters of the electronics system are summaries in table 1.

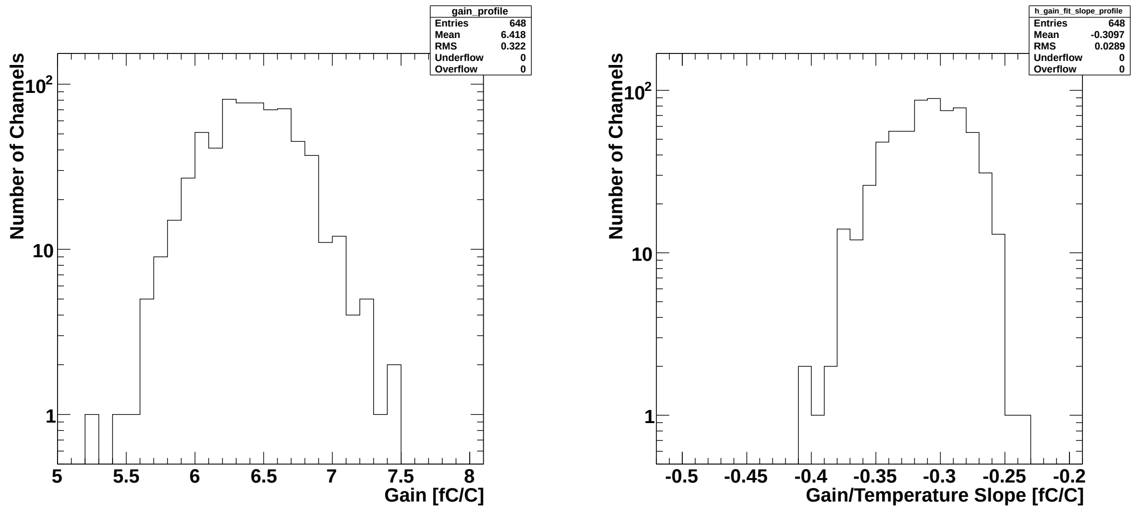
Table 1: Control Board Parameters

Bias Voltage Range	0–100 V
BV Setting Resolution	25 mV
BV Current Limit (per channel)	100 mA
Leakage Current Full Scale	40 mA
Leakage Current Least Count	10 nA
Temperature Resolution	0.018 ° C

4. Qualification measurements and quality control

Once built into the detector, the system has to operate reliably and stably for many years without the possibility for repairs or modifications. A comprehensive and diverse program of laboratory, test-beam, and on detector tests have been performed to validate the design. 108 channels of a pre-production have been installed into the CMS detector and are successfully collecting data since more than 2 years. The light mixer performance has been studied in details at the test-beam and in laboratory tests.

The final production cards undergo an extensive quality control and burn-in program before they get declared fit for use. This process starts with the characterization of the SiPMs operational parameters at the manufacturer. A sub-sample is re-tested at CERN where also accelerated aging and radiation hardness are measured. It is followed by tests at the production sites for the different boards: Fermilab (USA) mounting board, control card and bias card at TIFR (India). Finally, the assembled card-packs undergo a full system test in a setup similar to the detector readout at CERN for at least one week. The SiPMs and electronic cards are tracked during the full system production process, from the assembly to the final burn-in. Figure 6 shows



(a) Gain distribution of 648 SiPMs that have passed the quality control. The measurement was performed in the final system configuration.

(b) Temperature dependence of 648 SiPMs that have passed the quality control. The measurement was performed in the final system configuration.

Figure 6

the gain and the gain temperature dependence from already qualified card-packs. These are only two out of the many different parameters monitored during the quality control.

5. Schedule

During the first long LHC shut-down (scheduled to start Feb. 2013) all HCAL Outer HPDs, will be replaced with the new system. A complex choreography of detector access preparation, RM extraction, RM refurbishing, and quality control is currently developed to ensure an efficient use of the limited time during LHC shutdown. The removed HPDs will be reused as spare devices for the barrel and end-cap hadron calorimeters.

6. Summary

The CMS HCAL collaboration is replacing the existing photo-detectors (HPDs) in the Hadron Outer Calorimeter with SiPMs. A complete control system including bias voltage generation, leakage current monitoring, and temperature stabilization has been developed. The system is design to be a "drop-in" replacement of the HPDs with no need for new supplies or mechanical modifications. The full system of more than 2800 channels has been produced and the electronics is currently undergoing an extended quality check. The installation of the SiPM based readout will be performed during the first LHC long shutdown scheduled for 2013.

References

[1] Abdullin S *et al.* (CMS HCAL Collaborations) 2008 *Eur.Phys.J.* **C57** 653–663
[2] Freeman J 2010 *Nucl. Instrum. Meth.* A **617** 393–395
[3] Freeman J 2010 *Int. J. Mod. Phys.* A **25** 2421–2436
[4] Heering A *et al.* 2007 *2007 IEEE Nuclear Science Symposium Conference Record* **Vol. 2** 1545
[5] Heering A *et al.* (USCMS) 2007 *Nucl.Instrum.Meth.* **A576** 341–349
[6] P B Cushman A H H 2002 *ICFA Instrum. Bull.* **25** 1–16
[7] Shaw T *et al.* (CMS collaboration) 2002 *IEEE 2002 NSS*
[8] Zimmerman T and Hoff J R 2004 *IEEE J.Solid State Circuits* **39** 895–905