



The Compact Muon Solenoid Experiment  
**Conference Report**

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# Upgrade of the CMS hadron calorimeter for an upgraded LHC

Jake Anderson for the CMS Collaboration

## Abstract

The CMS barrel and endcap hadron calorimeters (Hcal) upgrading the current photo-sensors are hybrid photodiodes (HPDs) to meet the demands of the upgraded luminosity of the LHC. A key aspect of the Hcal upgrade is to add longitudinal segmentation to improve background rejection, energy resolution, and electron isolation at L1 trigger. The increased segmentation can be achieved by replacing the HPD's with multi-pixel Geiger-mode avalanche photodiodes. The upgraded electronics are required to operate in a harsh environment and are constrained by the existing infrastructure. The proposed solutions span from chip level to system level. They include the development of a new ADC ASIC, the design and testing of higher speed transmitters to handle the increased data volume, the evaluation and use of circuits from other developments, evaluation of commercial FPGAs, better thermal design and improvements in the overall architecture.

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# Upgrade of the CMS hadron calorimeter for an upgraded LHC

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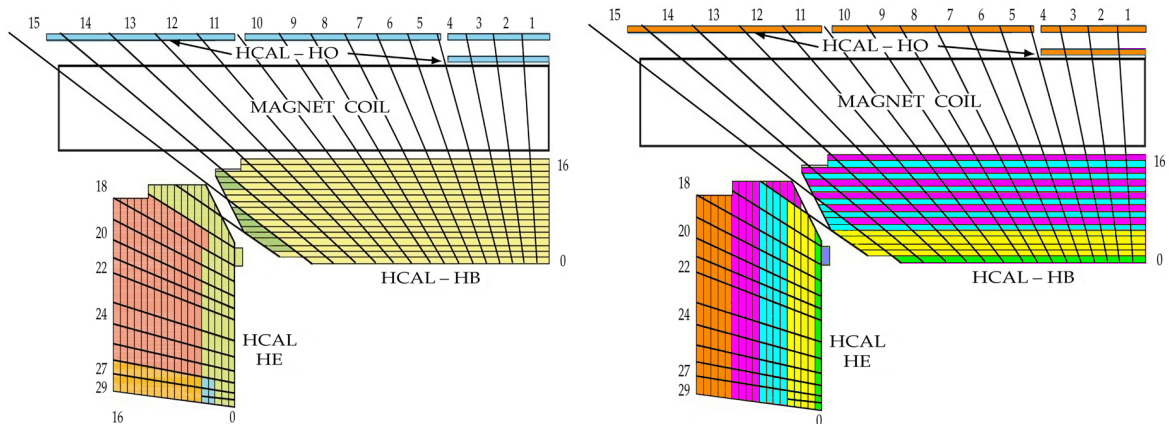
**Abstract.** The CMS barrel and endcap hadron calorimeters (Hcal) upgrading the current photo-sensors are hybrid photodiodes (HPDs) to meet the demands of the upgraded luminosity of the LHC. A key aspect of the Hcal upgrade is to add longitudinal segmentation to improve background rejection, energy resolution, and electron isolation at L1 trigger. The increased segmentation can be achieved by replacing the HPD's with multi-pixel Geiger-mode avalanche photodiodes. The upgraded electronics are required to operate in a harsh environment and are constrained by the existing infrastructure. The proposed solutions span from chip level to system level. They include the development of a new ADC ASIC, the design and testing of higher speed transmitters to handle the increased data volume, the evaluation and use of circuits from other developments, evaluation of commercial FPGAs, better thermal design and improvements in the overall architecture.

## 1. Introduction

The Large Hadron Collider (LHC) at CERN is planning to upgrade to higher instantaneous luminosities ( $\sim 5 \times 10^{34} \text{ cm}^2/\text{s}$ ). In order to improve the performance of its hadron calorimeter (Hcal), the Compact Muon Solenoid (CMS) Collaboration foresees upgrading the Hcal front-end electronics including the photo-sensors. The CMS Hcal is exploring replacing the existing hybrid photodiodes (HPD) with multi-pixel Geiger-mode avalanche photodiodes (also known as silicon photomultipliers or SiPMs). The new sensors and capabilities of the Hcal will require new ADC and data transmission ASICs.

The CMS hadron calorimeter is composed of barrel (HB), endcap (HE) and tail-catcher (HO) subsystems visualized in Fig 1. There is also a forward (HF) subsystem not shown. Reference [1] contains a detailed description of the CMS detector and its calorimeters. The HB and HE are composed of scintillating tiles interleaved with brass absorber layers and lie within the 3.8 T CMS solenoid. The scintillator tiles are read out via wavelength-shifting fiber (WLS) using HPDs. The calorimeter energy deposits are digitized on the front-end before being transmitted off of the detector via optical fiber. This paper is a report on some of the ongoing research and development to upgrade the front-end readout system of the HB and HE subsystems. It includes the upgrade goals, the SiPM sensor development, new ADC ASIC development, foreseen improvements to the digital readout electronics and some results from prototypes used in beam tests.

The goals are to improve the performance and reliability of the Hcal even under the more demanding luminosity environment of the upgraded LHC. These goals include: lowering instrumental noise, improving the calorimeter's ability to separate physics signals from the



**Figure 1.** Diagram of the longitudinal segmentation of the HB and HE for the current detector (left) and a proposed upgrade (right).

multiple proton-proton interactions that occur each LHC bunch crossing, rejecting backgrounds from out-of-time sources, improved robustness against component failure. Along with these goals, there are also constraints on the reuse of service infrastructure such as cooling, cables, fibers, etc. The development of the SiPM sensor has the potential to allow CMS to achieve its goals while staying within its present constraints.

Because the SiPM is a compact sensor it has allowed CMS to explore increasing the longitudinal segmentation of the Hcal, in particular the HB. Figure 1 shows the current segmentation of the Hcal and one proposal for how to increase the segmentation. The increased segmentation would provide additional handles to deal with pile-up from multiple proton-proton interactions and to maintain calorimeter performance after higher radiation doses. The SiPM is also well suited to achieve the Hcal goals because of its large gain, its insensitivity to magnetic fields, its fast signals and its radiation tolerance.

## 2. SiPM research and development

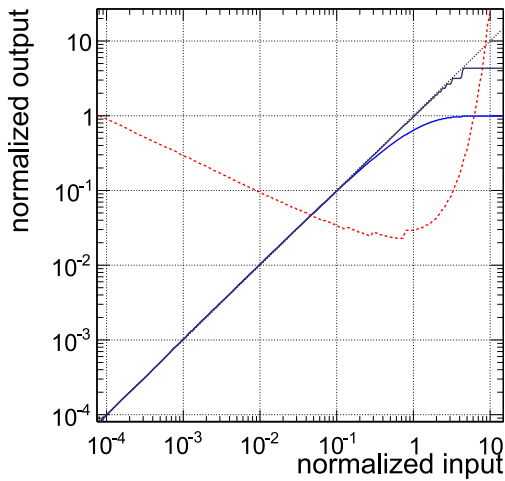
To the end of specifying a SiPM sensor for the CMS Hcal, we have developed a simplified device simulation which models most of the essential characteristics of the device, namely its dynamic range, pixel recovery time, cross-talk and temperature dependence. Figure 2 shows some of the output of such a model. We have also cross-checked the model with measurements of devices from various vendors. Using this model we have been able to find for a light pulse which is distributed in time, like that from our WLS fiber, a SiPM with a fast pixel recovery time can see a significantly extended dynamic range as seen in Fig. 3. We observe that we could get  $\sim 3\times$  boost in the dynamic range for a SiPM with fast pixel recovery. Using our models and measurements from the test bench and test beams we have been able to create a list of requirements for a SiPM for the HB/HE subsystems shown in Table 1.

## 3. SiPM radiation hardness

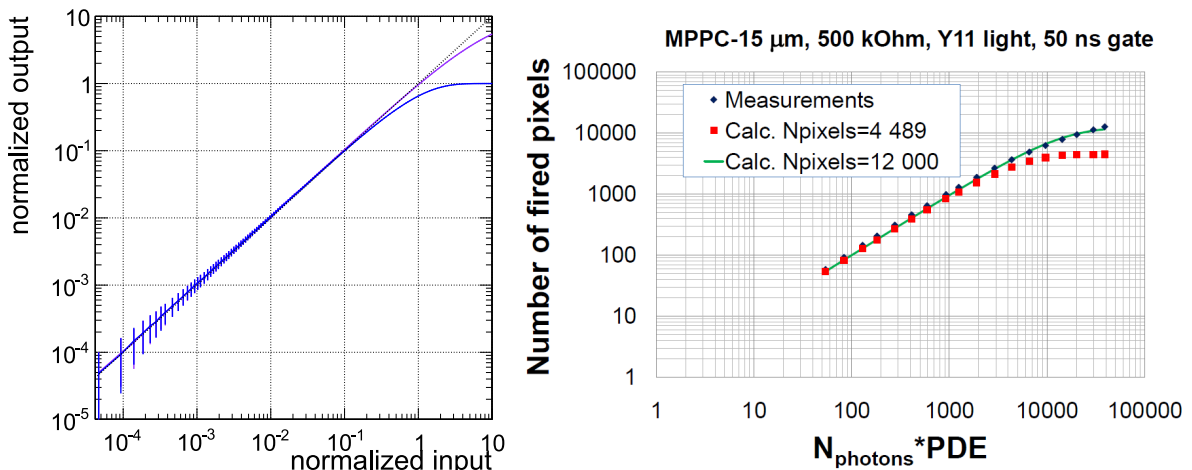
We have also investigated the radiation hardness of the SiPM sensors. The neutron dose at the location of the front-end electronics is expected to be around  $2 \times 10^{12} \text{ n/cm}^2$ . Using the irradiation facilities of the CERN PS, we observe deterioration of photon-detection efficiency (PDE) and gain and an increase in the leakage current through the diodes. The results for several devices can be seen in Fig. 4. In addition to these gradual degradations with dose, we look for radiation induced anomalous signals from the sensors. We do observe such signals in some of the diodes,

**Table 1.** Key requirements for a SiPM device to meet the needs of the CMS Hcal HB/HE.

Parameter	Spec value	Parameter	Spec value
size	2.2 mm <sup>2</sup>	gain	$6 \times 10^4$
effective pixels/device	> 20k	pixel recover time	$\tau_{RC} < 10$ ns
photo-detection efficiency (515 nm)	> 15%	excess noise factor	< 1.4
leakage current after $2 \times 10^{12}$ n	< 200 $\mu$ A	optical cross-talk	< 15%
neutron sensitivity	no	bias voltage	< 100 V
operating temperature	22° C	temerature dependence	< 5%/°C

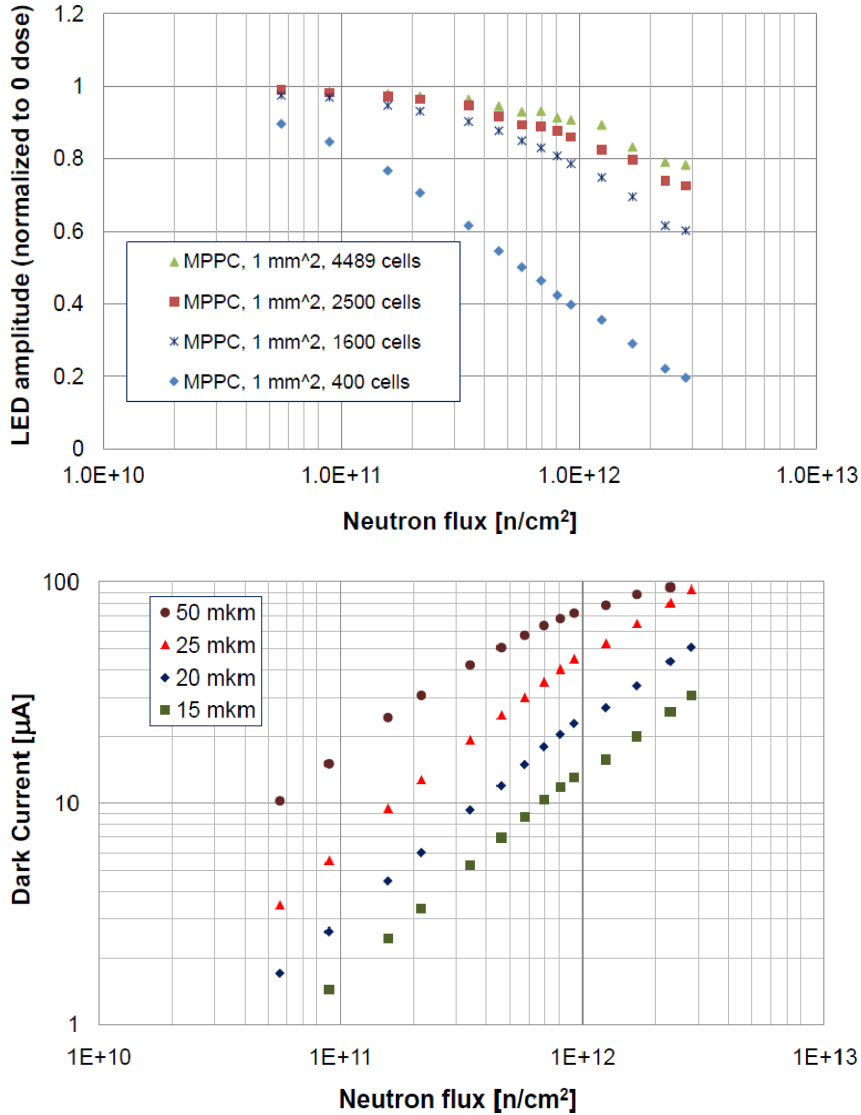


**Figure 2.** Simulation of a SiPM device the input and output are normalized to the total number of micro-pixels on the device. The blue curve is the raw output of of the device after QIE ADC simulation. The black curve is the output after correction for saturation. The red curve shows the total fractional error on the correction and includes contributions from the SiPM itself, Poisson statistics of the photons and uncertainty due to the correction.



**Figure 3.** Increase in dynamic range of a fast SiPM device for a pulse from a Y11 WLS fiber. The left plot is from simulation where the purple curve is for the fast SiPM and the blue is for a slow one. The right plot is a measurement for a device with  $\sim 4500$  pixels and shows a measurement of the same behavior.

but at a rate low enough not to produce significant spurious energy deposits in CMS. We are further working with vendors to further reduce such signals.

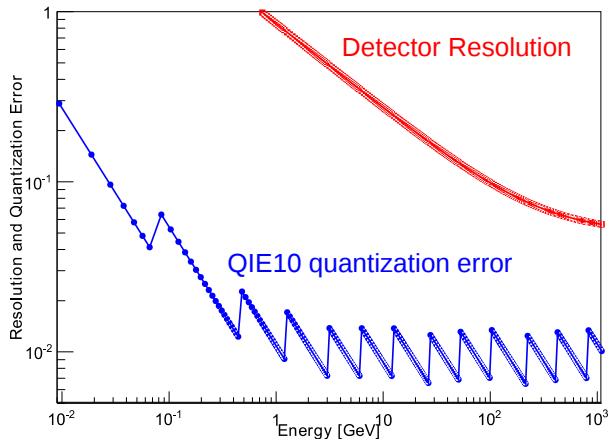


**Figure 4.** Effects of radiation damage on SiPM sensors from Hamamatsu as a function of neutron fluence. The top plot shows the degradation of gain  $\times$  PDE. The bottom plot shows the increase in leakage current. There is no bias correction applied in either case.

#### 4. ADC and readout development

The added gain of the SiPM device requires an improved ADC over the current QIE ASIC used by the CMS Hcal. In a joint project between the CMS and ATLAS collaborations, Fermilab is developing a new version of their QIE ADC ASIC. This new ASIC takes a similar approach as the previous QIE designs compressing the number of bits needed to cover a large dynamic range by increasing the distance between codes. Figure 5 shows that the quantization error of the QIE10 will be  $\sim 1\%$ , much lower than the detector resolution. This new QIE10 chip will have a significantly increased dynamic range compared to the QIE8 chip currently used. It

will also include TDC functionality to provide precision timing of the signal within the 40 MHz integration frequency. CMS expects to have a full prototype of the ASIC in the latter portion of 2012.



**Figure 5.** A comparison of the QIE quantization error and the detector resolution. The blue QIE resolution is significantly smaller than the overall detector resolution in red.

In addition to a new ADC, the data links from the CMS detector to the back-end electronics will be upgraded. We need additional bandwidth to accommodate the increased data payload of the QIE10 ADC+TDC information and the added longitudinal segmentation. We are evaluating the GBT chipset being developed by CERN[2, 3]. In addition to transmitting data off of the detector the same links can be used to distribute the LHC clock to the read-out electronics.

## 5. Beam test results

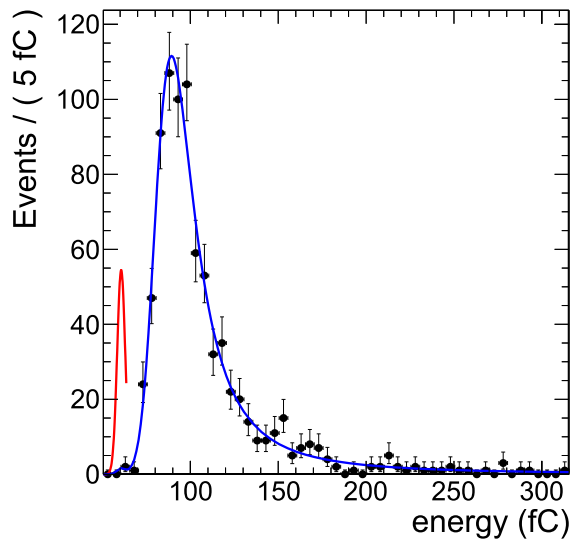
We have received and evaluated high pixel-density sensors from Hamamatsu[4], FBK[5], Zecotek[6] and Ketek[7]. The Zecotek diodes have a pixel recovery time which is too slow to be a viable option for the CMS Hcal. The others are much faster in particular the Hamamatsu pixel recovery time is  $\sim 3.3$  ns. The Ketek and FBK sensors have the smallest anomalous response to neutrons. Each of these has been further tested in the CMS Hcal calorimeter setup at the CERN SPS H2 test beam line.

We can observe muon signals in the calorimeter and confirm the improved signal to noise ratio. The MIP signal from only the first depth in the HB, as seen in Fig. 6, has a separation from pedestal similar to that observed for the entire HB with an HPD.

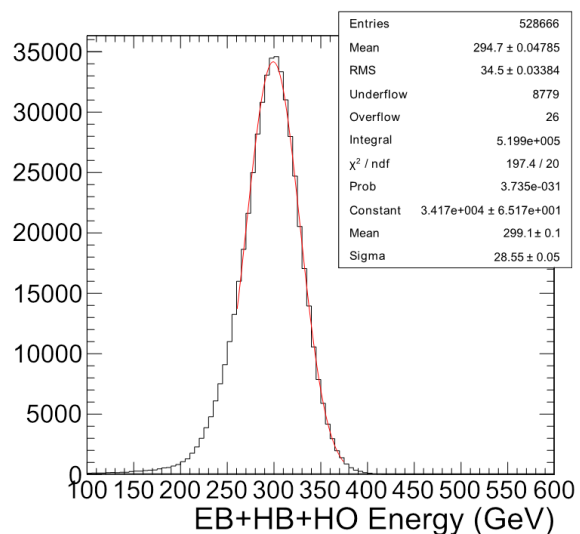
We use pion beams to look at the hadronic resolution of the calorimeter. A representative distribution is shown in Fig. 7. We observe comparable resolution with new SiPM sensors and 4-depth longitudinal segmentation to that from previous beam tests using HPD sensors [8].

## 6. Summary

The CMS Hcal has embarked on an advanced study to replace its existing photo sensors with SiPMs. This has identified characteristics that are required for a device to meet the needs of the Hcal and perform in the challenging LHC environment. In conjunction with the new sensors, we are improving our digitization and read-out chain to increase dynamic range, add precision timing and increase bandwidth. The development of these systems is getting very advanced and prototype tests have been done in the lab and in test beams. The Hcal plans to upgrade its HB and HE front-end electronics systems during the LHC long shutdown two currently foreseen in 2017 and 2018.



**Figure 6.** The distribution of 150 GeV muons in the first depth of the CMS Hcal in the H2 test beam. The blue curve is a fit to a Landau shape and the red curve is the pedestal distribution.



**Figure 7.** The distribution of the energy sum in the calorimeters for a 300 GeV pion beam. The Hcal has four longitudinal depths, read out via SiPMs. The red curve is a simple fit with a Gaussian shape.

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