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5 **The upgrade of the CMS hadron calorimeter with silicon** 6 **photomultipliers**

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11 **ABSTRACT:** The upgrade of the hadron calorimeter of the CMS experiment at the CERN Large
12 Hadron Collider is currently underway. The endcap sections will be upgraded in the winter of
13 2016–2017 and the barrel sections during the second LHC long shutdown in 2019. The existing
14 photosensors will be replaced with about 16 000 new silicon photomultipliers (SiPMs), resulting in
15 the first large installation of SiPMs in a radiation environment. All associated front-end electronics
16 will also be upgraded. This paper discusses the motivation for the upgrade and provides a description
17 of the new system, including the SiPMs with associated control electronics and the front-end readout
18 cards.

19 **KEYWORDS:** Calorimeters; Front-end electronics for detector readout; Radiation-hard electronics

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9 1 Introduction

10 The CMS hadron calorimeter (HCAL) [1] consists of 17 layers of brass absorber and scintillator
 11 tiles in barrel (HB) and endcap (HE) sections, complemented by an outer (HO) and quartz-fiber
 12 forward (HF) detector. The focus of this paper is on the HB and HE detectors, more details on
 13 HO and HF can be found in refs. [2, 3]. In the current CMS detector wavelength-shifting fibers
 14 transport the scintillation light from the HB and HE tiles to hybrid photodiodes (HPDs), whose
 15 electric signals are then integrated and digitized by the Charge Integration and Encoder version 8
 16 (QIE8) ASIC before being sent to off-detector readout electronics.

17 The CMS HCAL detector has been operating successfully throughout Run 1 and the ongoing
 18 Run 2 of the CERN Large Hadron Collider (LHC). However, radiation damage has caused the
 19 scintillator tiles to darken. Given the expected integrated luminosity of $3\text{--}5\text{ ab}^{-1}$ to be delivered
 20 by the LHC over the next years, it is clear that mitigation strategies need to be put in place in
 21 order to retain the ability to reconstruct signals of particles showering in the detector. The Phase-I
 22 upgrade of the CMS HB and HE detectors aims to keep detector performance high by updating
 23 the photosensors and readout electronics rather than replacing the scintillator tiles themselves. The
 24 photosensors chosen for the upgraded system are silicon photomultipliers (SiPMs), and this will be
 25 the first large installation of SiPMs in a radiation environment. The installation of the upgraded
 26 HE system is planned for winter 2016–2017, whereas the HB system will be installed during the
 27 second long shutdown (LS2) of the LHC during 2019.

28 This paper discusses the upgrade of the HB and HE detectors with SiPMs, starting from a more
 29 in-depth discussion of the motivation for the Phase-I upgrade in section 2. This is followed by a
 30 description of the overall readout chain in section 3, a detailed discussion of the SiPMs with their
 31 control electronics in section 4, and a description of the front-end readout card in section 5. Full
 32 system test results are briefly reported in section 6 before finishing with a summary in section 7.

2 Motivation for the Phase-I upgrade

Radiation damage to the HCAL scintillator tiles is the main motivation for the Phase-I upgrade of the HB and HE detector readout. The full Phase-I upgrade was envisioned to be put in place during LS2, before the radiation damage became too large. However, the incurred radiation damage during the past running periods of the LHC has been higher than originally expected, resulting in an increased signal loss, in particular for the most forward regions. As a result, the decision was made to advance the HE upgrade schedule by 2 years. It is now understood [4] that the radiation damage does not only depend on the total ionizing dose, but also on the dose rate, because of chemical effects related to oxygen diffusion. Higher dose rates result in less damage. The dependence of the response of the detector can be modelled by an exponential decay,

$$\text{response} \propto \exp - \frac{\text{dose}}{D}, \quad (2.1)$$

where the decay constant D depends on the dose rate. Figure 1 shows the relative response of the HE scintillator during the LHC running periods in 2012, 2015, and 2016. The degradation over time is clearly visible, as is the change in slope when going to a higher instantaneous luminosity during 2016.

Figure 1. Response of the HE scintillator tiles as a function of the delivered integrated luminosity for several pseudorapidity values η . The blue, red, and black dots represent response measurements performed during 2012, 2015, and 2016, respectively. The colored lines are fits to the 2012 measurements for different η values using the functional form from eq. (2.1). The box in the lower left corner contains the fitted value for the decay constant D for each fit.

1 The effect of this radiation damage on physics quantities, such as missing transverse energy
 2 and jet energy resolution, can be mitigated by replacing the HPDs with SiPMs. A key SiPM feature
 3 in this respect is the three times better photon detection efficiency compared to HPDs, which will
 4 directly increase the signal size. They are also much smaller, meaning that we can fit more channels
 5 in the same physical space. In the current system, the 17 detector layers are read out in 1–3 groups
 6 or ‘depths’, where the light from layers in any given group is optically added together by sending it
 7 to a single HPD. Therefore, having more channels allows for a finer depth segmentation, as shown
 8 in figure 2, which is ideal to perform a more precise calibration of the depth-dependent radiation
 9 damage. With the increased light yield and better calibration, the performance for physics quantities
 10 is recovered. For example, the upgrade results in an improvement of the jet energy resolution of
 11 $>50\%$ at $|\eta| \approx 2.8\text{--}3$ after 500 fb^{-1} of integrated luminosity is delivered by the LHC.

Figure 2. The HCAL depth segmentation in the current (left) and upgraded (right) system. Light from layers that are depicted with the same color are optically added together before reaching the photosensors.

12 **3 The Phase-I readout chain**

13 The upgraded HB and HE detectors consist of three main components: the active scintillator
 14 material, the on-detector or ‘front-end’ electronics, and the off-detector or ‘back-end’ electronics.
 15 The front-end electronics are organized into readout boxes, of which there are 36 for HE and 36 for
 16 HB. Each readout box contains four readout modules, a calibration unit, and a clock, control and
 17 monitoring unit (CCM). Each HE (HB) readout module consists of 48 (64) SiPMs in their thermal
 18 enclosure, an optical decoder unit (ODU) that maps the detector layers onto the SiPMs, a SiPM
 19 control card, and four front-end readout cards, as shown in figure 3. The calibration unit allows us
 20 to send LED light to the SiPMs, and the CCM handles the distribution of the clock and fast reset
 21 signals, as well as the control and monitoring of the front-end readout cards and SiPM control card.

22 The HE readout chain, shown schematically in figure 4, starts with the scintillation light from
 23 the active material that is wavelength-shifted and then sent to the SiPMs via clear optical fibers.
 24 The charge output from the SiPMs is then fed into the front-end readout cards, which each include
 25 twelve QIE11 ASICs [5] and one Microsemi Igloo2 FPGA. Each QIE11 integrates charge from one
 26 SiPM at 40 MHz without dead time. Each Igloo2 FPGA serializes and encodes the data from the
 27 twelve QIE11 channels. The encoded data is optically transmitted to the back-end electronics via
 28 the CERN Versatile Twin Transmitter (VTTx) [6] at 4.8 Gbps. The back-end electronics buffer the
 29 data, form trigger primitives, and ship the appropriate data to the central data-acquisition system

Figure 3. Illustration of the HE readout module, which consists of four front-end readout cards (or QIE boards), the optical decoder unit, the SiPMs in their thermal enclosure, and the SiPM control card.

Figure 4. The data acquisition chain of the upgraded HE detector including the SiPMs, the front-end readout card and the optical link to the back-end electronics. The front-end readout card contains twelve QIE11 ASICs for charge integration, one Igloo2 FPGA for data serialization and encoding, and one VTTx optical transmitter.

- 1 upon receipt of a trigger accept signal. The HB readout chain is identical to the HE readout chain
- 2 except for adjustments related to the increased channel count per front-end readout card.

3 **4 Silicon photomultipliers and control electronics**

4 The SiPMs used in the upgraded HE system have been produced by Hamamatsu. Two different SiPM
5 sizes are used, 2.8 and 3.3 mm in diameter, in order to handle the varying number of scintillator
6 layers that are optically added together. The SiPMs contain 4500 pixels/mm², each of which is
7 operated in Geiger mode. The total SiPM signal is the sum of all fired pixels. The SiPMs have a
8 fast recovery time of 10 ns, which increases the effective pixel count by a factor of about three by
9 allowing each pixel to fire more than once during the illumination time of the scintillation light.

10 SiPMs have several advantages compared to the HPDs that are currently used in the CMS
11 HCAL detector. SiPMs have a smaller size, a better photon detection efficiency of around 28–35%,
12 and a very high gain ($2.7\text{--}3.5 \times 10^5$) that is two orders of magnitude larger than the HPD gain,

Figure 5. (Left) SiPM gain versus over-voltage for both SiPM sizes. (Right) Photon detection efficiency (PDE) for 515 nm light versus over-voltage for both SiPM sizes.

1 assuming that the SiPMs are operated at 3–4 V above their breakdown voltage V_b . Figure 5 shows
 2 the SiPM photon detection efficiency and gain as a function of over-voltage $V - V_b$. In addition, the
 3 high-energy anomalous noise that is observed in HPD operation is eliminated for SiPMs because
 4 the SiPMs are not sensitive to magnetic fields and are operated at a much lower voltage of around
 5 68 V compared to the roughly 8000 V that is needed for HPDs.

6 SiPMs also have several disadvantages compared to HPDs, in particular, the SiPM gain has a
 7 temperature dependence of $2\%/^{\circ}\text{C}$ and a voltage sensitivity of $30\%/V$. However, these temperature
 8 and voltage dependencies can be managed with careful detector design, as described below. The
 9 dark current is negligible for unirradiated SiPMs but reaches $50\text{ }\mu\text{A}$ at 3 V over-voltage and 5°C
 10 operation for a neutron fluence of $1 \times 10^{12}/\text{cm}^2$. Even with this level of dark current, SiPMs still
 11 possess better signal/noise than HPDs at high neutron fluence [7].

12 Eight SiPMs are mounted in a single package, and 6 of these packages are used per HE readout
 13 module. The packages are mounted on the SiPM mounting board, which is a rigid-flex construction
 14 with a rigid part that holds the SiPMs inside their cooling assembly, flex cables that interface with
 15 the QIE11 chips for the charge integration, and a flex cable that transfers the desired bias voltage
 16 to each SiPM independently. Temperature and humidity sensors are installed next to the SiPMs on
 17 the mounting board.

18 To achieve a SiPM gain stability and accuracy to within 1%, the SiPM control electronics
 19 must provide a precise control of the bias voltage and of the temperature. The SiPM control board
 20 generates the bias voltage (BV) needed to operate the SiPMs in two stages. In the first stage, a
 21 custom boost converter generates the bulk BV of $O(100\text{ V})$ from the voltage on the backplane (about
 22 9.5 V) of the readout box. This bulk BV is then stepped down to the operational voltage for each of
 23 the 48 individual SiPM channels. The value of the stepped-down voltage is tuneable from 0–80 V
 24 with 20 mV precision via a 12-bit DAC. For reference, the breakdown voltages of the SiPMs are
 25 around 65 V. This bias voltage tuning results in an approximate precision of 1% on the SiPM gain
 26 at an operating point of 3 V over the breakdown voltage.

27 The temperature of the SiPMs is controlled via a Peltier cooling element. The current tem-
 28 perature is read out from the sensor on the mounting board via the SiPM control board. An online
 29 software control loop configures the Peltier based on the difference between the measured value
 30 and the desired operating temperature of 5°C . A 12-bit DAC on the control board is used to tune
 31 the Peltier voltage, resulting in a temperature control precision of 0.01°C .

1 All 144 control boards needed for the HE installation have gone through quality control, and
2 the response of each bias voltage channel has been measured. The channels are very uniform, with
3 a response RMS of only 0.3%, and this small variation will be calibrated to achieve uniform SiPM
4 gain across all channels of the detector.

5 **5 Front-end readout card**

6 The HE (HB) front-end readout card contains 12 (16) QIE11 ASICs, one (two) Microsemi Igloo2
7 FPGA, one VTTx module containing two 4.8 Gbps optical links, and one Microsemi ProASIC3L
8 FPGA. The necessary voltages for operating the front-end readout card are supplied by the radiation
9 and magnetic field tolerant CERN FEASTMP DC-DC converters [8].

10 The Fermilab QIE11 ASIC integrates charge in 25 ns intervals and has a 17-bit dynamic range
11 with 8-bit readout. The dynamic range is extended with respect to the previous generation (QIE8),
12 which had a 14-bit dynamic range with 7-bit readout, in order to match the larger SiPM gain
13 compared to HPDs. The QIE11 achieves a $\approx 1\%$ resolution over the full dynamic range by using
14 four integration ranges (scaled by factors of 8) with a 6-bit pseudo-logarithmic ADC, resulting in
15 four subranges for each range. The dynamic range extends to 350 pC with the least significant bit
16 corresponding to 3 fC. The QIE11 also features a programmable current shunt, with values that
17 can range between 1 and 1/11.5, that makes it possible to tune the SiPM gain independently of the
18 photon detection efficiency and increase the dynamic range even further.

19 All QIE11 chips are thoroughly tested after packaging, but before they are mounted on the
20 front-end readout cards. A custom test setup is used, consisting of a test board and a robotic arm
21 with vacuum head that moves the QIE chips. A total of 1120 chips can be loaded into the test
22 setup. The test suite, which covers the full chip functionality, takes about 2.5 minutes per chip to
23 complete. Very good acceptance was obtained, 98% for basic functionality checks, and 86% for
24 the final selection which includes uniformity requirements. As an illustration, figure 6 shows the
25 distribution of the QIE11 pedestal RMS and of the bin width of the third subrange in the first range.
26 Chips that pass all selection requirements are shown in purple, whereas orange signifies chips that
27 failed at least one component of the test suite.

28 The digitized data from all 12 (16) QIE11 chips on the HE (HB) front-end readout board is sent
29 to the Igloo2 FPGA via an 8-bit 80 MHz bus using the LVDS standard. The Igloo2 FPGA is radiation
30 tolerant and is thus ideally suited for use in on-detector electronics receiving 10^{12} neutrons/cm²,
31 10 krad of ionizing dose, and 10^{11} 20 MeV hadrons/cm² over 3000 fb⁻¹. It serializes the data and
32 formats it using 8b/10b encoding. This encoded data is then sent via the VTTx to the μ TCA-based
33 back-end electronics [9]. The ProASIC3L FPGA is not a direct part of the data path. Rather, it is
34 used as an I2C bridge between the CCM module on the one hand and the QIE11 and Igloo2 FPGA
35 on the other hand. Any information regarding the configuration or current state of these chips passes
36 through the ProASIC3L FPGA. It can also communicate with a temperature and humidity sensor
37 on the front-end readout board, as well as the chip containing the board's unique identifier.

38 All HE front-end readout cards have gone through quality control in preparation of the upcoming
39 installation. This includes a visual inspection upon arrival from the assembler and a range of tests
40 such as reading and writing registers on the QIE11 ASICs and the FPGAs, checking the QIE11
41 pedestal values, and using the internal charge injection feature of the QIE11 ASIC to verify that

Figure 6. Two tests of the QIE11 ASIC with the corresponding selection criteria (grey vertical lines). The purple contribution corresponds to chips passing all selection criteria, while the orange indicates chips that failed at least one test. The y axis corresponds to the number of chips on a logarithmic scale. (Left) Measurement of the pedestal RMS in ADC counts. The mean pedestal RMS corresponds to ≈ 1.5 fC. (Right) Measurement of the bin width for the third subrange in the first range. For good chips, the mean bin width is 13.1 fC with a variation of about 1.3%.

1 the data is transmitted off the card in the correct way. A yield of 94% was obtained. Following the
 2 quality control, the response of each QIE11 ASIC on each readout card has been measured with
 3 negligible statistical uncertainty for all shunt values using a custom charge injector board, allowing
 4 the calibration of the initial 1.3% spread in the bin widths.

5 6 System testing

6 During the summer of 2015 the HE preproduction system was tested at the CERN H2 beamline
 7 using muon and pion beams of various energies. This test demonstrated the excellent performance
 8 of the SiPMs compared to the HPDs, especially in terms of signal-to-noise ratio. All features of the
 9 front-end readout cards were found to be fully functional and performing as expected. More details
 10 on this test can be found in ref. [10].

11 The upgraded HE front-end electronics were also subjected to radiation testing at the CHARM
 12 facility at CERN. Two one-week long tests were performed, in October 2015 for the preproduction
 13 system and in September 2016 for the final production system. The system was exposed to a total
 14 ionizing dose and 1 MeV-equivalent neutron fluence exceeding the levels expected to be accumulated
 15 during the lifetime of the HE system. No failures were observed during this time, and the measured
 16 rates of single event effects are manageable and within expectations.

17 7 Summary

18 The CMS experiment at the LHC is upgrading the endcap and barrel sections of its hadron calorime-
 19 ter with silicon photomultipliers. About 16 000 readout channels will be present after the upgrade,
 20 making this the first large installation of SiPMs in a radiation environment. During the winter of
 21 2016–2017, the endcap sections will be upgraded. The barrel sections will follow during the second

long shutdown in 2019. The main motivation of the upgrade is to mitigate the effects of radiation damage to the scintillator tiles. This is done by replacing the existing hybrid photodiodes with new silicon photomultipliers which have a higher photon detection efficiency and much higher gain. To read out the data from the new photosensors, all associated front-end electronics will also be upgraded. The upgraded system will consist of readout modules housing the SiPMs, a calibration unit, and a clock, control and monitoring module. The readout modules also contain the SiPM control electronics and the front-end readout cards, which feature the Fermilab QIE11 ASICs, the Microsemi Igloo2 FPGA, the CERN VTTx with two 4.8 Gbps optical links, and the Microsemi ProASIC3L FPGA. With these new electronics in place, the jet energy resolution will improve by $>50\%$ at $|\eta| \approx 2.8-3$ after 500 fb^{-1} of integrated luminosity is delivered by the LHC.

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