The Compact Muon Solenoid Experiment

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Performance of the prototype readout system for the CMS endcap hadron calorimeter upgrade

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Abstract

The CMS experiment at the CERN Large Hadron Collider (LHC) will upgrade the photon detection and readout systems of its barrel and endcap hadron calorimeters (HCAL) through the second long shutdown of the LHC in 2018. The upgrade includes new silicon photomultipliers (SiPMs), SiPM control electronics, signal digitization via the Fermilab QIE11 ASIC, data formatting and serialization via a Microsemi FPGA, and data transmission via CERN Versatile Link technology. The first prototype system for the endcap HCAL has been assembled and characterized on the bench and in a test beam. The design of this new system and prototype performance is described.

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ABSTRACT: The CMS experiment at the CERN Large Hadron Collider (LHC) will upgrade the photon detection and readout systems of its barrel and endcap hadron calorimeters (HCAL) through the second long shutdown of the LHC in 2018. The upgrade includes new silicon photomultipliers (SiPMs), SiPM control electronics, signal digitization via the Fermilab QIE11 ASIC, data formatting and serialization via a Microsemi FPGA, and data transmission via CERN Versatile Link technology. The first prototype system for the endcap HCAL has been assembled and characterized on the bench and in a test beam. The design of this new system and prototype performance is described.

KEYWORDS: CMS; HCAL; calorimeter; Phase 1 upgrade; SiPM.

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1. Introduction

During Run 1 of the Large Hadron Collider (LHC), the Compact Muon Solenoid (CMS) Hadron Calorimeter (HCAL) [1] played a crucial role in many important results, including the discovery of the Higgs Boson and searches for supersymmetry [2]. However, as the LHC's instantaneous luminosity continues to increase, the HCAL will receive a significant dose of radiation both in the active material and the on-detector, or front-end, electronics. The readout electronics will be upgraded with new technologies to reduce the impact of radiation effects, without replacing the active material, as part of the CMS Phase 1 upgrade program.

The CMS HCAL Phase 1 upgrade [3] is currently underway and will continue for several years in order to upgrade the full chain of readout electronics and photosensors for the HCAL. The upgrades are being deployed in a staged approach, starting with the off-detector, or back-end, electronics and prioritizing the forward regions of the detector. With the installation of the back-end electronics nearing completion and the upgrade of the Hadron Forward detector well underway, the final stage of the upgrade is the Endcap (HE) and barrel (HB) front-end readout. The individual components of the HCAL are shown in Figure 1 (left).

This proceeding discusses the beam test of prototype HE readout electronics performed in August 2015 at the H2 beamline at CERN. Section 2 details the new electronics to be installed on-detector for the HE. Section 3 describes the H2 beam facility and the experimental setup used for this test. The results and early analysis are discussed in Section 4.

2. HE Phase-I Front-end Electronics

Radiation damage to the active material in the HCAL is the primary motivation for the upgrade of the HB and HE front-end readout system. The primary effect of radiation exposure in the HCAL is darkening of the scintillator and the wavelength shifting fibers, resulting in lower light yield. This effect is corrected by careful monitoring of the transmittance of the scintillator and

Figure 1. The four sub-detectors of the CMS HCAL (HB, HE, HO, and HF) are shown for the initial configuration (left) and a possible configuration after the Phase 1 upgrade (right). The individual channels are color coded, indicating which layers are optically summed together.

fibers using a laser monitoring system and beam collision data. This is difficult with the hybrid photodiodes (HPD) that are currently used to read out HB and HE because their low signal-to-noise ratio makes it difficult to cleanly detect signals from heavily degraded scintillator. Additionally, due to the limited channel count in the current HPD-based readout, many layers of active material are optically summed into a single channel on the HPDs. Because radiation damage is dependent on depth in the detector, this reduces the effectiveness of light-yield corrections.

Both issues are solved by replacing the HPDs with Hamamatsu Silicon photomultipliers (SiPM), see Figure 2 (right) [9]. The high gain of the SiPMs (3.5×10^5) and low noise allows for ample dynamic range to measure even low amplitude pulses from heavily radiation-damaged scintillator. The SiPMs are also much smaller than the HPDs they replace. This allows for more readout channels in the same space, and finer depth segmentation of the layers of the calorimeter, as seen in Figure 1 (right). Additionally, SiPMs are radiation and magnetic field tolerant and operate with a modest 70 V bias.

The readout system for HE is organized into readout modules (RM), each containing 48 SiPMs, a single control card, and four front-end readout cards. Each RM also houses the optical decoder unit (ODU), which maps the incoming fibers from the active material to the correct SiPM faces. Four RMs are installed together with a clock and control module (CCM) to make a readout box (RBX). The final component of the RBX is a calibration module (CM) which uses LEDs to provide a calibration light source directly to the SiPMs. Figure 3 (right) shows an overview of the DAQ readout.

Each RBX receives its fast and slow control signals through the CCM module. This module receives the clock and fast reset signals via optical signals from the back-end electronics, and distributes these signals to each card in the RBX. Configuration information for the front-end is received over the optical link as well. Finally, the CCM is responsible for aggregating and returning all status information about the RBX, again transmitted to the back-end via an optical link.

The SiPMs are read out using version eleven of the Charge Integration and Encoder (QIE11) ASIC developed at Fermilab [6, 7]. The QIE11 is a zero dead-time charge integrator designed to operate at 40 MHz. The QIE11 unevenly splits the input current between four integrator circuits, each designed to cover a different dynamic range. The accumulated charge of the integrator with

Figure 2. (Left) The HB and HE prototype wedges are seen on the translation table. The beam counters and wire chambers can be seen in the bottom of the picture. (Right) The inside of the SiPM enclosure showing 48 SiPMs from a single readout module.

Figure 3. The upgraded HE and HB DAQ readout chain including the SiPMs, the front-end readout card, and the back-end readout electronics.

the smallest unsaturated range is then digitized using a 6-bit quasi-logarithmic ADC. The QIE11 also contains a time-to-digital converter which measures the time when the input charge first passes a set threshold within each integration window to half-nanosecond accuracy. The digitized data is transmitted off the QIE11 by an 8-bit 80 MHz bus.

The HCAL front-end electronics are read out at the full 40 MHz data rate to the back-end

electronics. To achieve this, the front-end readout cards use the Microsemi Igloo2 FPGA to format and serialize the raw QIE11 data. The latest revisions of the Igloo2 FPGA have proven to be very radiation tolerant and are ideal for the on-detector electronics at the LHC. Each front-end readout card contains one Igloo2 which collects the data from twelve QIE11 chips. The serialized data is then transmitted to the back-end electronics via a CERN Versatile Twin Transmitter (VTTx) module [4, 5] containing two 4.8 Gbps optical links. The μ TCA-based back-end which receives the data is described in further detail in Reference [3]. The new front-end cards use the FEASTMP radiation and magnetic field tolerant DC-DC converters [8] developed by CERN to regulate the voltage in the RBX, thereby reducing cable losses over the existing system.

The final component of the RM electronics is the control card. The control card drives a peltier cooler, with active feedback, which is used to stabilize the temperature of the SiPM packages because they have a temperature-dependent gain. The control card also supplies the bias voltage and DC current monitoring for 48 SiPMs. The card provides the bias voltage via a boost converter from the low voltage input power, and it is capable of providing separate bias voltage to each SiPM to allow for fine tuning of each SiPM's gain.

3. Testbeam Configuration

The H2 beam facility is located at the North Area of the CERN SPS complex. The beam for the H2 facility is produced by colliding protons from the SPS with a target to produce a secondary particle spectrum containing hadrons, muons, and electrons. By use of various absorbers, magnets, and collimators, the user can produce beams of electrons, muons, and pions in the energy range 30 to 300 GeV. The beam spill structure consisted of a slow asynchronous spill lasting roughly five seconds.

The H2 beam facility contains a prototype wedge of HB and HE, Figure 2 (left). The HE wedge is instrumented for 20° in ϕ . The wedge is read out via four RMs, each responsible for a 5° wedge, split between two RBXs. The entire HCAL prototype wedge sits on a translation table, allowing for full translation in the $\eta - \phi$ plane such that the incoming beam originates from the position corresponding to the nominal interaction point in CMS.

The HB and HE segments are constructed of seventeen alternating layers of brass absorber and plastic scintillator tiles, 70 mm and 9 mm thick respectively. Each layer's active material is divided into rectangular tiles in $\eta - \phi$ which transition to larger tiles in the highest eta region by combining adjacent tiles in ϕ . The scintillator tiles are read out using wavelength-shifting fibers bonded to clear fibers. The clear fibers bring the light from the active tiles to the RBXs mounted on the back corner of the HE wedge. The scintillator tiles and readout fibers were not modified for this test.

One HE RBX, covering 10° in ϕ , was instrumented with new SiPM-based readout electronics, while the second was read out using the original HPD readout chain to provide a baseline. During the test two different ODUs were used. The first was designed with a possible channel mapping intended for installation on the CMS detector, as shown in Figure 1 (right). Data was also taken with a second ODU that allowed the independent readout of each layer of a limited region of the HE wedge. The HE CCM prototype was not available for use in these tests, so the clock and slow controls to the front-end were provided by an emulator card that interfaced with a CCM module

designed for the HF detector. To read out the new front-end electronics, a new μ TCA back-end crate was installed and integrated with the DAQ.

The beam trigger signal was provided by four trigger tiles placed in the path of the beam. The primary tiles of $14 \times 14 \text{ cm}^2$ provided a loose beam trigger. The trigger window could be tightened by the inclusion of smaller $4 \times 4 \text{ cm}^2$ and $2 \times 2 \text{ cm}^2$ trigger tiles. This is particularly useful for the muon beam configuration, which produces a wider beam than the pion configuration. The beam position and profile were monitored with a series of wire chambers to ensure high beam quality. Although the trigger rate ranged from a few thousand to a few hundred thousand triggers per spill, the speed of the readout was limited to a few thousand events per spill. More details of the beam infrastructure can be found in Reference [10].

4. Testbeam Results

Data were collected from both muon and pion beams. The table position and relative energy calibration of the calorimeter were measured with a 150 GeV muon beam. The detector response to hadrons was then tested using pion beams with the full range of available energies.

For each event, the DAQ recorded ten time samples (TS) from each QIE11, with the beam trigger timed to fall in the fifth TS. The total charge collected for each channel per event, q , was reconstructed using a simple pedestal-subtracted sum of the time samples around the trigger, as in equation 4.1. The decay time of the scintillator and wavelength-shifting fiber combination gives a roughly 50 ns (2 TS) long pulse. However, the asynchronous beam spill led to an uncertainty in the pulse arrival time of one TS; therefore, the pulse was reconstructed using the sum of three TS centered on the triggering sample. For each event, the pedestal was estimated by the average of the first three time samples.

$$q = TS_4 + TS_5 + TS_6 - (TS_0 + TS_1 + TS_2) \quad (4.1)$$

By looking at the muon data, it is immediately clear that the SiPMs are superior to the HPDs they replace. Figure 4 shows the reconstructed charge spectrum from an HPD and a SiPM with a 150 GeV muon beam centered in a single channel with the widest trigger. The wide trigger enhanced the pedestal distribution in each spectrum. The particular SiPM channel summed the signal from four layers, while the HPD channel summed the signal from twelve layers. The muon signal, or minimum ionizing particle (MIP) peak, is clearly visible in both spectra; however, in the SiPM spectrum, the separation between the MIP peak and the pedestal peak is much more pronounced, and the individual photoelectron peaks are clearly visible. After accounting for the difference in number of layers, the SiPMs show nearly a 1000 times greater separation between the pedestal and MIP peak, giving plenty of room to detect signals from a radiation-degraded detector.

The linearity of the SiPM response as a function of beam energy is shown in Figure 5 (right). The hadronic energy resolution was calculated using the full range of pion energies. Individual towers were constructed by summing all layers for each position in the $\eta - \phi$ plane. To ensure complete shower containment, the pion beam was centered on the middle of a tower read out with SiPMs, which was surrounded on all sides by other towers. This allowed all charge to be summed in a 3×3 cluster centered around the target tower in the $\eta - \phi$ plane. This choice meant that one-

Figure 4. The pedestal-subtracted charge spectrum for an HPD (left) and a SiPM (right). The series of narrow peaks visible in the SiPM spectrum between the pedestal and MIP peak are the individual photoelectron peaks.

third of the towers in the cluster were read out with HPDs, but ensured complete containment of the shower.

To account for inter-channel differences in light yield, the MIP distributions for each channel were fit and the position of the MIP peak and the single photoelectron (SPE) peaks were extracted after pedestal subtraction, as shown in Figure 6. The SPE distribution shows the excellent performance and gain uniformity of the Hamamatsu SiPMs, which were all biased to 70.0 V. The MIP distribution contains the convolution of the SiPM gain differences with the optical efficiency variation between channels. A relative calibration factor was applied to each channel to adjust the mean value per layer of the MIP peak to match the average for all channels. The energy resolution after application of the relative calibration, shown in Figure 5 (left), is in good agreement with measurements made on the same calorimeter in 2008 [11]. A fit to the energy resolution of the form $\sigma/E = A \oplus B/\sqrt{E}$ yields $A = 0.021 \pm 0.012$ and $B = 1.23 \pm 0.03\sqrt{\text{GeV}}$ after application of the MIP calibrations.

To complete the functionality test of the new electronics, the TDC values were also read out and analyzed. For each channel, the TDC value was chosen from the first TS with a valid TDC inside the three samples used to reconstruct the charge. A valid TDC value is defined when the TDC discriminator transitions from below to above threshold during the TS. Due to the asynchronous beam, the absolute timing distribution is a flat distribution spread over 25 ns. To give a sense of the resolution of the TDC, the time difference between the second and third depths in the target tower was taken. These distributions for 30 and 300 GeV pions are shown in Figure 7.

The final set of data collected included the special ODU to read out each layer of a small region of the detector independently. The MIP-based relative calibration was recomputed for this configuration and the charge per channel was reconstructed as in Equation 4.1. For a 300 GeV pion, the two-dimensional average depth profile is shown in Figure 8 (left). On the right, the one-dimensional average profile is shown as a ratio of the energy deposited to each layer over the energy

Figure 5. (Left) The distribution of beam energy versus reconstructed charge with the pion beam targeted at a single tower. (Right) The energy resolution as a function of beam energy before and after applying the relative MIP calibration.

Figure 6. (Left) The distribution of single photoelectron peak locations for all channels. (Right) The distribution of mean MIP charge per layer for all channels.

deposited in the whole 3×3 cluster. Additionally, bands containing 68, 95, and 99% of all events in each layer are shown. Accounting for shower fluctuations, a 300 GeV pion can deposit up to 40% of its energy into a single layer.

5. Conclusion

The beam tests performed with the prototype HE Phase 1 readout electronics confirmed that the prototype system functioned well and that the chosen SiPMs meet or exceed the design requirements in a realistic environment. Additionally, all features of the front-end readout card were found to be functional and performed as expected. This successful test is an important milestone for com-

Figure 7. The TDC time difference between depths two and three for 30 and 300 GeV pion showers.

Figure 8. The one-dimensional (right) and two-dimensional (left) average shower profile of a 300 GeV pion beam with each layer of the detector read out separately. The colored bands indicate the bounds in which 68, 95, and 99% of the events for each depth can be found.

170 pleting the installation of the HE and HB upgrade hardware by the end of long shutdown 2 of the
 171 LHC in 2019. Although only HE components were tested, the HB upgrade will use functionally
 172 identical components with only a different form factor.

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