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CMS CR -2022/049

The Compact Muon Solenoid Experiment

Conference Report

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25 March 2022 (v3, 16 May 2022)

Phase 1 Upgrade of the CMS Hadron Calorimeter

Candan Isik for the CMS Collaboration

Abstract

The Phase 1 upgrade of the CMS Hadron Calorimeter detector (HCAL) involved installing silicon photomultipliers (SiPM) to measure the scintillator light output with better signal/noise and upgrading the read-out electronics, allowing for increased longitudinal segmentation and better performance. This talk will summarize the design, testing, installation, and commissioning of the HCAL Phase 1 upgrade. Performance results for the HCAL endcap and forward detectors using Run 2 data will be presented, together with prospects for Run 3.

Presented at *VCI2022 16th Vienna Conference on Instrumentation*

Phase 1 Upgrade of the CMS Hadron Barrel Calorimeter

Candan Isik on behalf of the CMS Collaboration

Abstract

The Phase 1 upgrade of the CMS Hadron Calorimeter (HCAL) involved the installation of new silicon photomultiplier devices (SiPMs), which replaced older hybrid photodiodes (HPDs). SiPMs measure the scintillator light output with better signal/noise. The upgraded readout electronics also allow for increased longitudinal segmentation and better performance. This report describes the design, testing, installation, and commissioning of the HCAL Barrel Phase 1 upgrade. Performance results for the HCAL Endcap during Run 2 are presented and expectations for the HCAL Barrel during Run 3 are discussed.

Keywords: CMS, HCAL, HB, HE, HPDs, SiPMs

1. Introduction

At the CERN laboratory near Geneva, Switzerland, there are four points around the Large Hadron Collider (LHC) accelerator ring to collide proton beams, corresponding to the positions of four major particle detectors. The Compact Muon Solenoid (CMS) is one of these four detectors [1]. The CMS has the typical onion-like structure of modern high-energy physics experiments at particle colliders, consisting of multiple layers of subdetectors to measure the energy and momentum of particles. The CMS Hadron Calorimeter (HCAL), which is installed between the electromagnetic calorimeter and the solenoid of CMS, completes the calorimeter system. The HCAL is a sampling calorimeter that provides energy measurements of charged and neutral hadrons like protons, neutrons, pions, and kaons. It is divided into four subdetectors: the HCAL barrel (HB), endcap (HE), forward (HF), and outer barrel (HO) (Figure 1). The HB and HE detectors, which are constructed of alternating layers of brass absorber and plastic scintillator, provide coverage in the pseudorapidity (η) range $|\eta| < 1.4$ and $1.3 < |\eta| < 3.0$, respectively [2]. All four HCAL subdetectors have the same type of back-end electronics.

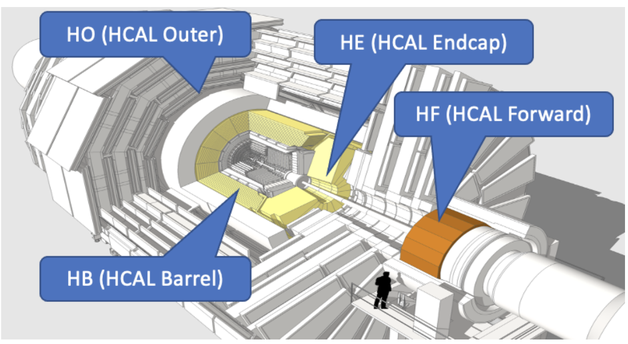

Figure 1: Illustration of four subdetectors of the CMS HCAL.

2. Upgrade Motivation

The main motivation for the Phase 1 upgrade of the CMS HB calorimeter was to improve its performance during LHC Run 3 and throughout the HL-LHC era. Before the upgrade, the HB detector used Hybrid Photodiode transducers (HPDs). In 2019, the HPDs were replaced with silicon photomultiplier devices (SiPMs), which allow significantly higher gain and better photon detection efficiency. The higher gain provides strong electrical signals that reduce the effect of electrical noise and allow for signal splitting for TDC (time-to-digital converter) measurements. Their increased effective quantum efficiency and ability to detect single photoelectrons improves the ability to calibrate and monitor the calorimeters [3]. The HPDs in HE were replaced by SiPMs during the 2016–17 extended year-end technical stop. Figure 2 shows the effect of replacing HPDs with SiPMs, which provide many advantages including a significant improvement in energy resolution.

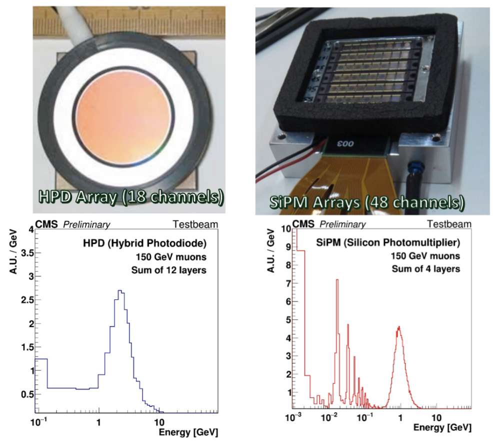

Figure 2: Top left: Picture of an HPD. Top right: Picture of a SiPM. Bottom: Energy spectrum for 12 (4) scintillator layers read out by a HPD (SiPM). Data are from a 150 GeV muon test beam impacting HE modules [4].

SiPMs are able to withstand the expected CMS radiation dose, which is 14 Gray for both neutrons and ionizing particles. The target tolerance dose of SiPMs is 100 Gray for both neutrons and ionizing particles. Figure 3 represents the signal loss in the high-η region of the HE detector as a function of integrated luminosity in 2017. The lines show the response loss of all 72 tiles at the same η and layer position but at different locations in ϕ. While thin lines represent individual tiles read out by HPDs, the two bold lines correspond to the tiles read out by SiPM photodetectors. It is seen that the signal loss for the two scintillator tiles read out by SiPMs is much smaller than scintillator tiles read out by HPDs.

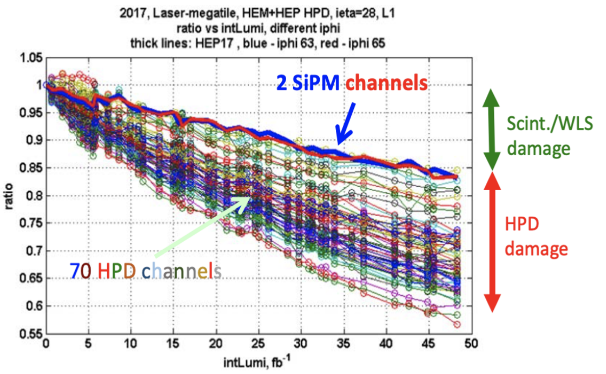

Figure 3: Signal loss in the high-η region of the HE detector as a function of integrated luminosity in 2017. A significant portion of signal loss resulted from aging HPDs, which have since been replaced by SIPMs.

The other advantage of SiPMs is their readout allows an increased number of channels, which can be exploited to increase the depth segmentation in HB (Figure 4). This mitigates the effect of radiation damage to HB scintillator tiles, provides better calibration of depth-dependent effects, and brings some physics benefits like long-lived particle detection. Moreover, the new depth segmentation maintains good physics performance for jets and missing transverse energy.

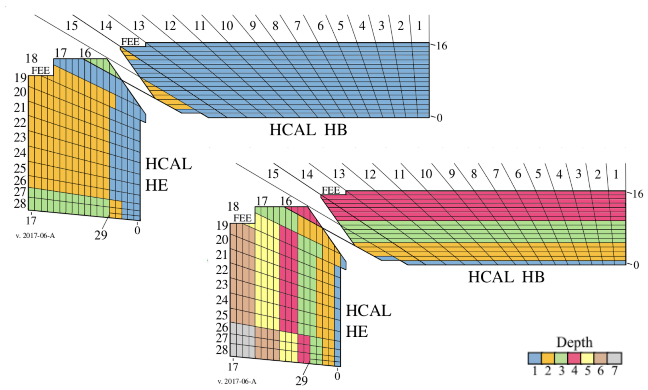

Figure 4: Depth segmentation of the HB and HE detectors.The segmentation of the Phase 0 detector (top) is compared to the Phase 1 detector (bottom).

3. Front-end (FE) Electronics for the HB Upgrade

The front-end (FE) electronics are installed on the detector within the Readout Box (RBX) at the edge of the HCAL absorber. The major components of the RBX are Readout Modules (RMs), Clock Control Modules (ngCCMs) and a Calibration Unit (CU). Each RM mainly consists of an Optical Decoder Unit (ODU), one SiPM Mounting Board (SiPM MB) hosting eight SiPM arrays, one SiPM control board, and four QIE boards (Figure 5).

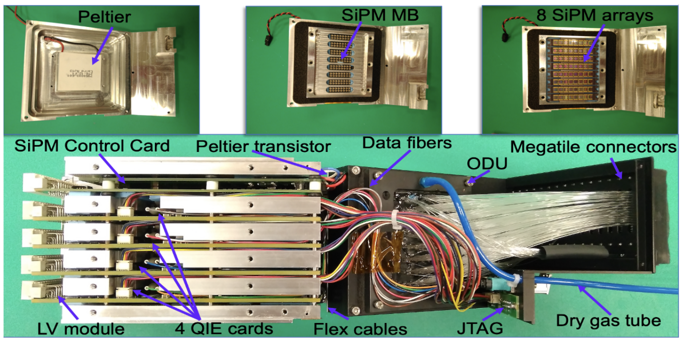

Figure 5: Inside an HB Readout Module.

Figure 6 describes the data flow in HB/HE. The scintillator tiles connect to the RM by a set of multi-fiber optical cables that connect to the ODU. Each optical cable carries the signals from all η values of a given scintillator layer. The ODU remaps these signals to distribute the light from various layers to the appropriate phototransducer. At this point, SiPMs receive light from the calorimeter segments and convert it into electrical pulses. The electrical pulses are received on the QIE boards, where integration and timing measurements are performed by QIE chips and the digital results are transferred to two FPGAs. These FPGAs are responsible for data formatting and for interfacing between the ngCCM modules and the QIE chips. The data are next sent off-detector by a GBT chip and Versatile Link transmitter (VTTx) residing on the QIE board. Finally, the data are transferred to the back-end electronics by a μHTR module, and from there to the CMS data acquisition (DAQ) by an AMC13 module [3].

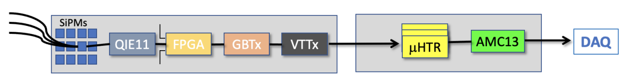

Figure 6: The data flow in HB/HE through the front-end and the back-end electronics to the CMS DAQ.

4. Installation of the HB Electronics

During the installation of the HB Phase 1 FE electronics, a total of 36 RBXes, 144 RMs, 72 ngCCMs, 36 CUs, and nearly

2500 megatile cables were installed. Installation and commissioning were carried out in the following steps:

- Uninstall Phase 0 components from RBX.
- Install front-end electronics.
- Test control link and communication with ngCCM, RMs, and CU.
- Test RM data links to μHTRs.
- Take FiberID, LED, and Laser data.
- Connect megatile cables.
- Perform radiation sourcing scan with ^{60}Co.
- Calibrate using ^{60}Co data.

5. Calibration with ^{60}Co Sourcing

After completing the installation of the HB front-end electronics with SiPMs, improvements in the detector response are readily observed by inserting a ^{60}Co source into tubes embedded in HB megatiles. Each megatile consists of an array of individual scintillator tiles in the same ϕ wedge. To deliver the signal to individual HCAL tiles, a device called “sea monster” is used. Figure 7 shows the sea monster device and where it is located on the detector. The sea monster consists of a motor and a wire to which the ^{60}Co source is soldered. The wire travels inside HCAL along plastic tubes, delivering the source to different scintillators tiles in turn. The tubes inside one HB megatile are shown in Figure 8. ^{60}Co data-taking provides a validation of the tile-by-tile channel mapping and effectively tests the complete data readout chain. An example of proper megatile cabling and readout is given in Figure 9. Much stronger signals are obtained with the Phase 1 SiPM devices than with the Phase 0 HPDs. Figure 10 shows the detector’s response, and the single photoelectron peaks are clearly visible.

Figure 7: The picture of sea monster (left) and where it is located on the detector (right).

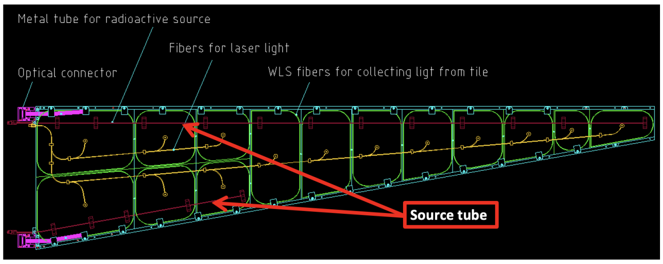

Figure 8: Illustration of the tubes for moving the ^{60}Co source inside one HB sector.

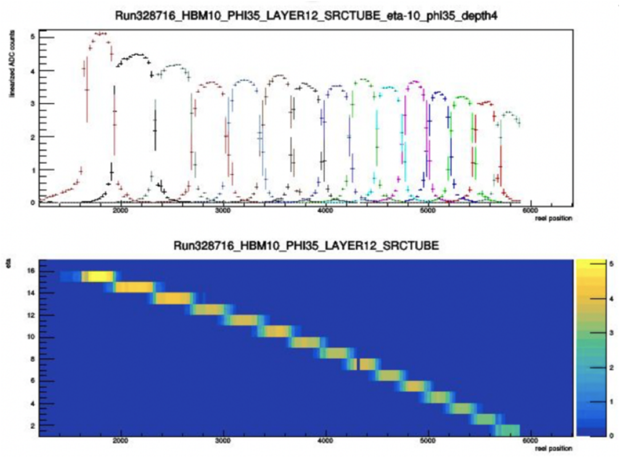

Figure 9: Confirmation of correct megatile cable and readout. The colored fingers represent the signal from individual scintillator tiles from a ^{60}Co source, and the steps demonstrate proper channel mapping.

6. HB Low Intensity LED Run

In addition to ^{60}Co sourcing data, calibration using LEDs has been carried out for the new HB electronics. In Figure 11 top left, a Generalized Poisson (GP) fitting procedure is performed for each channel for each run. It is assumed that SiPM spectra obey a GP distribution of fired pixels convolved with Gaussian noise. The SiPM gain has been measured from the distance between photoelectron peaks by applying low-intensity LED light to each SiPM. As SiPM gain and SiPM bias voltage are linearly related (Figure 11, top right), the SiPM bias voltage for individual channels is tuned to make the gain 40 fC per photoelectron for all channels (Figure 11, bottom).

7. Response of HB to Cosmic Ray Data

HCAL participated in global CMS runs to collect cosmic ray data in 2019. The cosmic ray data, which contains muons and cosmic ray showers collected using ~4 million Drift Tube (DT) triggers, has been analyzed to evaluate the new HB front-end electronics. Figure 12 shows the signal in four HB depths with a threshold of 6 photoelectrons. The expected correlation of signals for depth 4 versus depth 3 in HB is shown in Figure 13, where the x-axis (y-axis) represents the η index of the signal

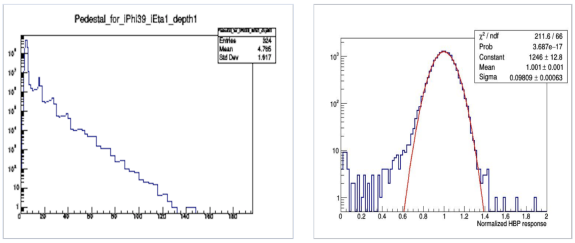

Figure 10: Photoelectron peaks in linearized ADC counts (left) and detector response (right) from the signal from a ^{60}Co wire-source inserted into tubes embedded in HB megatiles.

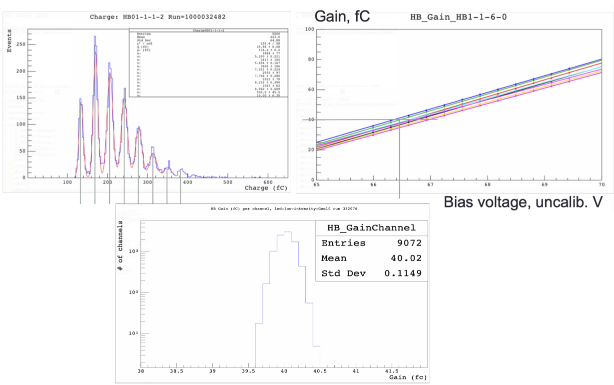

Figure 11: The SiPM gain from the distance between photoelectron peaks (top left), SiPM gain and SiPM bias voltage linearly, eight different colors represent eight SiPM arrays (top right), the SiPM bias voltage for individual channels (bottom).

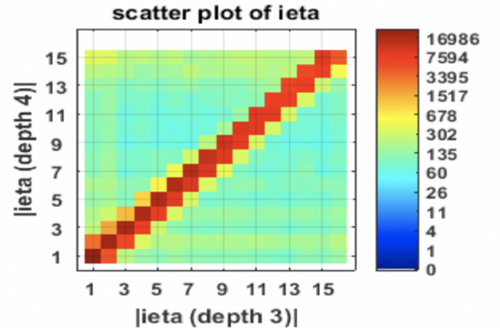

Figure 13: The correlation of signals between Depth 3 and Depth 4 for HB. The diagonal line indicates that cosmic ray muons pass through both scintillator depths, as expected.

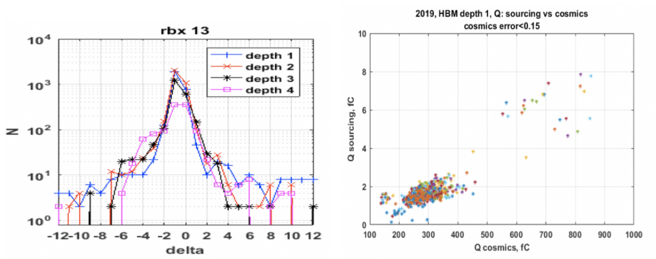

Figure 14: The difference of muon track η and HCAL signals (left). Correlation of charge measurements for different scintillator tiles in HB-minus depth 1, where signals from the ^{60}Co source are plotted vs. signals from cosmic ray data (right).

in depth 3 (depth 4) for signals above 3 photoelectrons. Figure 14 (left) shows the difference of muon track η and signals in HB greater than 2 photoelectrons. Figure 14 (right) shows the correlation of signals for HB-minus depth 1. Here, the x-axis represents signals from cosmic ray data and the y-axis represents signals from the ^{60}Co source. During this cosmic ray data-taking period, the electronics worked very well and the expected performance was achieved for all four HB depths.

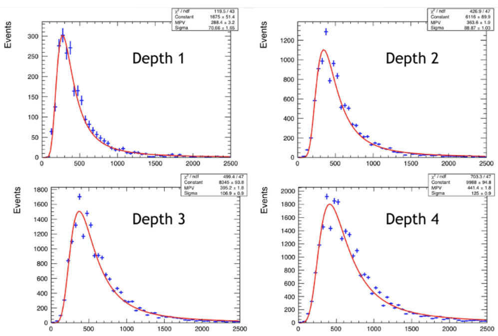

Figure 12: The signal in four HB depths with a threshold of 6 photoelectrons.

8. Conclusion

The full installation and commissioning of the CMS Phase 1 HCAL Barrel upgrade was completed in 2019, ahead of schedule. All issues and challenges have been solved or addressed. The HE already operated with new SiPM devices during Run 2, which resulted in a significant improvement in detector performance. With the successful of Phase 1 upgrade of the HB electronics, the same strong performance is expected for the HB during Run 3.

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