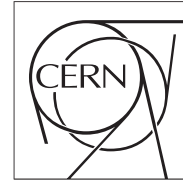




The Compact Muon Solenoid Experiment
Conference Report

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First results from the CMS SiPM-based hadronic endcap calorimeter

Federico De Guio for the CMS Collaboration

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We compare SiPM performance to that of the previous hybrid photodiode / QIE8-based readout and describe how the factor three improvement in photon-detection efficiency, increased longitudinal segmentation, and improved response stability allow for mitigation of scintillator radiation damage and simplified calibration. We report in situ measurements of radiation-induced SiPM dark current. Overall, we show that the upgraded SiPM-based system brings more than 50% improvement in radiation-induced response degradation.

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First results from the CMS SiPM-based hadronic endcap calorimeter

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1. Introduction

The general-purpose CMS (Compact Muon Solenoid) detector [1] was designed to study proton-proton collisions at the centre-of-mass energy of 13 TeV and luminosities that exceed $10^{34}\text{cm}^{-2}\text{s}^{-1}$ and successfully operates at the LHC at CERN. The high magnetic field provided by the superconducting solenoid allows high-precision vertex and track reconstruction by the silicon pixel and strip trackers. The CMS calorimeter system includes a lead-tungstate scintillating-crystals electromagnetic calorimeter, a brass-scintillator sampling hadron calorimeter and steel-quartz-fiber forward sampling calorimeters. The hadron calorimeter (HCAL) plays a crucial role in the measurements of jet and missing transverse energy. It consists of the barrel (HB) at $|\eta| \leq 1.3$, endcaps (HE) at $1.3 < |\eta| \leq 3.0$, outer calorimeter (HO) or tail catcher, which roughly maps the towers of the barrel part and is placed outside the solenoid, and forward calorimeters (HF), which cover the pseudorapidity range at $3.0 < |\eta| \leq 5.2$. The segmentation of HE consists in tiles with a size of $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$ (0.17×0.17) for $|\eta| < 1.6$ ($|\eta| \geq 1.6$) while on the longitudinal axis the tiles are organized in 19 layers.

During the 2016-17 extended year-end technical stop, four of the Hybrid Photo Diodes (HPDs) in the HE (sector HEP17, covering a $\Delta\varphi = 20^\circ$ wedge and the entire HE pseudorapidity range in the positive z hemisphere) were replaced with Silicon Photomultipliers (SiPMs) as part of a first stage of the HE Phase-1 front-end upgrade. The new photodetector brings many advantages and among those a $\times 2.5$ higher photo detection efficiency (PDE) and a $\times 400$ higher response that allow for mitigation of scintillator radiation damage and to read out the channels with an increased longitudinal granularity (up to 7 depths, Fig. 1).

The pictures of a HPD and a SiPM sensor are shown in Fig. 2 together with the charge spectrum as measured with the two photosensors at the test beam with 150 GeV muons. Single photoelectron peaks are visible for the SiPM case showing the excellent sensitivity of the upgraded readout to a low amount of light.

Following the experience with HEP17, during the 2017-18 year-end technical stop the rest of the HE channels, has been equipped with SiPMs.

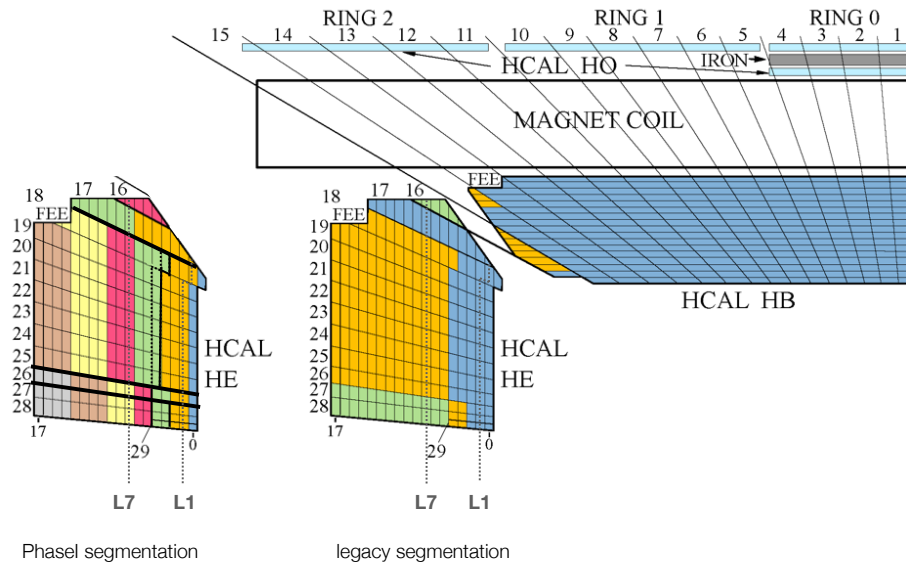


Figure 1. Longitudinal section of the HB, HE and HO detectors. The segmentation of the upgraded HE (left) is compared with the one for the legacy detector (right).

2. Understanding the detector response deterioration due to radiation

The HCAL uses a laser calibration system to monitor the response of the detector and, in particular, the radiation damage of the scintillators. In the HE ultraviolet light is injected into the scintillator tiles of two specific sampling layers, layer 1 (L1) and layer 7 (L7).

Previous in-situ assessments of the radiation damage of HCAL scintillators were performed using HPDs as photosensors, which are known to suffer from operation-induced deterioration [2]. As a consequence, the observed decrease of the HE response over time was not caused exclusively by radiation damage in the scintillator, and in wavelength-shifting or clear fibers. It was also known that the HPD deterioration varied significantly from HPD to HPD, some being more prone to damage than others, causing a marked ϕ -asymmetry in the overall signal loss that followed exactly the non-trivial granularity of the HPD readout.

The upgraded wedge has allowed to make a direct measurement of radiation damage of HE scintillators read out by SiPMs and compare with the performance from the HPD-based readout. The analysis of the 48.3 fb^{-1} delivered to CMS in 2017 confirms that a large fraction of signal loss in HE, up to 60%, is caused by HPD deterioration instead of being exclusively due to radiation damage of the scintillator. Figure 3 shows the signal loss in the front part and high η region of the HE detector as a function of integrated luminosity in 2017. The lines in represent the response loss of all 72 tiles at different ϕ sections, and at the same η and layer position. Thin lines correspond to individual tiles read out by HPDs, and the two bold lines correspond to the tiles read out by SiPM photodetectors. The figure illustrates that the signal loss for two scintillator tiles read out by SiPMs is smaller compared to scintillator tiles read out by HPDs.

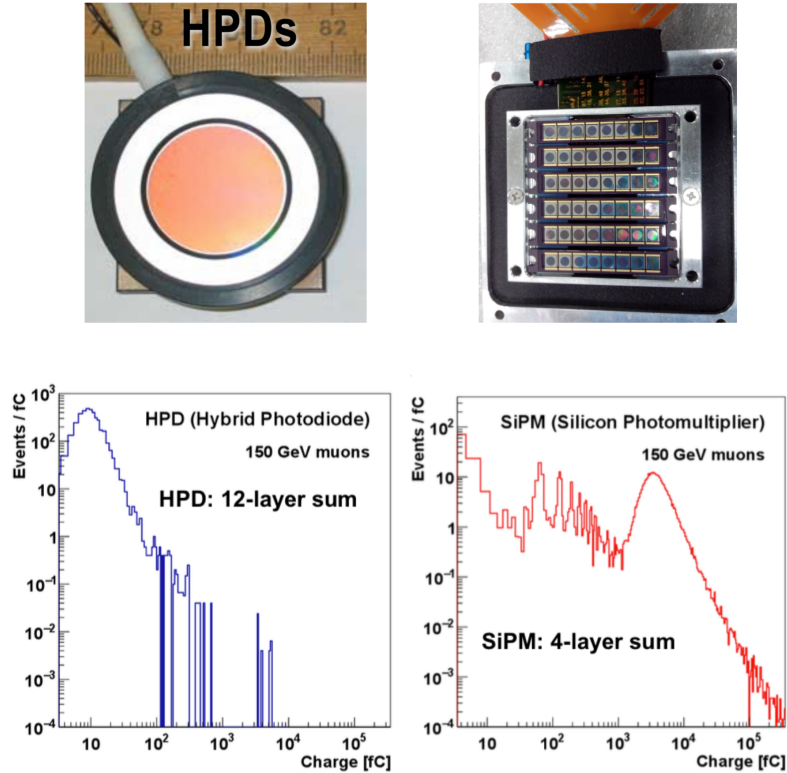


Figure 2. Top left: picture of an HPD. Top right picture of a SiPM. Bottom: energy spectrum for 12 (4) layers read out by a HPD (SiPM). Data includes a combination of pedestal and 150 GeV muon data.

After all the HE channels have been with SiPMs, a much improved uniformity of the raw response along phi has been achieved. This effect is already visible in the data collected while inserting a ^{60}Co wire-source into tubes embedded in HE megatiles during the installation phases of the new sensors (Fig. 4).

Following the removal of HPDs from HEP17, a post-mortem scan with laser light was performed on the photocathode of a highly damaged HPD. The results of the scan are shown in Fig. 5 and compared to a scan performed on a new HPD at the time of detector construction. The response is reduced in a highly not uniform way and, in addition, localized damage spots have appeared at the locations of incoming light from single fibres from the scintillators. This is what should be expected if the damage was caused by ion feedback.

3. SiPMs operational experience, calibration and performance

The experience of operating SiPMs in a high-rate collider detector in 2017 was extremely successful and all channels from HEP17 were functional during the data taking.

Two parameters of each SiPM channel have been monitored regularly during the year. On one side the gain was checked to assess the stability of the response making sure that it is not subject to unexpected drifts. The measurement of the distance between single photo-electron peaks in pedestal runs confirmed the gain stability at the 1% level for all channels. On the other side the amount of dark current, which is expected to increase as a function of the integrated luminosity with a slope which is proportional to the SiPM area (Fig. 6), was also monitored. At the end of 2017 the level of noise for SiPMs was measured to be ~ 35 MeV, very low if compared to the typical HPD noise which is instead ~ 300 MeV in the HCAL endcaps (Fig. 7). By the end of

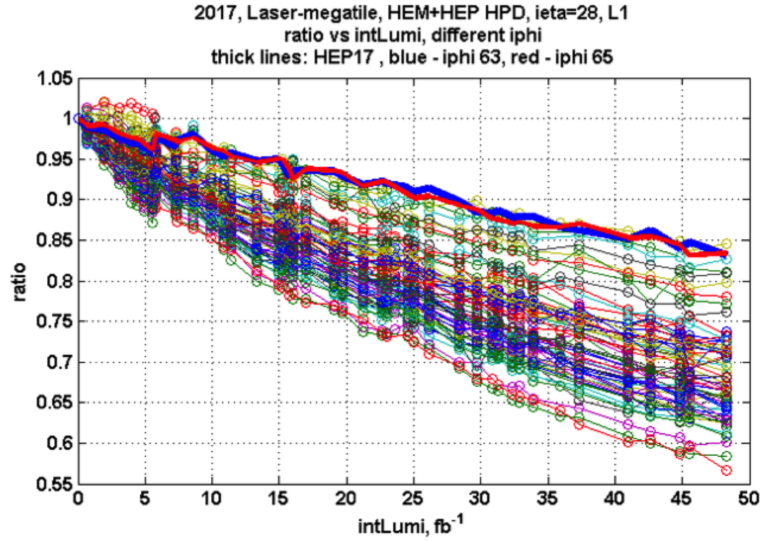


Figure 3. Signal loss in the HE detector (L1, $i\eta = 28$) as a function of integrated luminosity in 2017. The lines represent the response loss of all 72 tiles at different φ sections, and at the same η and layer position. The thin lines correspond to individual tiles read out by HPDs, while the two bold lines correspond to the tiles read out by SiPMs.

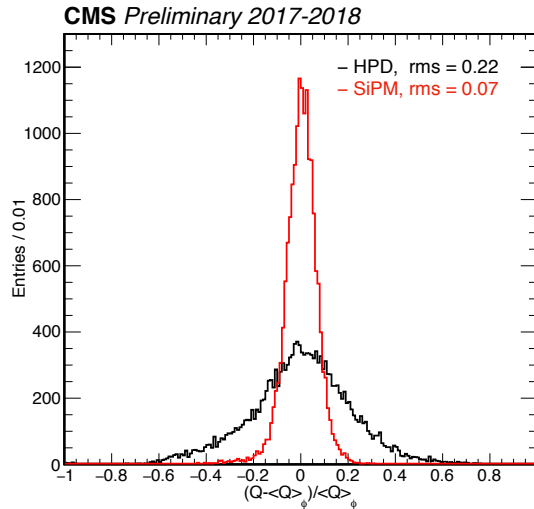


Figure 4. The signal from ^{60}Co wire-source inserted into tubes embedded in HE megatiles is used to compare the relative response of channels at the same η and depth. After the channels readout based on HPDs (black) was replaced with SiPMs (red), a much improved uniformity of the raw response is achieved.

the LHC Run3 (500 fb^{-1}) when the endcaps of the CMS will be dismantled, the noise in HE due to the increase dark current is expected to be slightly above 100 MeV.

An additional advantage deriving from the upgrade is the total absence of uncharacteristic noise for the channels read out with SiPMs. Since the beginning of the operations in 2009, the HPD channels manifested several different types of intermittent signals [3] classified in three main categories: ion feedback that could generate appreciable signals even when no light is incident

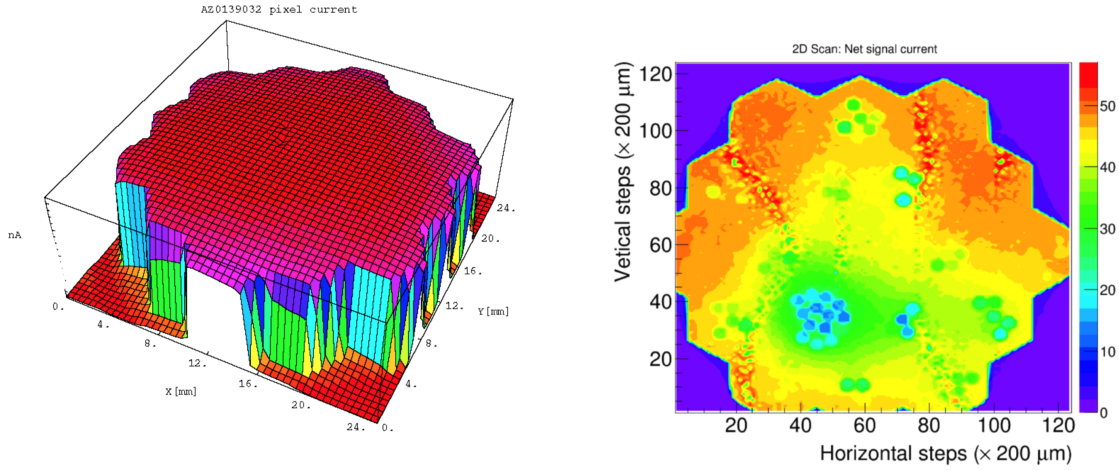


Figure 5. Scan of HPD photocathodes using laser light. The z-axis is proportional to the response of the device. Left: a new HPD scanned before installation on the HCAL detector; the response is uniform across the entire device. Right: a highly damaged HPD extracted from the HE wedge (HEP17) upgraded to SiPM readout in EYETS 2016-17.

on their photo-cathodes; HPD noise affecting all the channels in the same sensors and generated by the misalignments between the electric field within an HPD and the external solenoid field that can lower the flashover voltage of the HPD; Read Out Box (RBX) discharges that affect all the channels in the same RBX. None of these anomalous signals has been observed in channels read out with SiPMs.

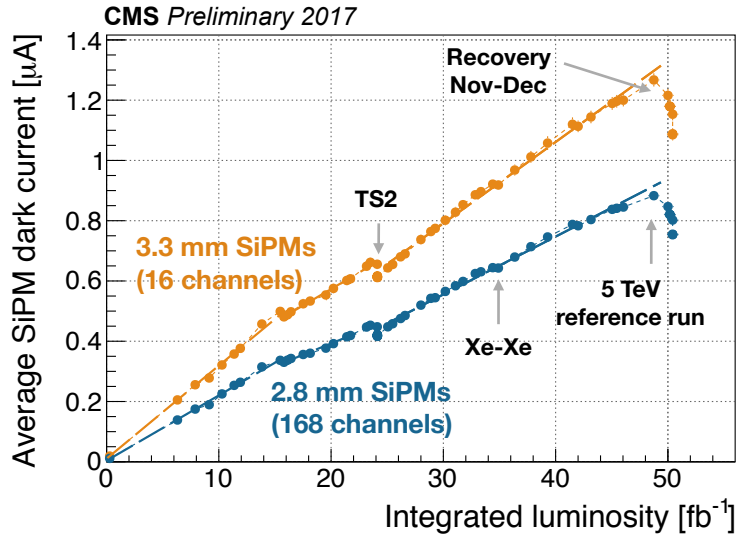


Figure 6. Dark current increases with integrated luminosity with a slope which is proportional to the SiPM area. Deviation from the linear behaviour is due to the recovery time in absence of beam and variation in instantaneous luminosity. The evolution of the dark current in 2017 is shown.

Given the increased longitudinal granularity of the upgraded detector, being able to equalize the response of each longitudinal segment becomes an important aspect. In order to do so

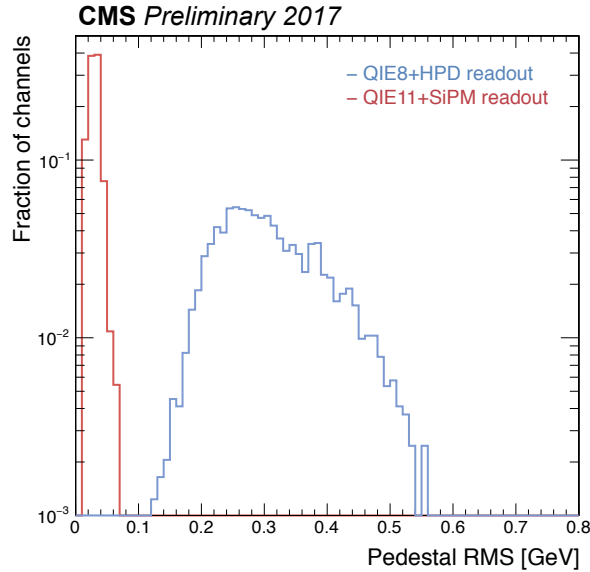


Figure 7. The RMS of the pedestal integrated in a 50 ns window is compared for channels with QIE11+SiPM readout (red) and channels with QIE8+HPD readout (azure). A pedestal run collected at the end of 2017 is used.

the energy deposited in the HE by muons that traverse the scintillator tiles can be used to inter-calibrate the response of different depths. Muon tracks are reconstructed in the inner and outer tracking system of CMS and extrapolated to the front and back layers of the HCAL using momentum and B-field information. Tracks that go through HE while remaining into the same tower are selected and the energy spectra are fitted using a gaussian and landau convolution function with the mean of the gaussian to be zero. The landau location parameter is used as the most probable value for the muon energy deposit in the HCAL depths and it is found to have a negligible dependence on the muon momentum in the range of the selected muon sample. In Fig. 8 the reconstructed muon signal from collision events in a HE tower readout via SiPM is compared with the signal from a tower readout via HPD (left). A clear improvement in the resolution of the reconstructed muon peak is visible thanks to the upgraded readout. To be kept in mind that, due to the increased longitudinal segmentation of the upgraded detector, the same portion of scintillator material read out by a single HPD channel, is readout via 4 SiPMs. The measured amount of energy per layer as a function of the depth number is also shown (right) and corresponds roughly to ~ 5 pe/MIP/layer as measured at the test beam. To be mentioned that the HE detector has a constant sampling fraction for depth 2 to depth 6, while the amount of passive material in front of depth 1 is larger.

4. Conclusions

As part of the Phase-1 upgrade program the readout of one wedge of the HCAL endcap has been replaced in 2017. SiPMs are used in place of HPDs and the experience from operating the upgraded sector is reported. Following the installation of the HEP17 pilot system in 2017, at the beginning of 2018 the full HE detector has been equipped with SiPMs. No problems have been experienced so far and the readout upgrade allows to recover up to 50% of the response making possible the mitigation of scintillator radiation damage and the improvement of the detector resolution.

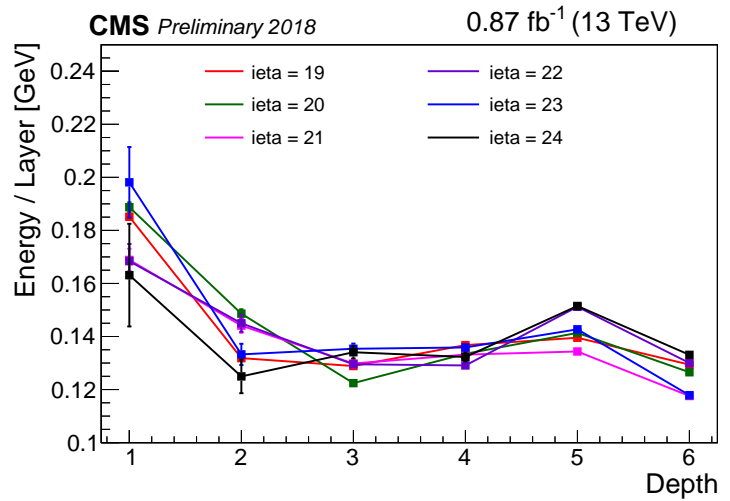
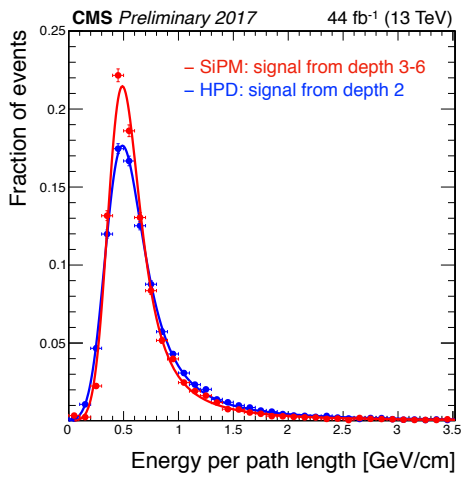


Figure 8. Left: the reconstructed muon signal from collision events in a HE tower readout via SiPM ($\eta=24$, $\phi=63$) is compared with the signal from a tower readout via HPD ($\eta=24$, $\phi=63$). The signal is divided by the muon track length in the active material. Right: Muon deposits in HE towers for different eta regions and depths. Muons from collision events are considered when their track traverses the HCAL while remaining within the same tower. The muon signal peak is fitted with the convolution of a Gaussian and a Landau. The Landau location parameter is divided by the number of scintillator layers in the considered depth.

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