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CMS CR -2009/057

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

14 April 2009 (v3, 28 April 2009)

Upgrade plans for hadron calorimeter in the CMS detector

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on behalf of CMS Collaboration

Abstract

The Large Hadron Collider (LHC) is expected to undergo upgrades in two phases in next decade. Luminosity at the completion of the second phase is expected to increase by an order of magnitude to $10^{35}/\mathrm{cm}^2$-sec. The upgrade of the CMS Hadron Calorimeter (HCAL) is being planned to sustain an increased dose of radiation and challenges arising from occupancy rate due to higher luminosity. Replacement of existing photo readout device by silicon photo multipliers is being planned for the HCAL. Detailed studies performed on this device are presented. Plans on the upgrade of the front-end electronics, DAQ, trigger, and the active elements in some part of the detector will be discussed in detail.

Presented at *Technology and Instrumentation in Particle Physics,11/03/2009,Tsukuba,Japan,20/04/2009*

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The Large Hadron Collider (LHC) is expected to undergo upgrades in two phases in next decade. Luminosity at the completion of the second phase is expected to increase by an order of magnitude to $10^{35}/\text{cm}^2$-sec. The upgrade of the CMS Hadron Calorimeter (HCAL) is being planned to sustain an increased dose of radiation and challenges arising from occupancy rate due to higher luminosity. Replacement of existing photo readout device by silicon photo multipliers is being planned for the HCAL. Detailed studies performed on this device are presented. Plans on the upgrade of the front-end electronics, DAQ, trigger, and the active elements in some part of the detector will be discussed in detail.

Key words:
Calorimeter, Scintillator, Silicon Photomultiplier, Quartz fiber, Trigger

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1. Introduction

The CMS (Compact Muon solenoid) experiment ([1]) at the Large Hadron collider (LHC) at CERN is ready for recording pp collisions. The entire experiment has been operated successfully at full field of 4 Tesla in the global data taking mode with a cosmic trigger as well as the *first beam* of protons at 450 GeV. Current design of the detector is optimised with peak luminosity of $10^{34}/\text{cm}^2$-sec with a bunch crossing interval of 25 ns. The LHC machine is expected to undergo major upgrades in two stages which is anticipated to enhance the peak luminosity by an order of magnitude to $10^{35}/\text{cm}^2$-sec. Though this upgrade will not lead to any fundamental changes in the CMS design, there may be need to improve on several fronts such as active elements in some parts of the detector, front end electronics, trigger and DAQ in order to meet the challenges arising due to the higher luminosity.

The HCAL in the CMS detector ([2]) is a sampling calorimeter made of scintillator or quartz fibers as the active element and brass or steel as the passive element. It is geometrically segmented into three regions viz; barrel $|\eta| < 1.3$, end cap (HE, $1.3 < |\eta| < 3.0$) and forward (HF, $3.0 < |\eta| < 5.0$). In the barrel region, the HCAL is further divided longitudinally into an inner barrel (HB) and an outer barrel (HO) region. The HB is located inside the CMS magnet. The HO detector which is primarily designed to enhance the sampling depth in the barrel region is located in the central muon system (outside the CMS magnet). Design of the HE is similar to that of HB. Scintillator as active media and Hybrid Photo Diode (HPD) as the photo readout element are used in these 3 subsystems of the HCAL. The size of each tower in HB/HO/HE is ~ 0.087 in eta and phi directions. The HF detector is located at 11.2 meters from interaction point and covers a pseudo rapidity range of $3.0 < |\eta| < 5.0$. Due to the very high radiation dose in the forward region, the HF uses quartz fibers as the active medium. PMTs are used to sense the Cerenkov light produced in the quartz fibers. The size of each tower in HF is typically 0.175 in η and ϕ directions.

2. Performance of Photo Readout Elements in HCAL

The performance of the HPD and the PMT have been studied extensively in the test beam facility at CERN using different particle beams (electron, pions, muons etc.). Response of readout elements to magnetic field has been also studied in detail.

2.1. Performance of Photo Multiplier Tube in HF

The HF uses 8 stage bi-alkaline Hamamatsu PMT (R7525) which are shielded adequately from the radiation dose and the magnetic field. However, when, a charged particle above Cerenkov threshold directly goes through the PMT, it produces a large signal due to Cerenkov light (Fig. 1) mimicking a fake jet or missing E_t signal, thereby, limiting the performance of the calorimeter. To resolve this limitation, it is proposed to use the recently developed super bi-alkaline PMT by Hamamatsu Photonics. These PMTs have an excellent quantum efficiency around the blue region (43% at 350 nm). The metal envelope and ultra thin window of the tube (0.6 mm) significantly reduces the production of the Cerenkov light due to passage of charged particles. These PMTs do not show any anomalous effect when exposed to muons. Also, the existing PMTs have borosilicate glass window which may have $\sim 30\%$ transmission loss within a year of SLHC, whereas the super bi-alkali PMT uses silica windows that can withstand 100 years of SLHC operation. The plans for the replacement of the existing PMTs by the super-alkaline tubes in the HF are being further investigated.

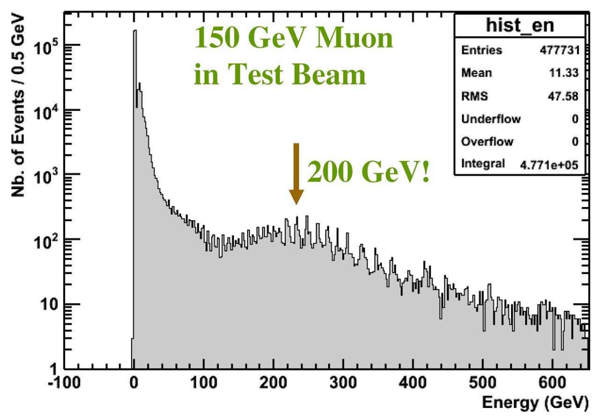

Figure 1: Response of Hamamatsu PMT model R7525 to muons

2.2. Performance of Hybrid Photo Diode

The HPD is a solid state device, it consists of a common photo-cathode and a total of 19 photo diodes are packaged in hexagonal shape on the same wafer. The photoelectrons produced in the photo cathode are accelerated between the cathode and the diode plane, by applying ~ 8 kV and subsequently multiplied in the diode, resulting in a gain $\sim$2000. In the CMS detector, these HPDs experience varying magnetic field depending on their location. Adequate care was taken to ensure no significant cross-talk due to the ExB effect. However, some of the HPDs showed a tendency to discharge when operated within the range of 0.2-3.0 Tesla (Fig. 2). The magnetic field experienced by the HPDs used in HB and HE do not lie in this range. However, for the HO, the HPDs located in towers in the pseudo rapidity region $0.35 < |\eta| < 1.3$ do experience a field of ~ 0.25 Tesla. Recently there has been significant progress in the development of Silicon Photo Multipliers (SiPM). SiPMs possess all the merits of the PMTs and HPDs and are being considered for replacing the HPDs in the discharge prone region of the HO. The performance of this device is described in the next section.

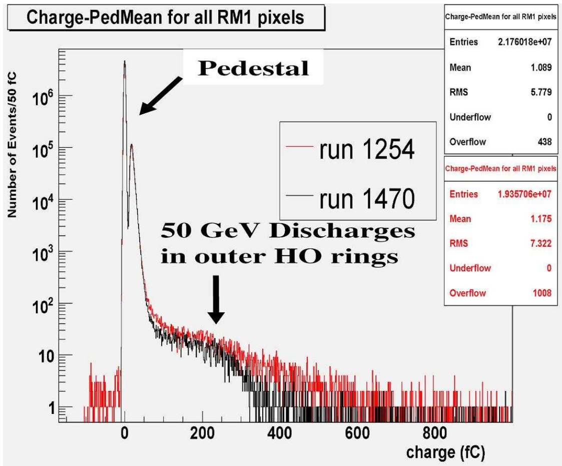

Figure 2: Pedestal distribution of HPD in magnetic field.

3. Silicon Photo Multipliers (SiPM)

The SiPM is a two pin device consisting of a large array of avalanche photo diodes with resistive coupling. It is operated a few volts above the break-down voltage, enabling a gain comparable to that of a PMT. The avalanche is controlled by a built-in self quenching mechanism. Typical size of each diode (pixel) is $\sim$ 5-50 μ and it acts as a logical device. A linear response from this device can be obtained by ensuring a sufficiently low density of photons falling on each pixel. The response of the SiPM (from IRST-FBK, Hamamatsu, Zecotec, CPTA) to muons, pions in HO including effects of radiation damage has been studied.

The SiPM when operated in the entire range of magnetic field (0-4 Tesla) did not show any indication of discharge as seen with the HPDs. The response to the muons passing through a scintillator tile (10 mm thick) in HO is shown Fig. 3. It is seen that the SiPM, as compared to the HPD, provides a much higher S/B ratio. A section of the ECAL followed by the HB/HO was exposed to pions directed at $\eta = 0.6$. The HB was read out with HPDs. The measurements at a pion beam energy of 300 GeV show that the response of the HPD and the SiPM are very similar.

The HO readout element receives a dose equivalent to 10^{11} p/cm^2 for 30 years of SLHC operation at its peak luminosity. SiPMs from different manufacturers were exposed to this level of radiation dosage. There was no significant drop in the performance of the SiPMs (Fig. 4) from most of the manufacturers. Overall, the SiPM has been shown to be a good alternative for the problematic HPDs. The proposal for replacing the HPDs by the SiPMs, in the discharge prone region, during the LHC period is being considered.

4. Upgrade plans for HCAL

During the SLHC period, the energy resolution of the HE may gradually degrade due to the radiation damage in the front layers. Replacement of these layers by quartz

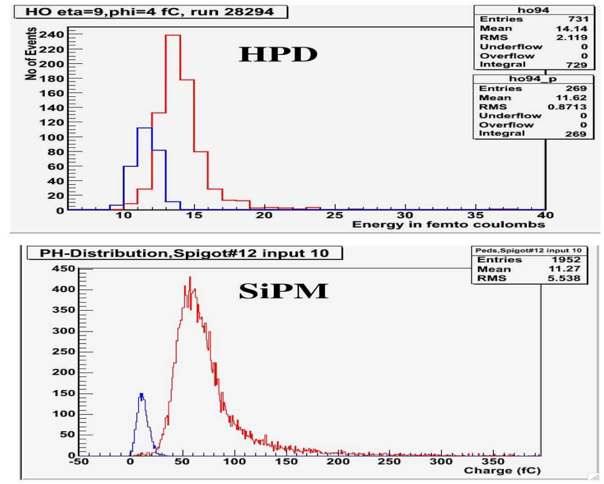

Figure 3: Pedestal and muon signal distributions for HPD and SiPM ([3])

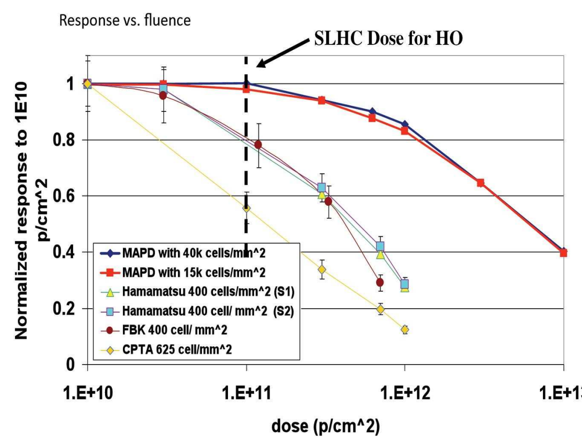

Figure 4: Radiation damage to the SiPMs ([4]).

plates, which are highly radiation hard, is being considered. The front layers in HB and HE will have a large occupancy due to the substantial increase in the pileup, thereby reducing the trigger sensitivity. Further, longitudinal segmentation in the readout of the barrel and the endcap regions (Fig. 5) is proposed to overcome these constraints. Each layer in HB/HE would be read out separately by SiPMs and the signals would be electrically added as per the segmentation requirement. Simultaneous measurement of the signal charge and time would help in reducing the instrumental background and pileup related hits in the front layers. However, this would increase the typical HCAL event size 8 times. The purity and the quality of the trigger at Level-1 has to be improved to maintain the trigger rate within the stipulated bandwidth. To accomplish this task, the technology with a higher interconnect speed and faster processors is required. The Telecommunication Computing Architect (TCA) has emerged out of the rapidly growing telecommunications industry and fulfills these requirements. The TCA can enable data copying across the detector boundaries and the possibility of providing a common platform to the ECAL and the HCAL trigger formation. Since the TCA architecture is commercial, it is also cost effective. Detailed feasibility studies of this architecture for the entire CMS calorimeter (ECAL+HCAL) are under progress.

In a subset of the HF, the performance of plastic cladded quartz fibers (QPF) is expected to degrade by as much as 75% within 5 years of LHC at its peak luminosity. However, the fluorine-doped silica cladding (QQF) can withstand 20 Grads (smaller than integrated SLHC dose), with less than 10% degradation. After a careful study of the radiation damage to the fibers during the LHC operation, replacement of a small fraction of the QPF by QQF would be considered.

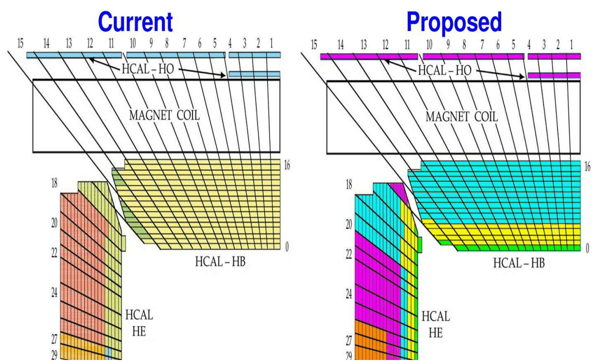

Figure 5: Current and proposed longitudinal segmentation of HCAL for ($\eta < 1.5$)

5. Summary

The CMS detector is ready to take data from pp collisions. With the upgrade of the LHC, the HCAL would have to be upgraded on several fronts. In the HF, replacement of a fraction of the existing PMTs with super-bialkali PMT and QPF with QQF fibers is being planned to address the problems due the anomalous signal produced in the PMTs and the radiation damage in the fibers, respectively. In the HE, the scintillator layers may be replaced with the quartz plates at the end of the first phase of SLHC operation. The performance of the SiPM for HCAL is very encouraging and is being considered as an alternative to the HPDs. Plans for further longitudinal segmentation in the HB/HE are being made to meet the challenges due to the high occupancy and instrumental background etc. Migration to the TCA architecture which provides high speed interconnect links and several other desirable features to meet various challenges in the SLHC environment are being examined.

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[4] Radiation damage studies on SiPMs for calorimetry at the super LHC, A. Heering et al., 2007 IEEE Nuclear Science Symposium Conference Record, Vol. 2, (2008)