The Compact Muon Solenoid Experiment
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Commissioning of the CMS Hadron Forward Calorimeters Phase I Upgrade

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Abstract

The final phase of the CMS Hadron Forward Calorimeters Phase I upgrade was performed during the Extended Year End Technical Stop of 2016 and 2017. In the framework of the upgrade, the PMT boxes were reworked to implement two channel readout in order to exploit the benefits of the multi-anode PMTs in background tagging and signal recovery. The front-end electronics were also upgraded to QIE10-based electronics which implement larger dynamic range and a 6-bit TDC. Following this major upgrade, the Hadron Forward Calorimeters were commissioned for operation readiness in 2017. Here we describe the details and the components of the upgrade, and discuss the operational experience and results obtained during the upgrade and commissioning.

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Commissioning of the CMS Hadron Forward Calorimeters Phase I Upgrade

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ABSTRACT: The final phase of the CMS Hadron Forward Calorimeters Phase I upgrade was performed during the Extended Year End Technical Stop of 2016 - 2017. In the framework of the upgrade, the PMT boxes were reworked to implement two channel readout in order to exploit the benefits of the multi-anode PMTs in background tagging and signal recovery. The front-end electronics were also upgraded to QIE10-based electronics which implement larger dynamic range and a 6-bit TDC.

Following this major upgrade, the Hadron Forward Calorimeters were commissioned for operation readiness in 2017. Here we describe the details and the components of the upgrade, and discuss the operational experience and results obtained during the upgrade and commissioning.

KEYWORDS: Calorimeters, Cherenkov and transition radiation, Radiation-hard detectors, Large detector systems for particle and astroparticle physics, Detector design and construction technologies and materials, Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others)

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1 Introduction

The Compact Muon Solenoid (CMS) [1] is a general-purpose detector designed to run at the highest luminosity provided by the CERN Large Hadron Collider (LHC). The CMS detector calorimeter has been designed to detect cleanly the diverse signatures of new physics through the measurement of jets and by measuring missing transverse energy flow. The CMS experiment has a 4 T superconducting solenoidal magnet of length 13.0 m and inner diameter 5.9 m. The magnet determines many of the features of the CMS calorimeters because the barrel and end-cap calorimeters are located inside this magnet.

Coverage between pseudorapidities (η) of 3.0 and 5.0 is provided by the steel/quartz fiber Hadron Forward (HF) calorimeter. The front face is located at 11.2 m from the interaction point and the depth of the absorber is 1.65 m. The signal originates from Čerenkov light emitted in the quartz fibers, which is then channeled by the fibers to photomultipliers. The absorber structure is created by machining 1 mm square grooves into steel plates, which are then diffusion welded. The diameter of the quartz fibers is 0.6 mm and they are placed 5 mm apart in a square grid. The quartz fibers, which run parallel to the beamline, have two different lengths (1.43 m and 1.65 m) which are inserted into grooves, creating two effective longitudinal samplings. The so-called “short fibers” start 22 cm inside the absorber, hence are mostly sensitive to hadron interactions.

There are 13 towers in η , all with a size given by $\Delta\eta \sim 0.175$, except for the lowest- η tower with $\Delta\eta \sim 0.1$ and the highest- η tower with $\Delta\eta \sim 0.3$. The ϕ segmentation of all towers is 10° , except for the highest- η which has $\Delta\phi = 20^\circ$. This leads to 900 towers and 1800 channels in the two HF calorimeter modules [2]. Figure 1 (left) shows a sketch of the CMS hadron calorimeters and Fig. 1 (right) shows a close-up sketch of the HF calorimeter. Details of the HF calorimeter design, together with test beam results and calibration methods, can be found in [3].

The photomultiplier tubes (PMTs) of the CMS HF calorimeter were shown to generate a large, fake signal when the PMT window is traversed by a relativistic charged particle due to Čerenkov light production at the PMT window. These PMTs had circular windows with 2.54 cm diameter and 2 mm thickness at the center that gets thicker towards the rim (Hamamatsu R7525 [4]). This

Figure 1. A sketch of the CMS detector highlighting the hadron calorimeters (left): Barrel (HB), endcap (HE) and forward (HF); and a sketch of the CMS HF calorimeter (right).

problem was observed in the 2010 and 2011 CMS data to degrade data quality and to constitute a potential to interfere with rare physics events.

In the framework of the CMS HF upgrade program, several types of PMTs were tested and the four-anode R7600U-200-M4 by Hamamatsu [4], was selected as the replacement PMT for the upgrade [5]. The new PMTs were tested in several beam tests as well as the actual collision environment in the CMS [6].

The upgrade readout box housing the new PMTs offers different readout options (single-channel, two-channel and four-channel) for the four-anode PMT in a single compact design with the utilization of an adapter board coupled to the readout board.

The associated front-end and back-end electronics were also upgraded. The major components of this electronics upgrade are the QIE10 (Charge Integration and Encoding) front-end card [7], which features TDC functionality and the μ TCA based back-end electronics replacing the VME based back-end electronics [8]. The major motivation for the TDC functionality is the significant time difference (a few ns) between the background and the calorimeter signal.

During Long Shutdown 1 (LS1), all of the original PMTs were replaced with R7600U-200-M4. At the same time, the back-end readout system was upgraded to micro-TCA readout. A number of PMTs were set to be read out with both the legacy and the upgrade QIE system. Also, a number of PMTs were put into two-channel readout to be read out with the upgrade QIE10 system which also provides the TDC information. All tests were successful.

The final phase of the Hadron Forward Calorimeters Phase I Upgrade was performed during the Extended Year End Technical Stop from December 2016 to April 2017 (EYETS 16-17). The PMT boxes were reworked to implement two channel readout in order to exploit the benefits of the multi-anode PMTs in background tagging and signal recovery. The QIE10 front-end electronics was also installed during this technical stop.

Following this major upgrade, the Hadron Forward Calorimeters were commissioned for operation readiness in 2017. Here we describe the details and the components of the upgrade, and discuss the operational experience and results obtained during the upgrade and commissioning.

2 The Components of the Phase I Upgrade

The primary component of the upgrade is the PMTs. The upgrade PMTs utilize thinner windows, four anode segments and basic properties exceeding the HF requirements. The thinner windows and the metal envelope reduce the size and rate of the window events. The upgrade PMT does not only reduce the intrinsic level of the background, but it also enables tagging of background events and recovering the underlying signal event (if any) by using the multi-anode features. For the calorimeter signal, the quad anode PMT views the well-mixed light from the air light guide, thus all 4 anodes should have the same signal (up to statistical variations). However, a MIP background affects one quadrant (or one half) of the PMT, thus generating increased anomalous signals in one of the readout channels but not the others. The background from a MIP may thus be tagged by various algorithms (which have already been studied extensively [5, 6]) comparing the anode signals; if the signals are sufficiently different, we can assume a background MIP causes it. Once an anode with a background is tagged, the signal can be recovered by using only the signals in the other anode(s).

HF requires 72 readout boxes, 216 baseboards with 1728 PMTs, and the ability for each 4-anode PMT to be read out in 1 or 2 channel operations. This design challenge was met with a single PMT board, the so-called base board, and multiple adapter boards. Figure 2 shows the pictures of the readout box (left) and the base and adapter boards (right). From LS1 until the end of 2016, the PMTs were read out in 1-channel mode. During EYETS 16-17, the 1-channel adapter boards were replaced with the 2-channel adapter boards. The readout box shown in Fig. 2 is in assembly for the 1-channel mode. The cables needed for the 2-channel readout can be seen as tied bundles. In order to comply with the different phases of the upgrade program, the adapter board is designed to provide convenient switching between different readout options. The adapter board uses through hole mounted MMCX (micro miniature coaxial) signal connectors. There are screw/standoff retainers for attachment to the base board.

Figure 2. Picture depicting the HF readout box anatomy during assembly (left). The PMTs appear inverted on the table. The base boards, adapter boards and internal cabling are also visible. The entire box can read out 24 PMTs in three front-end electronics boards. Picture of the base and adapter boards before assembly (right). Major parts of the boards are labeled.

An updated QIE, called QIE10 has been designed to digitize the PMT signal and the signal's arrival time information. It features deadtimeless integration and digitization of charge in 25 ns

‘buckets’; the same clock as the LHC. On board is a rising edge TDC with a resolution of less than 800 ps, which outputs a discrimination bit. It has a large dynamic range of 3 fC to 330 pC and holds this information in 17 bits. Its digitization error is less than the calorimeter resolution and is at the order of 2-3 %, held in 6 bits. It digitizes in 4 ranges, stored in 6-bit mantissa and 2-bit exponent. It matches the input impedance of the new PMTs. The QIE10 features a radiation tolerant FPGA (ProASIC3E from Microsemi) manufactured using the AMS 0.35-micrometer SiGe BiCMOS process. This FPGA is responsible for synchronizing and formatting the data from several QIEs. It also determines the pulse width from the time discriminator output. The chip is tolerant to 100 Gy, though it is expected to receive a total ionizing dose of 1.5 Gy. A new data link was developed by CERN to carry this information to the counting room. GBTx is a 4.8 Gbps data link that serializes the QIE10 data for transmission to the back-end electronics. 88 bits of user data can be carried every bunch crossing. A large-scale test station has been established to test all the QIE10 cards before installation in CMS.

The older VME-based back-end system was replaced with the new industrial standard known as μ TCA. The new electronics improve the noise rejection and the granularity of the HF readout and trigger. The Gigabit Ethernet (GbE) link is the primary communication path for configuration and monitoring in a μ TCA crate. Several connections are used for the distribution of clock signals in the crate.

3 Phase I Upgrade Operations

During EYETS 16-17, the PMT boxes were removed from the detector in quantities ranging from 9 to 15 at a time. The boxes were then surveyed by the CERN radioprotection services and were transported to the rework area which was designated as a temporary radiation zone for the rework purposes. The PMT box test station at the rework area was capable of testing three boxes simultaneously. The front-end and back-end electronics were the Phase I upgrade systems based on QIE10 and μ TCA respectively.

Three types of data taking modes were used: Pedestal, LED and histogram. As the boxes were available in the rework area, they were tested for initial performance assessment and reference for post-rework measurements. Three boxes were simultaneously tested. The PMT boxes were then opened for rework. The main operation of rework is the removal of the 1-channel adapter boards and the installation of the 2-channel adapter boards. Two special tools were developed for this purpose. The major risk in the operation is damaging the small “Winchester-to-MMCX” cables connecting to the adapter boards. During the rework operations, less than 1 % of all the Winchester-to-MMCX cables were replaced due to damage.

Once the 2-channel adapter boards were installed, the assembly went through cable testing. Following the cabling tests, the PMT box is closed. Three boxes were simultaneously exposed to the first post-rework testing with a pedestal and an LED data taking. A set of three boxes were then set up for overnight periodic LED data taking. Overnight data taking is done in order to check the stability of the performance for a relatively longer operation time and via automated scripts. Following the overnight data taking, the boxes were tested for the final post-rework performance evaluation.

The results of all the tests were available online within five minutes following the completion of the tests. This allowed immediate examination of the results with multiple team members, and also immediate availability of the results to the collaboration. Once the results confirmed that the rework for a particular PMT box was successful, the box was signed off from rework and marked as ready for installation back on the detector. The boxes were transported back to the experiment hall in quantities of 6 to 15. The reinstallation on the detector took approximately 20 minutes per box including the examination of the air light guides and the sleeves for alignment.

In parallel to the PMT box rework, the QIE10-based front-end electronics were installed in the experiment area. 16 front-end crates housing a total of 144 QIE10 cards, 16 control modules and 8 calibration modules were installed following a long commissioning period with extensive tests of each component. The front-end electronics installation was completed at the same time as the PMT box rework.

4 Commissioning of the Phase I Upgrade

Once all the Phase I upgrade components were in place at the detector, extensive testing was performed to validate the PMT box rework, external cabling and the front-end electronics integrity. The following data taking modes were used for commissioning: Pedestal (randomly triggered data taking with ten consecutive time samples of 25 ns each), LED (with LED light of tunable intensity provided by the upgrade calibration module), internal charge injection (QIE10 has the ability to inject charge internally) and laser (laser light is centrally injected into HFs). A small number of issues, almost all of them related to the external cabling connections, were identified and resolved in a timely manner.

As the ultimate test of the installation, the HF was tested with ^{60}Co radioactive source by inserting the source in each detector tower and recording the response as a function of the position of the source inside the tower. This test is most useful in identifying internal cabling issues and electronics map issues. No such issues were observed. In addition, the radioactive source measurements provide high precision information about the optical path and the readout chain integrity.

The HF Phase I Upgrade started the operations in 2017 data taking period with superior performance. Figure 3 (left) shows the TDC calculated signal time in ns versus the charge in fC for a specific HF readout channel, with the colors indicating the number of entries. There is a contribution with low TDC values (<5 ns) that originate from particles directly hitting the PMT window. Normal hits are populated around 8 ns. Above a charge threshold of 200 fC, the PMT hits can successfully be identified as early signals with TDC time values of less than 5 ns. This demonstrates the power of the Phase I Upgrade with the effective utilization of the TDC.

Figure 3 (right) shows the charge asymmetry defined as $(Q_1 - Q_2)/(Q_1 + Q_2)$, where Q_1 and Q_2 are the charge values measured by the two channels of the same PMT, versus total charge measured by a specific HF PMT. The colors indicate the number of entries. The contributions around ± 1 indicate significant asymmetry of the signals between the two channels reading out the same calorimeter section, hence the presence of PMT hits. Manifestly, exceptional handles on background identification and signal recovery with multi-anode readout is now enabled by the HF

Phase I Upgrade. It should also be noted that the background identification and recovery algorithms have been developed and demonstrated with beam test data several years ago [5, 6].

Figure 3. TDC vs charge of a specific HF readout channel. Also shown are the TDC selection for early/late hit separation above a charge threshold of 200 fC. The color palette shows the number of entries (left). Charge asymmetry versus total charge for a specific HF PMT. The color palette shows the number of entries (right).

5 Conclusions

The CMS Hadron Forward Calorimeter completed the last stage of the Phase I upgrade during the Extended Year End Technical Stop 2016-2017. The PMT boxes were reworked to switch from 1-channel readout to 2-channel readout of the four anode PMTs. At the same time, QIE10 based new front-end electronics were installed.

The CMS Hadron Forward Calorimeter Phase I upgrade has successfully collected data in the 2017 data taking period.

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