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

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Phase I Upgrade Status of CMS Hadron Forward Calorimeter

Yasar Onel for the CMS Collaboration

Abstract

The Hadron Forward Calorimeter of CMS is going through a complete Phase I upgrade. The current photomultiplier tubes (PMTs) are being replaced with thinner window, higher quantum efficiency, four-anode photomultiplier tubes. The new PMTs will provide better light detection performance, a significantly reduced background and unique handles to recover the signal in the presence of background. This report will describe the nature of the essential upgrade elements with supporting beam test results and the status of the upgrade progression.

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CMS Hadron Forward Calorimeter Phase I Upgrade Status

Yasar Onel[1]
On behalf of the CMS Collaboration

The University of Iowa, 203 Van Allen Hall, Iowa City, IA, 52242, USA

E-mail: yasar-onel@uiowa.edu

Abstract: The CMS Hadronic Forward Calorimeter has undergone upgrade maintenance during the LHC Long Shutdown 1. The Hamamatsu R7525 PMTs have been replaced with Hamamatsu R7600U-200-M4 PMTs, which have thinner window glass that reduces window-hit events. The R7600 PMTs also have multi-anode readout feature to further enable discrimination of window-hits while also allowing the recovery of true signal energy. Higher quantum efficiency of the R7600 PMTs improves calorimeter resolution. The new PMTs were tested and calibrated; new PMT baseboards were designed and tested, and can be configured to readout 1, 2, or 4 anodes of the R7600. New radiation hard (100Gy) QIE front-end electronics were designed for reading out the new PMTs and include a TDC with < 800ps resolution. New back-end electronics based on the microTCA industrial standard have been tested.

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). Coverage between pseudorapidities (η) of 3 and 5 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. Machining 1 mm square grooves into steel plates, which are then diffusion welded together, creates the absorber structure. 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 beam line, 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 $\Delta\eta \approx 0.175$, except for the lowest-η tower with $\Delta\eta \approx 0.1$ and the highest-η tower with $\Delta\eta \approx 0.3$. The ϕ segmentation of all towers is 10°, except for the highest-η which has $\Delta\phi = 20°$. This leads to 900 towers and 1800 channels in the two HF calorimeter modules [2]. 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 generate a large, fake signal when the PMT window is traversed by a relativistic charged particle due to Čerenkov light production at the

[1] To whom any correspondence should be addressed.

PMT window. These PMTs have circular windows with 2.54 cm diameter and 2 mm thickness at the center that gets thicker towards the rim (Hamamatsu R7525 [4]). This already-known 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. An upgrade plan was therefore formulated for CMS HF, summarized in Table 1. Figure 1 describes the timeline of LHC operations in the next ~ 10 years.

Table 1. HF Upgrade Schedule

Upgrade	**Date**
PMT Replacement	LS1 - 2014
PMT Support Cabling	LS1 - 2014
Front-End Electronics	Before 2016 [a]
Back-End Electronics	Before 2016 [a]

[a] Although scheduled for LS2, likely will be installed prior to LS2.

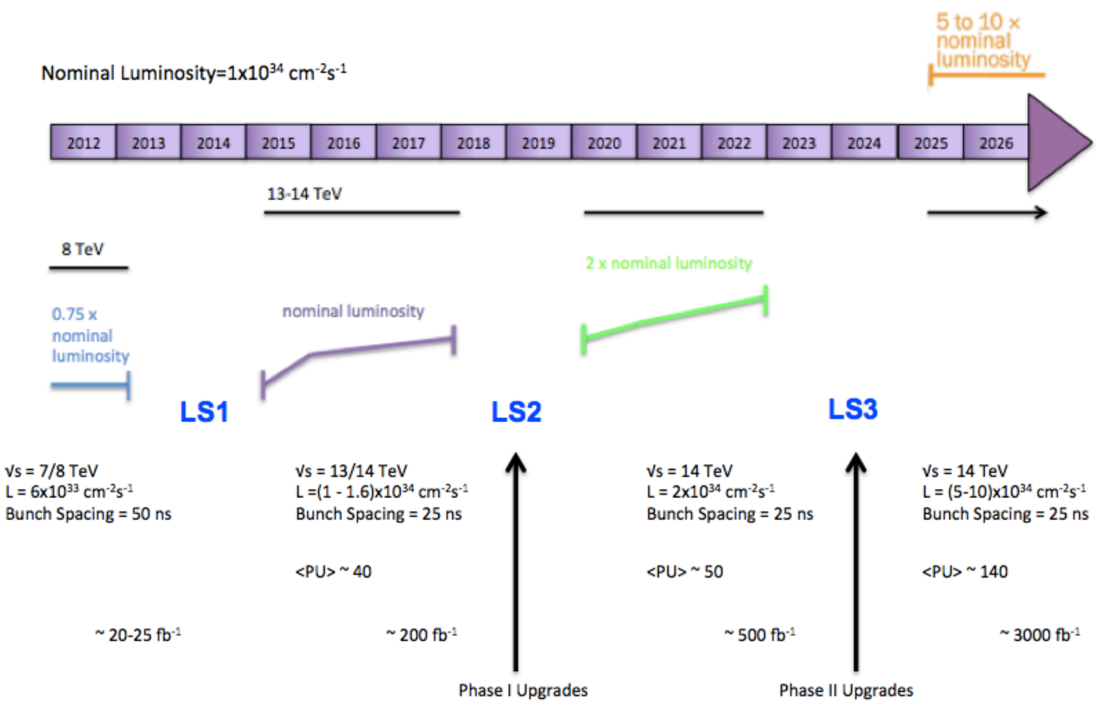


Figure 1. The timeline of LHC operations in the next ~ 10 years.

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 upgrade PMT has a square window of size 1.8 cm × 1.8 cm and thickness less than 1 mm indicating a significant reduction in the amount of glass seen by the traversing relativistic particles. The new PMT not only reduces the intrinsic level of background, but it also enables tagging of background events and recovering the underlying signal event (if any) by using the multi-anode features.

A readout box (RBX) prototype was built to enable the tests of different readout options for the new four anode PMTs. The new readout boards provide the flexibility to switch between four- channel, two-channel and single-channel readout of the four anode PMTs where the four-channel readout option enables the full multi-anode functionality. Both the internal and external cabling of the RBX were also specific designs and selections, therefore form an integral part of the prototype.

The prototype RBX was tested in the CERN H2 beam line [6] in Summer - Fall 2011 with electron and muon beams to mimic calorimeter and background responses respectively.

HF front-end and back-end electronics will be upgraded in order to support multi-channel readout of the R7600 PMT. Testing has been completed and commissioning is ongoing, with a goal to install before Long Shutdown 2.

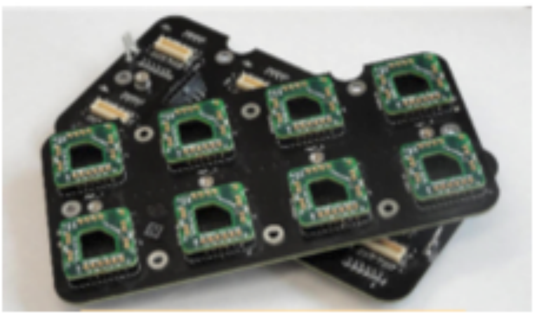
The front-end electronics, named QIE10 (Charge Integrator and Encoder), are radiation tolerant (up to 100 Gy) and include the addition of a TDC circuit. The TDC has a rising edge resolution of 390 to 780 ps (5 or 6 bits). This next generation QIE card has deadtimeless integration and digitization of charge in 25ns buckets; large dynamic range (3 fC to 330 pC) stored in 17 bits, and has digitization error less than the calorimeter resolution (2-3%). This increased data will require a new pipeline, and the SLHC beam conditions will require a radiation hard solution. The GigaBit Transceiver (GBTx) technology will serialize data from the QIE10 cards and transmit the data to the back-end electronics in the counting room. 288 new GBT data-link fibers will allow for the addition of the TDC bits, including the presence of multiple rising or falling edges. Upgraded HF back-end electronics will replace the current VME based system and will be installed into an industrial-standard microTCA crate. This is the first step of the Phase I electronics upgrade for HF.

Here we describe the necessity of the upgrade, the individual upgrade components and the status of progression in detail.

2. Upgrade Components

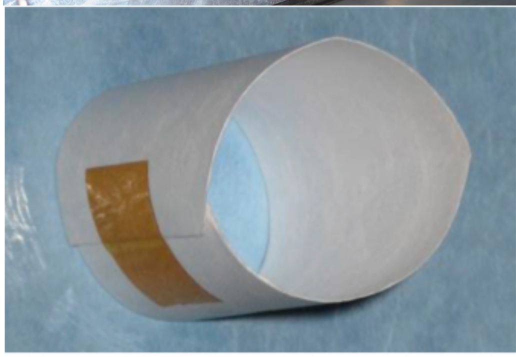
The Phase I Upgrade of the CMS hadron Forward calorimeters include the replacement of the R7525 PMTs with the R7600 PMTs, the design of the new base and adapter boards to include the flexibility of switching between 1, 2 and 4-channel readout options, associated light guides, sleeves and cabling. Table 2 summarizes the upgrade components. In addition to the components listed, the fron-end and back-end electronics will also be upgraded.

Table 2. HF Phase I Upgrade Components

Upgrade	**Image**
Baseboard	

ROBOX Light Guides

Light Sleeve



ROBOX Cabling

PMTs and Baseboard

Winchester Cable	

2.1. Upgrade PMTs

After it was discovered that muons traversing the CMS detector were interacting with the windows and bodies of the HF PMTs and were creating large anomalous signals in the detector, a program was developed to decide how to mitigate this signal contamination. Studies of the anomalous signal timing showed that muons from the interaction point arrived in the PMTs earlier than signals that traveled through the HF fibers. This resulted in the addition of a Time-to-Digital Converter (TDC) circuit to flag signals that arrived out of time with other HF signals. Studies of HF PMTs and multi-anode PMTs placed directly in beam in front of wire-chambers motivated the usefulness of a multi-anode PMT, as an interaction with one anode of the PMT window would be able to be discriminated by comparing the individual signals of the multiple anodes. The HF mixing modules should present light of roughly uniform intensity onto the face of the multi-anode PMTs, so a variation in light intensity between anodes larger than what would be expected statistically could be used to flag events. This upgrade has also motivated an updated readout box and accompanying front-end and back-end electronics.

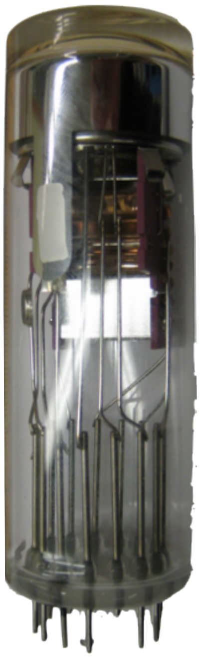


Figure 2. Hamamtsu R7525 – The original HF PMT

Figure 3. Hamamatsu R7600U-200-M4 – The 4-anode HF PMT replacement.

The R7600 PMTs have a thinner window that reduces the likelihood and intensity of a direct interaction with a particle. We have shown that the rate of interaction as well as the response of the interaction is greatly reduced regardless of angle of incidence [5]. The response of a MIP is reduced more than a factor of 5. The R7525 PMTs had glass bodies as well as glass windows; the R7600s contain glass only in its thin window, and the body is contained within a metal envelope.

A goal of the multi-anode PMT replacement was to design algorithms to tag and correct MIP interactions by comparing the relative levels of signal in each anode. The quad-anode design is most attractive for this purpose, though a two-channel readout design has been adopted for the current operation. The readout bases allow for configuring 1, 2, and 4 channel readout modes, enabling future operation of 4-channel readout. We have tested algorithms in test beam [8] and have shown that both readout modes can accurately flag MIP events, and have high efficiencies, (~98% 4-channel and ~90% 2-channel readout).

The actual signal within the MIP flagged events can be recovered whereas such events would be omitted with the old HF PMT readout. Since a light-guide mixing-module delivers roughly uniform light from the HF optical fibers to the face of the PMT, all 4 anodes should in principle receive almost equal amount of light. If a MIP hits the surface of the R7600, its Čerenkov radiation will be deposited into the quadrant it hits. One quadrant will produce a higher signal than the others, and different algorithms can be used to recover the signal that would have been recorded had the MIP not interacted with the PMT and contaminated the signal. This case is illustrated in Figure 4.

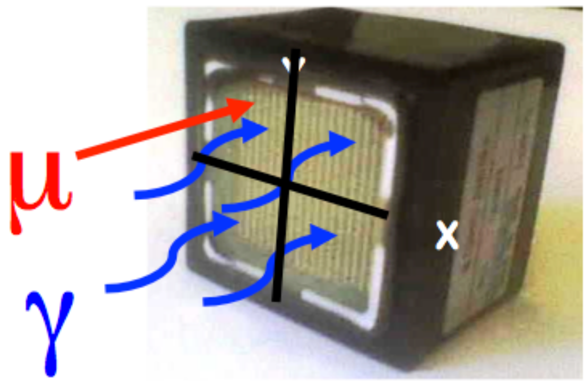


Figure 4. MIP interacting simultaneously with true HF Signal

The specifications of the R7600 PMTs exceed the optical demands of the HF detector. They have a higher quantum efficiency than the R7525, which will improve HF resolution. The mesh structure of the dynodes is less susceptible to interference from the magnetic field in CMS. Overall this is a straightforward replacement to the existing system, with no dramatic changes and significant retooling necessary.

2.2. Readout Boards

HF requires 72 readout boxes, 216 baseboards with 1728 PMTs, and the ability for each 4-anode PMT to be read out in 1, 2, or 4 anode operations. This design challenge was met with a single PMT board, shown in Figure 5.

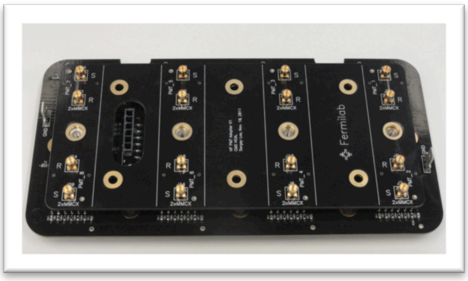


Figure 5. HF R7600 PMT Baseboard with adapter boards attached.

The R7600 baseboard has 8 power supplies (1 per PMT) with 3 sets of independent voltages (Vpc, Vd9, Vd10). The design incorporates conventional resistive bases and provides reference signals for the QIE readout card, and supplies ground connections to the PMT shields.

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.

2.3. Front-end Electronics

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 on 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.

A major design consideration was the intense radiation environment of the High Luminosity LHC. 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.

One feature of the MIPs that interact with the window of the PMTs is the difference in arrival time from true HF signal. The upgraded HF front-end electronics feature a TDC that determines the rising edge from the QIE10, in either 5 or 6 bit (390 or 780 ps) resolution. The falling edge is determined by the FPGA. The TDC data is transmitted in 4 bit codes corresponding to 3.125 ns intervals. A special code indicates multiple pulses.

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, and the total use of this bandwidth depends on the number of additional fibers installed into HF. If each fiber is required to handle data from 6 channels, only the rising-edge TDC value provided by the QIE10 will be available. If only 50% more fibers

(288) are installed, a falling-edge TDC can be provided along with the extra bits for determining multiple pulses.

2.4. Back-end Electronics

The upgraded electronics will take advantage of a new industrial standard known as microTCA. This crate standard will replace the existing VME crate system. This is the first step of the Phase I electronics upgrade.

The new electronics improve the noise rejection and the granularity of the HF readout and trigger. A prototype microHTR data acquisition board performed very well during the heavy ion collision run shortly before LS1, and figures 6 and 7 show the improvement of the microTCA over the VME system.

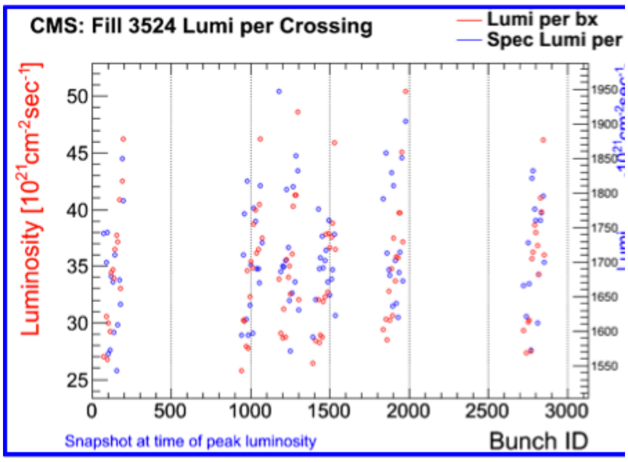


Figure 6. Lumi data from the existing VME system.

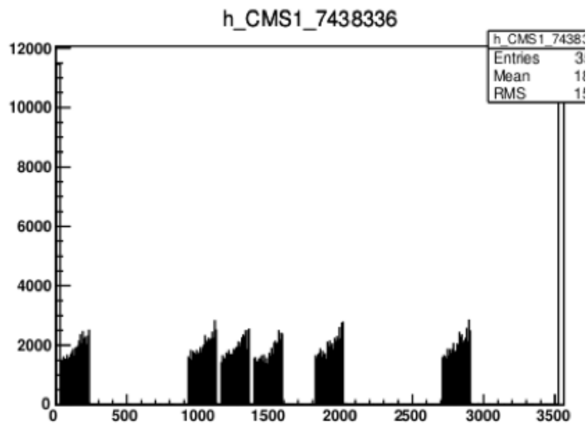


Figure 7. Lumi data from the new microTCA system.

The HF microHTR components were purchased in March 2013, and the boards are being produced in India.

3. Upgrade Status

Nearly 1800 upgrade PMTs (R7600s) were tested at the University of Iowa. The system involved: 3 dark boxes, a VME and CAMAC data acquisition system, an XY scanner for surface linearity testing, 3 picoammeters, 3 digital oscilloscopes, UV and visible light power meters, UV and Blue LED light sources, 2 nitrogen lasers, DC tungsten light bulbs, optical tables for mounting optical elements in the dark boxes, picosecond LED pulsers and 1 double pulse generator. Figure 8 shows the Iowa test station.

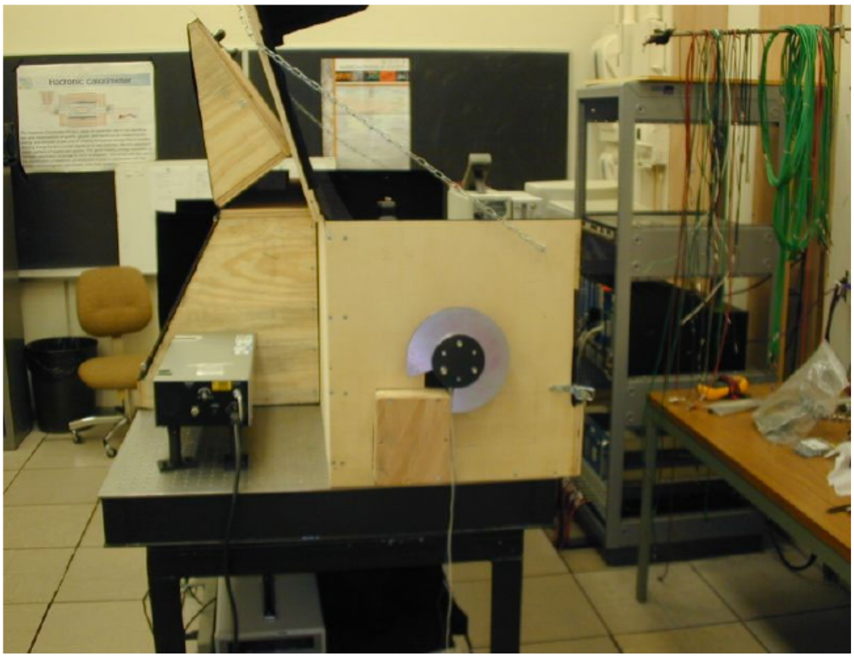


Figure 8. The University of Iowa PMT test station.

Reusing as much existing readout box infrastructure as possible was a major design goal of the project, while still meeting all criteria for proper PMT operation. Another huge consideration was the flexibility to change the number of channels read out per PMT. This capability became part of the baseboard design. These design considerations were prototyped and tested in CMS in the fall of 2010 during collisions with great success.

A slice-test readout box was designed and prototyped to directly compare HF PMT and R7600 readout in a real collision environment. Figures 9 and 10 show the hybrid HF Readout Box.

Figure 9. “Plate 2”; part of readout box with R7525s and R7600s for CMS HF.

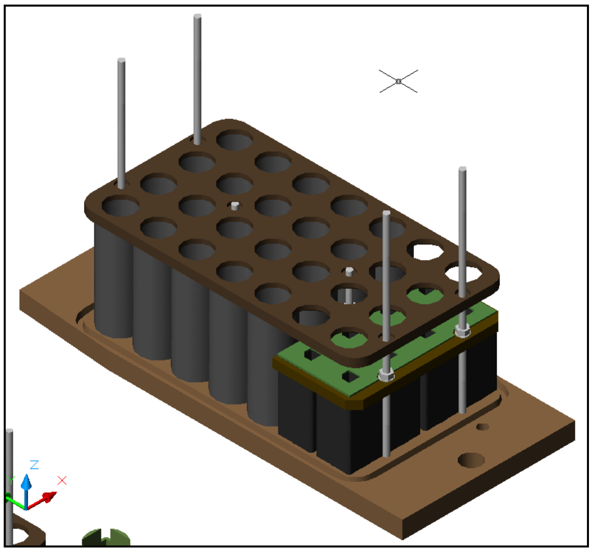


Figure 10. CAD model of readout box panel with HF PMT and R7600 for CMS HF.

The slice test mixed 20 R7525s with 8 4-anode R7600 PMTs. This ROBOX was placed in HF at iPhi 67 and covered towers iEta 29 through iEta 32 in HF +. The R7600 placed at coordinate (iPhi67, iEta 29) was blacked out so only Cherenkov light generated by MIP interactions would be recorded. Analysis of the collision data was consistent with test beam data, namely the mean energy of the MIP event reduced from 120 GeV to ~35 GeV, and the rate was significantly lower. The energy spectra from the blackened R7525 and R7600 are shown in Figures 11 and 12 respectively.

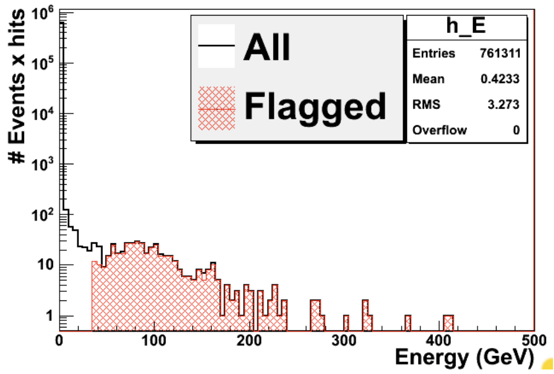


Figure 11. Energy spectrum from blackened R7525. Peak at ~120 GeV.

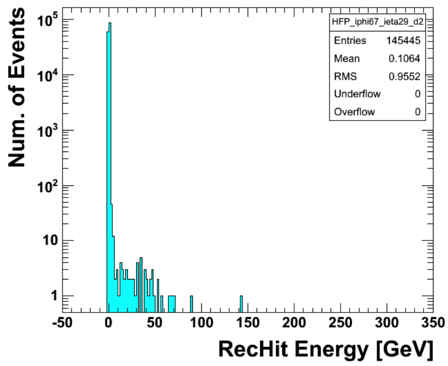


Figure 12. Energy Spectrum from R7600. Peak at ~35 GeV.

New shields (Figure 13) for the R7600 PMTs had to be manufactured, and the success of the pre-production prototype demonstrated that the design considerations are well understood.

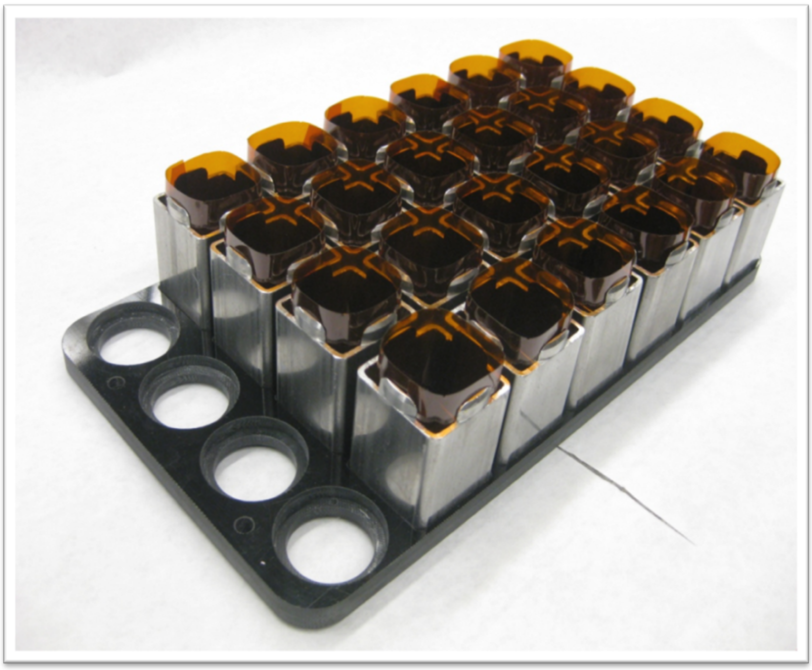


Figure 13. HF Pre Production Prototype Readout Box for R7600.

The upgrade readout box was tested at the CERN H2 test beam facility [8]. The operation was very successful, with no abnormal signals and no significant issues. The results show that we have a good understanding of the performance characteristics, and the R7600 PMTs have a uniform response under different readout conditions (1, 2, or 4 anode readout). A major success was the negligible response of MIPs with the tagging algorithm. The efficiencies of the algorithms were quantified with ~98% for 4-ch readout and ~90% for 2-ch readout. The 4-channel readout option has more controlling power on background elimination and is an unprecedented readout segmentation in an operational calorimeter.

By the time this note is written, the upgrade readout boxes are being assembled and tested at CERN. Following the installation and commissioning, the upgrade HF will be operational in 2015.

4. Physics Implications of Upgrade

The PMT upgrade stands to significantly reduce the occurrence and impact of anomalous signals, and at a time when HF will be very important to exotic physics searches as well as Higgs boson measurements.

Previous studies have shown the importance of HF to the measurement of Higgs production via vector boson fusion, whose signal includes very forward jets. These forward jets are not present in many background signals. Two-thirds of this signal would be lost without HF coverage, showing the importance of having a calorimeter at high-eta.

MIP window interactions can be tagged falsely as high pT jets and can bury real signal in this background. Previous studies show that the pT distributions of leading QCD jets in HF have an increased tail with PMT MIP events. Figure 14 shows that jets with transverse momentum, pT > 250 GeV, have a false increase of 68% significantly effecting rare physics signals. These extra HF false jets will lead to an increased background for the VBF Higgs search.

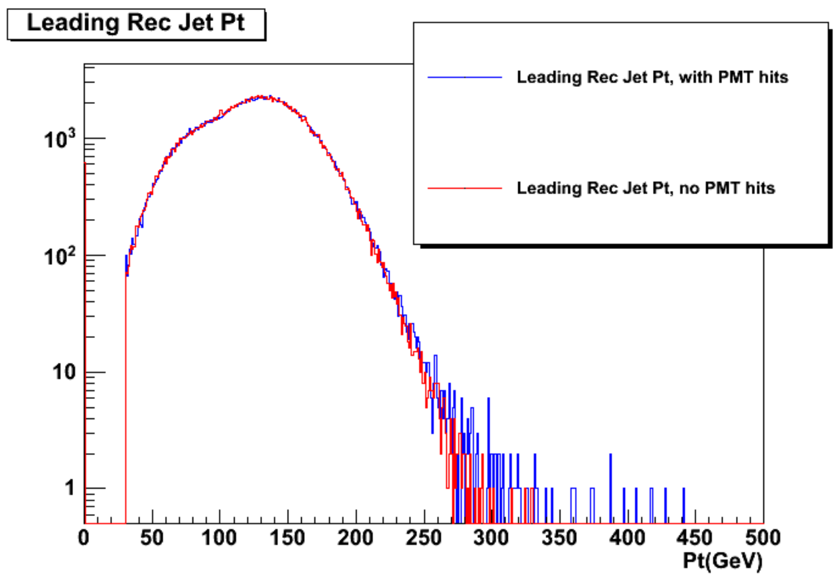


Figure 14. QCD Leading Jet with and without PMT window hits included.

Physics models with signatures of missing ET require HF at high-eta to improve the MET resolution of the CMS detector. SUSY, other exotic searches, which depend on high MET resolution, are also effected by the quality of the HF signal. HF itself reduces the MET tail (MET > 100 GeV) by a factor of 10 as compared to no HF hence is crucial for MET calculations.

5. Conclusions

The HF Phase I upgrade is underway with the construction of the upgrade readout boxes with complete upgrade components and readout options as of the day this note is written.

The multi-anode upgrade PMTs do not only reduce the rate of the background as a result of their physical specifications, but also enable the implementation of signal recovery algorithms pertaining to the multi-anode features. The design of the upgrade readout and adapter boards enables simple operation to switch between 1, 2 and 4-channel readout options. The new cabling significantly improves the space issues.

The front- and back-end electronics are developed to enable precision TDC for detailed signal shape information. The electronics is also associated with fast data links.

All the upgrade components are selected to provide the Hadron Forward calorimeters operations in the upgrade era with the desired performance characteristics. The components are extensively tested and the upgrade concept is validated with several beam tests. Progression of the upgrade is on schedule towards commissioning and operation planned in 2015.

6. References

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