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TECHNICAL REPORT

Characterization of 1800 Hamamatsu R7600-M4 PMTs for CMS HF Calorimeter upgrade

U. Akgun,[a,b,1] **G. Funk,**[a] **J. Corso,**[a] **Z. Jia,**[a] **D. Southwick,**[a] **L. Adams,**[a] **J. Kingyon,**[a] **E. Tiras,**[a] **T. Munhollon,**[b] **E. Troendle,**[b] **P. Bruecken,**[a] **V. Khristenko**[a,b] **and Y. Onel**[a]

[a]*University of Iowa, Department of Physics and Astronomy, Iowa City, IA, 52246 U.S.A.*

[b]*Coe College, Physics Department, Cedar Rapids, IA, 52402 U.S.A.*

E-mail: uakgun@coe.edu

ABSTRACT: The Hadronic Forward calorimeters of the CMS experiment are Cherenkov calorimeters that use quartz fibers and 1728 photomultiplier tubes (PMTs) for readout. The CMS detector upgrade project requires the current Hamamatsu R7525 PMTs to be replaced with 4-anode, high quantum efficiency R7600-M4 PMTs. The new PMTs will improve the detector resolution, as well as the capability of removing fake events due to signal created in the glass window of the PMT. Here, we report the dark current, anode gain, transit time, transit time spread, pulse width, rise time, and linearity measurements performed on 1800 Hamamatsu R7600-200-M4 PMTs.

KEYWORDS: Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Calorimeters; Cherenkov detectors

[1]Corresponding author.

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Contents

1 Introduction

After the discovery of the Standard Model Higgs Boson [1, 2], Large Hadron Collider (LHC) has a year long shutdown for detector upgrades in 2013. The Compact Muon Solenoid (CMS) experiment [3] Hadronic Forward (HF) Calorimeters [4] are Cherenkov detectors covering a pseudorapidity range of $2.8 < \eta < 5$ region on both sides of CMS. These quartz fiber calorimeters are very crucial for tagging forward jets and for the reconstruction of missing transverse energy. These methods are very important for Higgs decay channels with forward hadronic jets, and SUSY research. The HF calorimeters are cylinders with 1.65 m length and a radius of 1.4 m. The beam pipe passes along the central cylindrical axis and the absorber is made of iron. The absorber is divided into 18 wedges each with 24 towers. One-millimeter wide holes were drilled into the wedges parallel to the beam. Six hundred micron-thick quartz fibers were inserted into these holes and serve as the active media in the calorimeter. Long (1.65 m) and short (1.43 m) fibers alternate in the fiber matrix in order to create hadronic and electromagnetic parts within the same calorimeter. The short and long fibers from a specific tower are bundled separately. The Cherenkov light generated by the charged particle is carried by the quartz fibers to PMTs, operating in a readout box shielded from radiation and magnetic field. Each bundle is optically coupled to its own PMT through a 42-cm long light guide [5]. Within the particle showers, only electrons and positrons are fast enough to produce Cherenkov light, so the HF calorimeters are mainly sensitive to electromagnetic showers and the electromagnetic core of hadronic showers. Since slower particles and particles produced by possible radioactivity in the detector are below the Cherenkov threshold, the calorimeter is very efficient and the signal from the calorimeter is very clean [4].

There are 48 PMTs (24 short and 24 long fiber bundles) per wedge and a total of 18 wedges in one HF unit. This brings the total number of PMTs to be used in both ends of HF to 1728. Including spares, there were 1800 PMTs produced for the calorimeter. The successful operation of the HF Calorimeter depends heavily on the characteristics and the quality of the PMTs. During the first three years of LHC runs CMS HF calorimeters used Hamamatsu R7525-HA PMTs. We selected [6] and tested these PMTs in detail [7, 8] before installation. During last decade, as detector technologies are improved substantially, CMS HCAL Collaboration decided to replace the current PMTs with 4-anode Hamamatsu R7600-200-M4 PMTs with higher quantum efficiency (around 40%).

The switch to new multianode high quantum efficiency PMTs will not only increase the overall capabilities of the calorimeter, but will also solve a specific problem associated with using single anode PMTs. Our previous study showed that when a stray high-energy muon passes through the window of a PMT, the generated Cherenkov radiation delivers a strong burst of light to the cathode that would be mistakenly recorded as a high energy deposition in the calorimeter.

The thin glass windows of the R7600-M4 PMTs give smaller signal [9], and four-anode structure allow us to discriminate such events with better than 90% efficiency [10]. However, the CMS HF readout channel limitations might require combined anode outputs at the beginning. Looks like at first stage all four anodes that will be combined as a single output in order to make use of current HF DAQ. In the future as the number of readout channels increase multiple anodes will be in use. Both single and multiple anode scenarios require a good understanding of the parameters for these new PMTs in order to optimize the operation of the HF Calorimeters. The reported measurements will help the method of installation of the PMTs in the calorimeter and provide successful data acquisition. Furthermore, individual measurements may be useful in attempting to solve possible future problems related to the PMTs and HF. Here we report various characteristics of 1800 Hamamatsu R7600-200-M4 PMTs including timing, linearity, anode dark current, and anode gain.

2 PMT test setup and results

The University of Iowa PMT test station was built originally to test Hamamatsu R7525-HA PMTs for the CMS HF calorimeters in 2001 [11]. Throughtout the years the same test station has been altered for many needs of CMS HCAL Collaboration, including testing the multianode bases, LED calibration system, and Hadronic Endcap (HE) calorimeter upgrade studies [12, 13]. The station was augmented and altered in order to test 1800 R7600-200-M4 PMTs as they arrive in batches of 100 from the manufacturer. All the tests have been performed in light tight boxes, and any light used on the PMTs was passed through a blue filter, in accordance with the radiation damage studies suggesting to lose UV light tranmission within quartz fibers [14, 15].

A Tektronix Oscilloscope (DPO 7264 digital oscilloscope with 2.5 GHz Bandwidth and 40 Gs/s sampling rate) was used for timing measurements. Every PMT was powered by using special parallel dynode bases designed to support power eight R7600-M4 PMTs at the same time. The base also combines the 4 anode signal outputs, by this way we could test each R7600-200-M4 as direct replacement to current R7525-HA PMTs. The PMT baseboard assembly consists of 3 majors components: i) Baseboard with high voltage divider, power and safetey ground connectors, ii) PMT socket with local dynode voltage bypassing, and signal damping, and iii) adapter boards for forming different readout schemes (out of four available anodes). Baseboard common voltage divider with ratio of 1.5 – 1.5 – 1.5 – 1 – 1 – 1 – 1 – 1 – 1 – 1 – 1 (total resistance of 2.75 MΩ supports all 8 PMTs. Nominal standing current for PMT is 290 μA at 800 V, and the design of the board requires last two dynodes to have their own boost power supplies in order to provide better performance on high signal rates. During the PMT selection process each anode was tested separately for timing, gain, and dark current measurements. We did not observe any difference between 1 and 4 anode configurations for timing and gain measurements. Dark current values linearly add as one combines the anodes. Since the HF will begin with single anode output, all the data listed in this report are taken with one readout scheme of the baseboard. Gain and dark current measurements

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were performed using a Keithley-6485 picoammeter and an ExcelLINX data acquisition program in Microsoft Excel that recorded values from the picoammeter in a spreadsheet. Each PMT was logged in upon arrival and inspected visually prior to undergoing the complete tests. Any cracks, scratches, etc. were noted. The envelope was checked for HV conductive coating and opaqueness.

2.1 Timing and linearity tests

Well-defined time responses from the PMTs will be important for the smooth operation of the calorimeter. Since successive collisions at the LHC occur in every 25 ns, the resulting rise time, pulse width, and transit time combination should be less than this interval. The setup used in timing measurements has been described in detail in previous work [6, 7, 11]. The intensity of a 20 Hz, 337 nm nitrogen laser was reduced with a neutral density filter (NDF) and split via 30/70-beam splitter. The reflected light was directed to a PIN diode to provide the trigger and reference signal. The transmitted light passed through additional NDFs before hitting the PMT photocathode. A computer controlled neutral density filter wheel was used to adjust the light intensity with $10^{0.1}$ factor steps. PMT high voltage was set to 800 V, the baseboard provided the combined signal from 4 anodes.

Identical cables were used to bring the PIN diode signal and the PMT anode signal to the oscilloscope. The transmitted light traveled 70 cm extra distance compared to the reflected light. This difference was compensated with a 2.3 ns delay term in the analysis code. The transit time was measured as the time difference between the PIN diode and the PMT signals when both signals reached 50% of their peak values successively. The rise time was defined as the time interval when the PMT signal increased from 10% of the peak value to 90%. (What is mentioned here as rise time was actually the fall time since the PMT signal was negative.) Pulse width was simply recorded as the FWHM (full width at half max) of the PMT signal. For the transit time, pulse width, and rise time measurements, the oscilloscope recorded the data in the single sample mode, and the average values of the acquired 100 signals were recorded. The transit time spread (fluctuations in the transit time) was simply the standard deviation of 100 transit time values. Figure 1 shows the distributions that yield mean (RMS) values of 5.2 ns (0.26 ns) for pulse width, 2.3 ns (0.12 ns) for rise time, 5.5 ns (0.23 ns) for transit time, and 0.13 ns (0.033 ns) for the transit time spread. Measurements were performed on one PMT about 50 times to estimate the statistical uncertainty. The statistical fluctuations were; less than 0.4% for transit time, 9% for the pulse width, 8% for the rise time, and about 30% for the transit time spread. The mean transit time value of 5.5 ns is well under the HF requirement of less than 25 ns. All the PMTs had very similar transit times as the whole distribution was nearly contained within 1 ns, with the RMS value less than 0.25 ns. This will be very good for the smooth and stable operation of the calorimeter. The transit time spread RMS value was 0.033 ns which can be attributed mostly to the 30% statistical uncertainty. The rise time and pulse width distributions were very narrow with 0.12 ns and 0.26 ns RMS values, respectively.

The single pulse linearity tests were performed within 0–2000 photoelectron range by using NDF filter wheel. These tests utilized the same setup with the timing measurements. The NDFs with different factors are mounted on a wheel which is controlled by the computer. Data acquisition program sets the filter wheel to a specific position and takes data. The number of photoelectrons emitted from the photocathode is calculated by dividing the total charge accumulated at the anode by the current gain [6, 7, 11]. The PMT anode reponse vs light intensity graph deviation from

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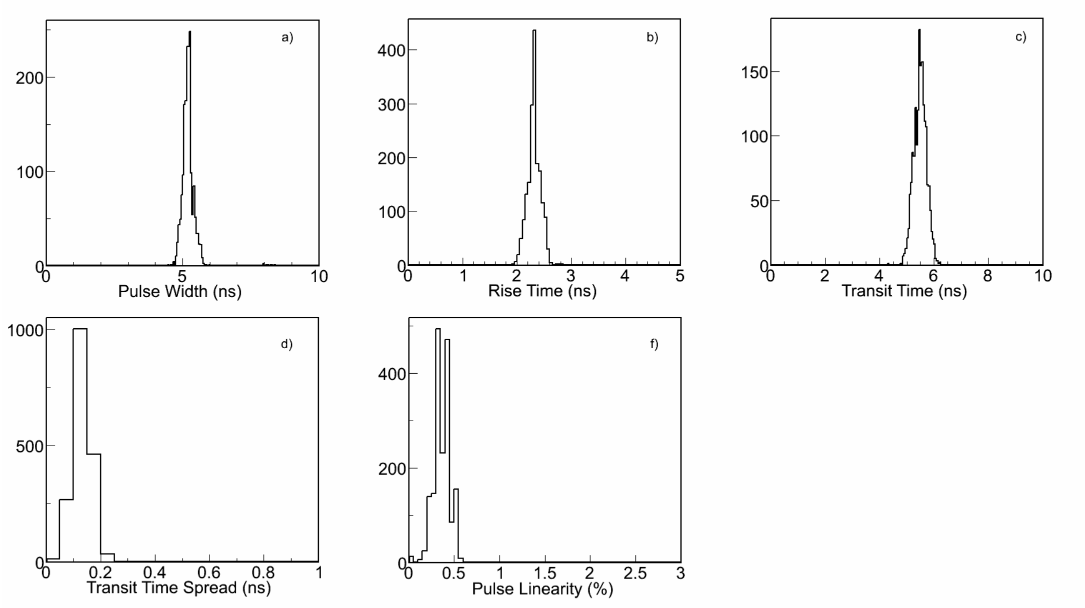

Figure 1. Pulse width, rise time, transit time, transit time spread and deviation from linearity distributions.

linearity was determined by the chi-square of the linear fit. The linearity distribution of 1800 PMTs, shown in figure 1, yields 0.36% mean value with 0.12% RMS.

2.2 Dark current and gain tests

CMS requires the HF PMTs to have less than 4 nA total (1 nA per anode) anode dark current at operation voltage. Dark currents exceeding this value would constitute a significant portion of the output current and hinder the reconstruction of the true signal.The dark current test was performed by measuring the anode current of each PMT while high voltage power was supplied and the box was kept completely dark. No data was recorded until the anode current leveled out and remained constant within few percent. When in HF, the PMTs will be given adequate time to warm up and reach a relatively constant sensitivity. The data acquisition system reads the dark currents for the PMTs using a Keithley-6485 picoammeter. The system took 20 samples for each PMT and the average of the samples was recorded as the dark current at 600 V. The high voltage was then increased to 900 V in increments of 50 V with the dark current recorded at each increment. The HV range between 600 V to 900 V gives us a good room to adjust the gain of PMTs as cathodes start to deplete in time. If there was ever a reading that seemed to be unusually high, another reading was taken after waiting for some additional time. The dark current distributions for HV values from 600 V to 900 V (shown in figure 2) show that the majority of the PMTs have dark currents below 2 nA, which is much lower than the HF requirement of 4 nA. The dark current distributions for 600 V, 650 V, 700 V, 750 V, 800 V, 850 V, and 900 V yield mean (RMS) values of 0.34 nA (0.68 nA), 0.36 nA (0.6 nA), 0.4 nA (0.57 nA), 0.48 nA (0.59 nA), 0.62 nA (0.68 nA), 0.66 nA (0.92 nA), and 1.27 nA (1.36 nA), repectively. The larger RMS values show the variations of dark current values from PMT to PMT. The bigger rise on dark current values from 850 V to 900 V should be noted, as well.

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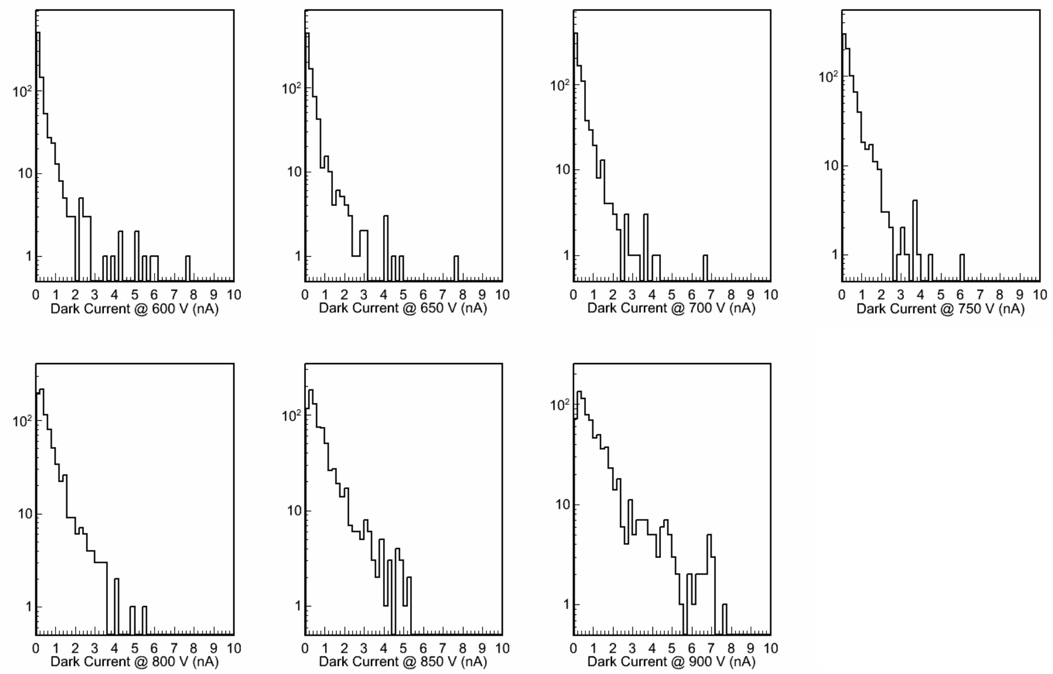

Figure 2. Dark current distributions for 600 V, 650 V, 700 V, 750 V, 800 V, 850 V, and 900 V.

The operation conditions of CMS HF calorimeter requires around 10^5 gain on PMTs. However, Hamamatsu lists R7600-M4 operation HV as 800 V which yields mean gain value of 10^6. So as to determine the gain, the anode and cathode currents of each PMT at various light intensities were recorded. A tungsten lamp was installed in the dark box at the end opposite the readout baseboard. A NDF with factor of 3, a blue filter, and a 20 degree light diffuser were placed in front of the lamp. The NDF reduced the light amplitude to a safe level for PMTs, and the diffuser distributed the light evenly over the face of each PMT. The distance between the lamp and the readout baseboard was 140 cm. The lamp was rated for 6 V but operated at 5 V to ensure a stable light intensity. The light intensity at PMT position in the base was monitored by a Newport optical power meter. The anode current for each PMT was recorded at voltages ranging from 600 V to 900 V in increments of 50 V as in the dark current procedure. The PMTs were then mounted in a baseboard that reads only the cathode current, the NDF is removed to increase the incoming light. Eveything else was kept in the same position.

The cathode currents were measured while applying appropriate voltages between the cathode and the first dynode. For each high-voltage applied to the anode-cathode circuit (from 600 V to 900 V) there is a corresponding voltage for the cathode-first dynode circuit (from 72 V to 108 V). These voltages were calculated by using the voltage divider ratio of the cathode-first dynode and the cathode anode resistor circuit. The cathode current was recorded at the different voltages in the same way as anode current. At each voltage, the anode current to cathode current ratio multiplied by the corresponding cathode light intensity to anode light intensity ratio gave the gain. The gain distributions for HV values of 600 V, 650 V, 700 V, 750 V, 80 V, 850 V, and 900 V (shown in figure 3) yield mean (RMS) values of 2.2×10^5 (1.8×10^5), 4.5×10^5 (3.6×10^5), 8.5×10^5 (5.2×10^5), 1.6×10^6 (1.3×10^6), 2.8×10^6 (2.3×10^6), 4.7×10^6 (3.7×10^6), and 7×10^6

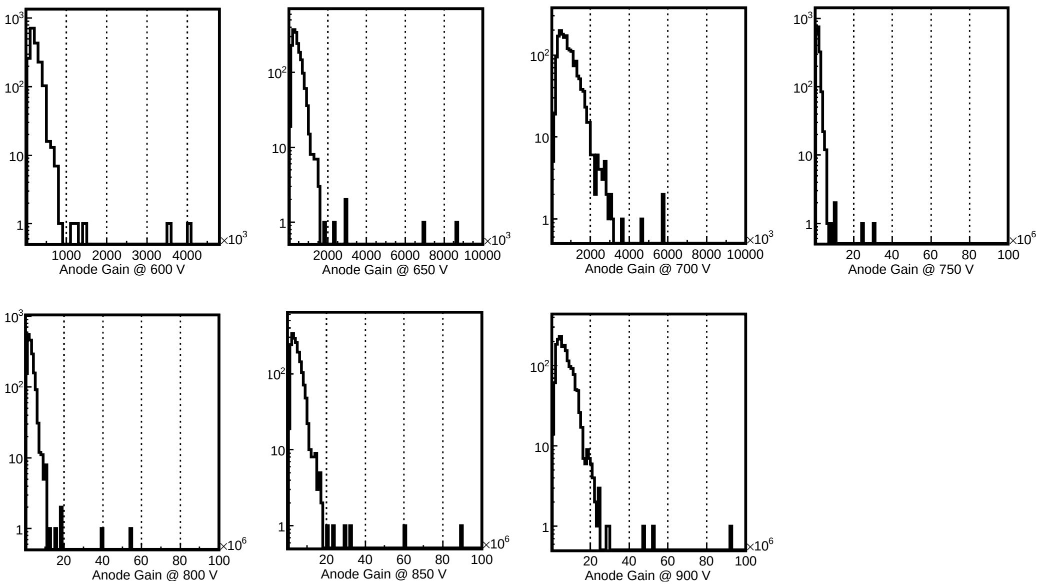

Figure 3. Gain distributions for anode HV values of 600 V, 650 V, 700 V, 750 V, 800 V, 850 V, and 900 V.

(4.7×10^6), respectively. The statistical uncertainties for dark current and relative gain were determined by re-measuring the values for the same PMTs. Uncertainty for gain and dark current values were both found to be about 10%.

3 Conclusion

The timing, linearity, dark current and gain tests results of each PMT were organized into a database easily accessible by the CMS collaboration through the CERN computing cluster. In addition to the individual distributions displayed in this report, various combinations of the measured quantities have been investigated for possible systematic correlations. Possible time-dependent systematic effects were investigated by re-testing the first 100 PMTs after finishing the tests of about 1,000. The differences were contained within the statistical fluctuations for each measurement. Among the 1800 PMTs tested for the CMS-HF Forward Calorimeter, 20 (less than 2%) were rejected, mainly for high dark current. Several were also rejected due to low gains. All the other PMTs had sufficiently low dark currents, sufficiently high gains, and highly uniform timing characteristics including sufficiently low transit times. All of the passing PMTs were sorted according to gains so that all the PMTs in an HF readout box will have relative gain deviations of only 2-3%. To provide uniform gains over similar locations in each wedge, PMTs with similar relative gains should be installed in the readout boxes corresponding to those wedges. Low gain PMTs will be used for EM (long fiber) sections and high gain PMTs for hadronic (short fiber) sections. In addition, high gain PMTs will be installed in higher pseudorapidity regions so that they can be used to readout weaker signals that are the farthest from the collision point. Furthermore, the electronics that will process the PMT signals require low-amplitude signals. Therefore, the PMTs should be operated at a low gain but still satisfy all the timing, gain, and dark current requirements. The Hamamatsu R7600-M4 PMT was chosen because its specifications meet all of these requirements. Quality control and a check of each PMT to be used in the calorimeter was the main function of these tests.

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