Study of Various Photomultiplier Tubes for Window Events: Upgrade R&D for CMS Hadron Forward Calorimeters

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Abstract. The PMTs of the CMS Hadron Forward calorimeters were found to generate a large amount of signal when their windows were traversed by energetic charged particles. This signal, which is due to Čerenkov light production at the PMT window, could interfere with the calorimeter signal and mislead the measurements. In order to find a viable solution to this problem, the response of different types of PMTs to muons traversing their windows at different orientations is measured at the H2 beam-line at CERN. Certain kinds of PMTs with thinner windows show significantly lower response to direct muon incidence. For one specific type - the four anode PMT - a simple and powerful algorithm to identify such events and recover the PMT signal using the signals of the quadrants without window hits is also presented. For the measurement of PMT responses to Čerenkov light, the Hadron Forward calorimeter signal was mimicked by two different setups in electron beams and the PMT performances were compared with each other. Superior performance of particular PMTs was observed.

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 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. There are 13 towers in \( \eta \), all with a size given by \( \Delta \eta \approx 0.175 \), except for the lowest-\( \eta \) tower with \( \Delta \eta \approx 0.1 \) and the highest-\( \eta \) tower with \( \Delta \eta \approx 0.3 \). The \( \phi \) segmentation of all towers is \( 10^\circ \), except for the highest-\( \eta \) one which has \( \Delta \phi = 20^\circ \). This leads to 900 towers and 1800 channels in the two HF modules [2]. Details of the HF design, together with test beam results and calibration methods, can be found in [3].

In the framework of the Super LHC (SLHC) upgrade plans, one of the problems to be solved is the large signal generated by the photomultiplier tubes (PMTs) of CMS HF calorimeters.
(hereon called HFPMT) when the PMT window is traversed by relativistic charged particles. The primary reason for this signal is Čerenkov light production at the PMT window, followed by the liberation of photoelectrons at the photocathode of the PMT. The expected rate is around 0.1% of the events at low luminosity conditions of LHC. This would have impact on the hadronic energy measurements of HF and missing transverse energy calculations, and could even result in fake triggers and mismeasured online luminosities.

2. Experimental Setup and Data Acquisition

Table 1 summarizes typical properties of the PMTs used in this study. Additionally, HFPMT window is 2 mm thick at the center and gets thicker towards the rim, single and four anode PMT windows are slightly less than 1 mm thick and miniPMT window is around 0.5 mm thick.

| PMT Type        | PMT Type Number | Photocathode | Quantum Efficiency (max. %) | Typical Gain | Window Area (mm²) app. |
|-----------------|-----------------|--------------|------------------------------|--------------|------------------------|
| Four Anode PMT  | R7600U-100-M4   | Super Bialkali | 35                           | 1.3 × 10⁶    | 324 (square)           |
| Four Anode PMT  | R7600U-200-M4   | Ultra Bialkali | 43                           | 1.3 × 10⁶    | 324 (square)           |
| Four Anode PMT  | R8900U-100-M4   | Super Bialkali | 35                           | 1.0 × 10⁶    | 324 (square)           |
| Single Anode PMT| R7600U-100      | Super Bialkali | 35                           | 1.0 × 10⁶    | 324 (square)           |
| Single Anode PMT| R7600U-200      | Ultra Bialkali | 43                           | 1.0 × 10⁶    | 324 (square)           |
| miniPMT         | R9880U-110      | Super Bialkali | 40                           | 2.0 × 10⁶    | 50 (round)             |
| HFPMT           | R7525           | Bialkali     | 25                           | 5.0 × 10⁵    | 490 (round)            |

Tests were performed at CERN H2 beamline [5]. Two different setups were used to test the muon response of the PMTs. In the first setup, PMTs were lined one after the other with their windows facing the beam direction. In the second setup, PMTs were placed side by side, their windows being parallel to the beam direction. Both PMT boxes were made light-tight and they were placed in front of wire chamber E (WCE) as the first test apparatus on the HF test table in order to perform precise position measurements with 1 mm resolution.

Two test stations were used to measure the differences in the response of the PMTs to Čerenkov light from electron showers: ~1 cm diameter bundle of regular HF quartz fibers (with 0.6 mm diameter) and the quartz fiber calorimeter. The fiber bundle was placed in ~3 cm diameter light guide and it splits into two parts at the readout end. The HFPMT was kept in place at one end of the fiber bundle while the candidate PMTs were interchanged at the other end. The portion of the fiber bundle that sees the beam was aligned to make ~45° with respect to the beam direction in order to maximize the Čerenkov light capture. The length of the bundle from the beam interaction to readout was ~1.5 m. WCE was used to select events with electrons that pass through the fiber bundle. The quartz fiber calorimeter consisted of an array of 6 mm diameter, 45 cm long steel rods in a 20 cm x 20 cm x 45 cm housing with quartz fibers (0.3 mm core diameter, 65 cm long) inserted in between the rods. The fibers were then bundled at the back of the calorimeter to form a single readout. The light guides at the readout end were 20 cm long with the same reflective material as HF light guide. Details of the readout can be found in [6].
3. Testing Muon Interactions with PMT Windows

Figure 1a shows the QIE charge profile as a function of wire chamber coordinates for the HFPMT. Using these profiles, a position cut with the correct dimensions at the PMT window edges was applied to study only the events where the charged particles traversed the PMT windows for all PMTs. The cut for the HFPMT window is shown in Fig. 1a. Figure 1b shows the responses of different types of PMTs when the muon beam hits the PMT window from the front. All responses are normalized to the gain of the HFPMT. Since HFPMT window is much thicker than that of the other PMTs, Čerenkov signal produced is much higher. It has a signal magnitude that is more than a factor of two compared to the single anode and four anode PMTs and a much larger spread with a long tail in the high end of the spectrum. The four anode and single anode PMTs both have ultra bialkali photocathodes and they exhibit the same behavior in the overall picture.

![Figure 1](image_url)

**Figure 1.** (a) Integrated charge profile (in fC) as a function of WCE coordinates for HFPMT. The boundary of the PMT window event selection is shown as a black ring. (b) Charge distributions of the four anode PMT (R7600U-200-M4), the single anode PMT (R7600U-200), the miniPMT and the HFPMT produced by the front beam incidence.

With the PMT window cuts applied, PMT window event rates were also measured as the ratio of the number of events above pedestal to the total number of events: HFPMT 90%, four anode PMT 69%, single anode PMT 64% and miniPMT 51%. As expected, the window event rates were found to be correlated with the thicknesses of the PMT windows.

One of the four anode PMTs was used to study the dependence of the charge distribution on the angle of incidence of the beam. The PMT was exposed to beam with its window making an angle of 90° (front incidence), 70°, 50°, 30°, 10° and 0° (side incidence) with respect to the beam direction. Beam position cuts were applied around the PMT window using WCE information for each orientation. Figure 2a shows the charge distributions for 50°, 10° and 0°. As the angle is reduced from 90°, the thickness of the PMT window that is exposed to beam increases leading to an increase in signal magnitude (Fig. 2b). The results of the angular study are consistent with the results presented in [7] for bialkali photocathodes.

4. Testing Čerenkov Response of PMTs

Figure 3a shows the charge distributions for the PMTs reading out the fiber bundle signal. The distributions were normalized to the HFPMT gain. Single anode and four anode PMT signals both have a mean ~1.5 times the HFPMT signal.
Figure 2. (a) Charge distribution of the four anode PMT (R8900U-100-M4) for different angles of muon beam incidence. (b) Mean charge at all angles studied.

Figure 3. (a) Fiber bundle charge distributions for the four anode PMT (R7600U-100-M4), the single anode PMT (R7600U-100) and the HFPMT. Gaussian fits are also shown. (b) Quartz fiber calorimeter charge distributions for four anode PMT (R7600U-200-M4), single anode PMT (R7600U-200), miniPMT and HFPMT.

Figure 3b shows the charge distributions of the four anode PMT, the single anode PMT, the miniPMT and the HFPMT when they were reading out the quartz fiber calorimeter. The distributions were normalized to the HFPMT gain. No PMT window area corrections were applied since proper light guides were utilized for each PMT window geometry.

5. Selecting PMT Window Events and Recovering the Signal with Four Anode PMT

A simple algorithm for identifying window events in the four anode PMTs has been developed with the assumption of using them in HF. Details of the algorithm is provided in [6]. Figure 4 shows the application of this PMT window event identification and signal recovery algorithm to a set of front muon incidence data. No pedestal subtraction has been applied to the data.
The algorithm successfully selects the PMT window events and recovers the signal back. The distribution is suppressed towards zero, slightly above pedestal - which is shown by the blue, crossed distribution - except for the events with muon hits around the center of the PMT window which correspond to ~2.5% of all the front-incident muon events.

**Figure 4.** PMT window event selection and signal recovery for the four anode PMT with front incidence of muons. The blue, crossed area is the pedestal.

The algorithm was also applied to the data from the HF fiber bundle. The result is shown in Fig. 5a. The algorithm misidentifies about 6% of the signal events as PMT window events and reconstructs the signal suppressing it towards lower values. The misidentification is due to the algorithm itself; however, the suppression towards lower values is due to slight alignment variations that result in uneven illumination of the quadrants or real interference from particles scattered towards the four anode PMT or cosmic muons. For some of the runs, the fiber calorimeter was rotated by 60° or 90° to allow the electron shower to leak behind, and the fiber bundle PMTs were placed in the beamline at the back of the calorimeter. Although the probability for the PMTs to get real particle hits together with the bundle signal is too low, the algorithm was tested with this setup for its effectiveness in selecting PMT window events within a real signal. The result is shown in Fig. 5b. In the low signal region of the spectrum, the signal is suppressed towards lower values as in the case of the algorithm applied to pure signal. The most important aspect of this result is that the high tail in the original distribution, which clearly comes from PMT window events, disappears after the utilization of the algorithm.

6. Conclusions

In the search for a new photomultiplier tube for the CMS forward hadron calorimeters, candidate PMTs with different specifications were tested. The response of PMTs to relativistic charged particles traversing their windows at different incidence orientations was tested with 150 GeV/c muon beam. The HF calorimeter signal was also mimicked with two test setups in 80 GeV/c electron beam in order to compare PMT performances: around 1 cm-diameter bundle of HF quartz fibers and a 20 cm x 20 cm x 45 cm steel rod calorimeter with quartz fibers placed in between and alongside the rods. The fiber bundle was split into two at one end enabling two readout channels simultaneously.

At front incidence of muons on the PMT windows, the candidate PMTs exhibit significantly better performance with their reduced response magnitude and spread, and PMT window event...
Figure 5. (a) Charge distributions before and after the algorithm for selection of PMT window events and signal recovery was applied to the four anode PMT of the HF fiber bundle. (b) The result of the application of selection and signal recovery algorithm to HF fiber bundle when the PMTs were in the beamline.

rates. Side muon incidence response is higher and has a wider spectrum when compared to front incidence response. Measurements with various angles of muon incidence also prove that the response becomes larger as the angle between the PMT window and the beam direction is decreased.

Measurements show that the candidate PMTs have superior performance over the HFPMT on detection of Čerenkov light as expected from their proposed quantum efficiencies.

For the four anode PMT, an effective and simple algorithm for selecting PMT window events and recovering the signal from the quadrants that do not show PMT window event signature is presented and implemented on muon incidence data as well as the fiber bundle data. This simple method proves to be an effective way of selecting PMT window events and recovering the signal with available information. The method can be utilized both for refining detector measurements and for the elimination of cosmic interference online or offline.

References

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