Detector Upgrade R&D of the CMS Hadronic Endcap and Forward Calorimeters

Ugur Akgun *(for the CMS Collaboration)*

***Abstract*–The CMS Hadronic Endcap (HE) and Hadronic Forward (HF) calorimeters cover the pseudorapidity range of from 1.4 to 5 on both sides of the CMS detector, contributing to superior jet and missing transverse energy resolutions. Here we discuss possible upgrade scenarios for both calorimeters. Recent studies revealed abnormally high amplitude signals due to punch through charged particles, mostly muons, producing Cherenkov photons at the HF calorimeter PMT window. Our studies show that these events can be eliminated either by using the timing properties, or replacing the HF PMTs with new generation four anode PMTs. As the integrated luminosity of the LHC increases, the scintillator tiles used in the CMS Hadronic Endcap calorimeter will lose their efficiency. This report outlines two possible radiation hard upgrade scenarios based on replacing the HE scintillators with quartz plates.**

I. 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 Hadronic Endcap (HE) and Hadronic Forward (HF) Calorimeters are positioned both sides of the CMS detector, and cover the $1.4 < \eta < 5$ region. These calorimeters are going to be the vital tool on new physics discoveries, with superior ability to reconstruct the jets and missing transverse energy, in this high pseudorapidity region [2].

The HF calorimeters collect the Cherenkov light created in quartz fibers embedded into steel absorbers. The technical details and performance of the HF detector can be found elsewhere [3]. The quartz fibers are bundled and carry light into Hamamatsu R7525-HA PMTs [4, 5, 6] via 42 cm air core light guides [7]. The PMTs, inside the readout box, are facing to the interaction point. Our previous studies showed occasional large events due to charge particles interacting with borosilicate glass PMT window [3]. The charge particles from late showering particles or punch through muons can create large Cherenkov signal at the PMT front window. In this report we discuss two possible solutions to eliminate the HF PMT events: ***i)*** Replacing the current photo-multiplier tubes with new generation tubes that have thinner and narrower glass windows. ***ii)*** Using timing properties to discriminate the PMT events.

Large Hadron Collider (LHC) is designed to provide a 14 TeV center of mass energy with p-p collisions every 25 ns. The starting peak luminosity of the accelerator is going to be 10^{33}cm^{-2}s^{-1}. This value is planned to increase each year, reaching 10^{35}cm^{-2}s^{-1} in 2023 [8, 9]. The accelerator luminosity upgrade will require CMS HE calorimeter to be modified for higher radiation conditions as well. The CMS HE calorimeter consists of 19 layers of scintillator tiles sandwiched between 70 mm brass absorbers. Light generated in these scintillators (Kuraray SCSN81) is carried to hybrid photodiodes by Kuraray Y-11 double clad wavelength shifting (WLS) fibers. Both scintillators and WLS fibers have been shown to be moderately radiation hard up to 2.5 Mrad. The simulation studies predict radiation levels up to 10 Mrad in high η towers. This value reaches up to 30 Mrad for the front towers where the Electromagnetic Endcap (EE) calorimeter does not shield the HE calorimeter [10, 11, 12]. As a solution to this radiation damage problem, we propose to substitute the scintillators with quartz plates [13, 14, 15]. In previous papers, we reported results from radiation hardness tests on various types of quartz material in the form of fiber. Results show that quartz can withstand the radiation doses of up to 1.25 Grad [16, 17]. Here we summarize the studies performed on two scenarios based on quartz plates: ***i)*** Covering the quartz plates with radiation hard scintillators and reading the signal from the plate. ***ii)*** Using UV absorbing WLS fibers to carry the signal to readout box.

II. ELIMINATION OF ABNORMAL EVENTS AT HF CALORIMETER

A. Beam Tests on Candidate Replacement PMTs

The PMT events of the HF calorimeter have big size mainly due to the thick front glass of current HF PMTs (Hamamatsu R7525-HA). The front glass thickness of HF PMTs is 0.2 mm at center and reaches to 6 mm at the edges. Replacing them with new generation high quantum efficiency PMTs with thinner PMT window (less than 0.1 mm) can help to solve this problem. For this purpose we performed beam tests to compare the performances of various candidate PMTs with the HF PMT [18]. The properties of the PMTs are listed in Table I.

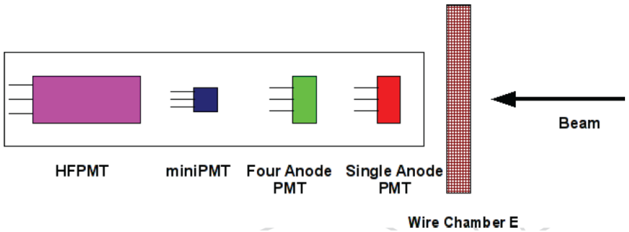

Fig. 1. The setup to test the muon interaction at PMT front windows.

U. Akgun is with the Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242 USA (telephone: 319-335 3574 email: ugur-akgun@uiowa.edu).

TABLE I. THE PROPERTIES OF THE CANDIDATE REPLACEMENT PMTS FOR CMS HADRONIC FORWARD CALORIMETER

PMT Type	Max Quan. Eff.	Window Area, Shape
R7600U-100	35%	324 mm^2, square
R7600U-200	43%	324 mm^2, square
R7600U-100-M4*	35%	324 mm^2, square
R7600U-200-M4*	43%	324 mm^2, square
R8900U-100-M4*	35%	324 mm^2, square
R9880U-110	40%	50 mm^2, round
R7525-HA	25%	490 mm^2, round

*) Four Anode PMTs

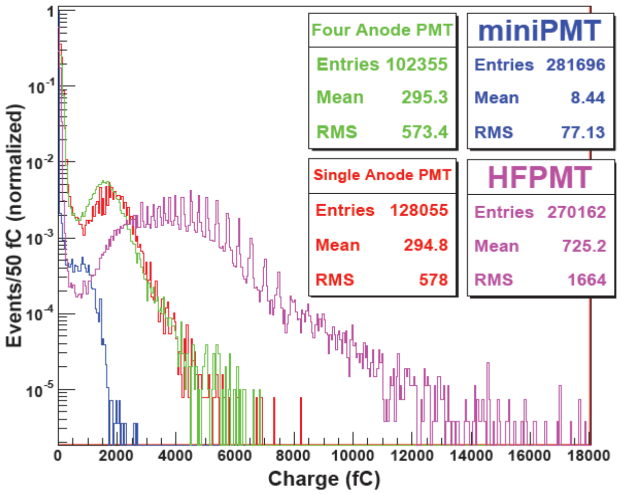

Fig. 2. The response of the PMTs to muon signal generated at the front window.

The PMTs were tested with 150 GeV muon beam and 80 GeV electron beam of CERN in H2 beam test area. In order to test the muon response, the PMTs were lined along the beam line in a dark box (see Fig. 1). Figure 2 shows that the muon beam creates less signal on the "thinner" front window of the candidate PMTs.

Two test stations were used to measure the differences in the response of the PMTs to Cherenkov light from electron showers (see Fig. 3). During electron shower tests, a 5 cm steel absorber is positioned upstream in order to create electromagnetic shower and produce Cherenkov light inside the fiber bundle, which has two PMTs attached to the end. The 1 cm diameter bundle of regular HF quartz fibers (with 0.6 mm diameter) was split into two parts with 26 mm regular HF light guides at the end. The HF PMT was kept at one end of the fiber bundle while the candidate PMTs were interchanged at the other end. The possible signal difference between the two ends due to fiber mixing was also measured.

The second test station for the electron showers was the quartz fiber calorimeter (see Fig. 3). It 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.

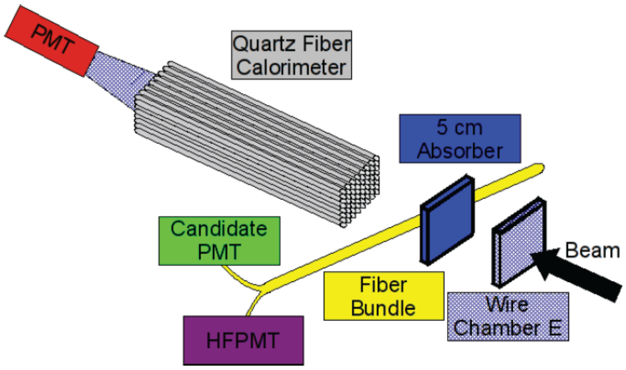

Fig. 3. The setup to test the Cherenkov light collection efficiency of the PMTs.

Fig. 4 shows the charge distributions for the PMTs reading out the fiber bundle signal. The distributions were normalized to the HF PMT gain. Single anode and four anode PMT signals both have a mean ~ 1.5 times the HF PMT signal. The single anode PMT is of type R7600U-100 and the 4-anode PMT is of type R7600U-100-M4 both with new generation super bialkali photocathode. The 4-anode PMTs also provide a unique opportunity to develop a simple algorithm to discriminate the muon events, which can create a signal on only one anode [18].

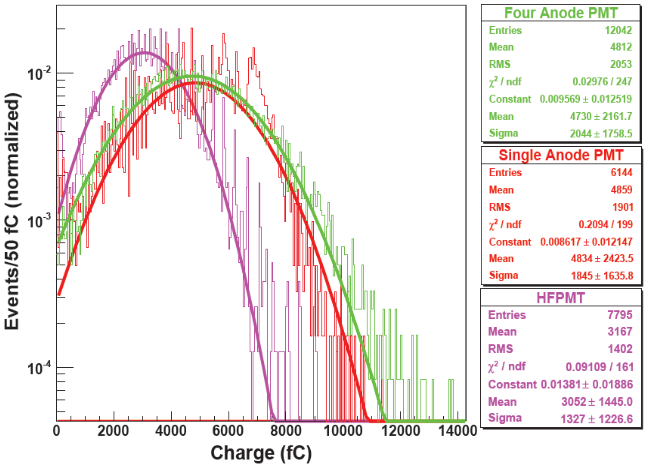

Fig. 4. Fiber bundle charge distributions for the four anode PMT (R7600U-100-M4), the single anode PMT (R7600U-100) and the HFPMT.

B. *Investigating the Timing Properties of the PMT Events*

The pulse width of the signal due to muon interactions at the front window of Hamamatsu R7525-HA PMT have been investigated first with cosmic muons in University of Iowa CMS laboratories. We confirmed these preliminary results with 150 GeV muon beam at Cern H2 area. The Hamamatsu R7525-HA PMT was put into a light tight box and positioned facing the muon beam (see Fig. 1) and each trigger was recorded by a digital oscilloscope. We recorded over 700 events from the interacting muons.

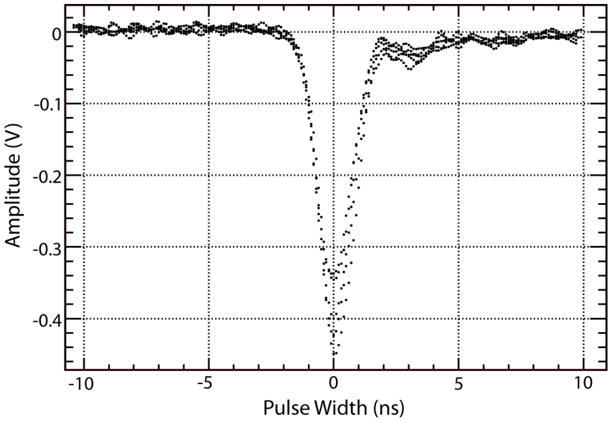

Fig. 5. Overlapped scope views of five events created by muons interacting on the window of PMT.

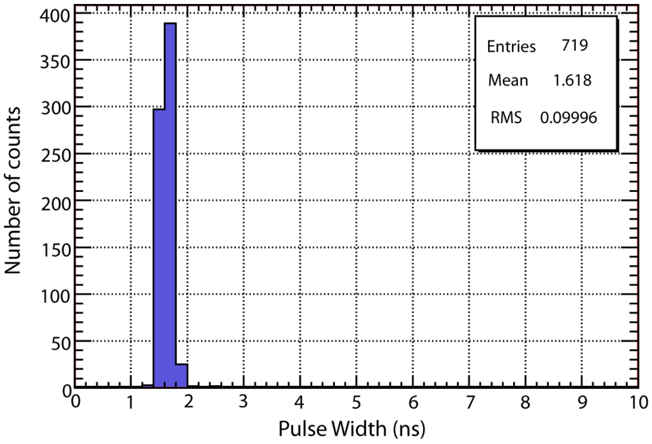

Fig. 6. Measured pulse width distribution of over 700 events from muons interacting with the front window of HF PMTs

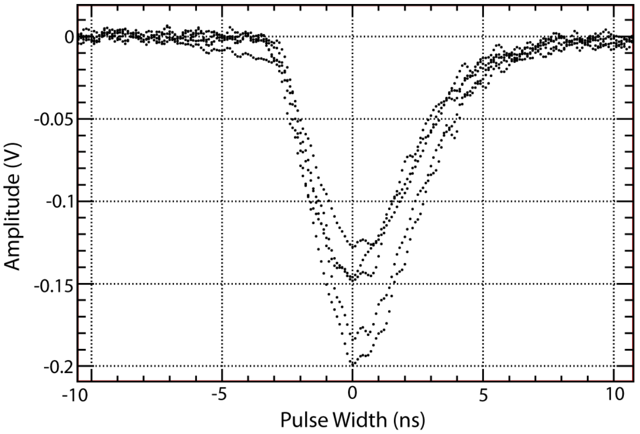

Fig. 7. Overlapped scope views of five Cherenkov signals created at the quartz fibers.

Figure 5 demonstrates the characteristic pulse shape of the PMT events by overlapping the scope view of five of them. Although the amplitudes of the events vary, the width and shape of the pulses are almost identical. Figure 6 gives the pulse width distribution of over 700 PMT events, the mean value is 1.6 ns with all of the events having narrower than 2 ns pulse width.

To mimic the regular Cherenkov light from HF calorimeter, we used 80 GeV electron beam, and 2 m long quartz fiber bundle with 1 cm diameter (see Fig. 3). The setup is designed to have 80 GeV electron beam hitting to 5 cm iron absorber to create electromagnetic shower. To demonstrate the characteristic of the pulse shape, the overlapped scope views of five events are given in Figure 7. Unlike the PMT events, a typical Cherenkov signal from quartz fibers is asymmetrical with sharper leading edge and a tail on rise time. To have high statistics, we have recorded over 4600 Cherenkov events from fiber bundle. Figure 8 shows the pulse width distribution of these events which yield mean value of 4.5 ns. with no event having less than 3.8 ns pulse width.

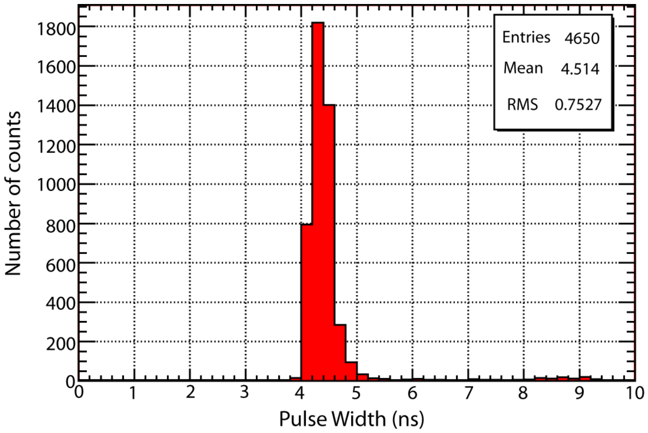

Fig. 8. Measured pulse width distribution of over 4600 Cherenkov signals created at the quartz fibers.

III. UPGRADING THE HE CALORIMETER WITH QUARTZ PLATES

The quartz plates can solve the radiation damage problem of the plastic scintillators. But we need to collect the Cerenkov light and carry the photons out of the calorimeter, effectively. For this purpose, we developed two options and built calorimeter prototypes for each.

A. Readout from the Quartz Plates

To improve the light production inside the quartz plates, we covered the surface with 2 μm thick radiation hard p-terphenyl (pTp) scintillator. The light readout was performed from the edge of each plate with Hamamatsu R7525-HA PMTs. By this way we have increased the light yield for minimum ionizing particles by at least a factor of four compared to plain quartz plates. In light of the preliminary studies, we have built a 20 layer quartz plate calorimeter prototype with 7 cm iron absorbers between each layer. Since the CMS HE calorimeter has 19 layers of 7 cm brass absorbers, our prototype model is a very good representation of the small solid angle of the upgraded HE calorimeter. The prototype was tested at the CERN H2 test area

Figure 9 shows the detector linearity for the test of the prototype with various pion beam energies. Both beam test and Geant4 [20, 21] simulation results yield around 1% hadronic response linearity. Figure 10 shows the energy resolution of the hadronic calorimeter together with the prediction of the simulations. Both data and simulation results are fitted to the non-compensated energy resolution parameterized as;

$$\frac{\sigma(E)}{E} = \frac{210.3\%}{\sqrt{E}} \oplus 9.0\% \qquad (1)$$

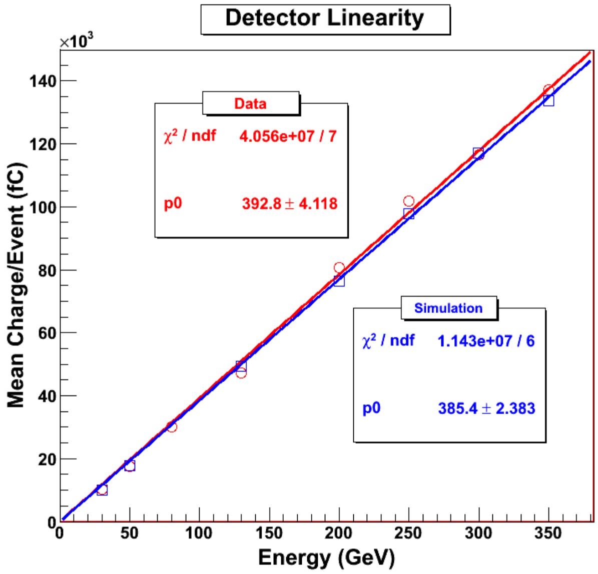

Fig. 9. Detector linearity for the hadronic calorimeter prototype. Solid lines are fits to a first order linear dependence.

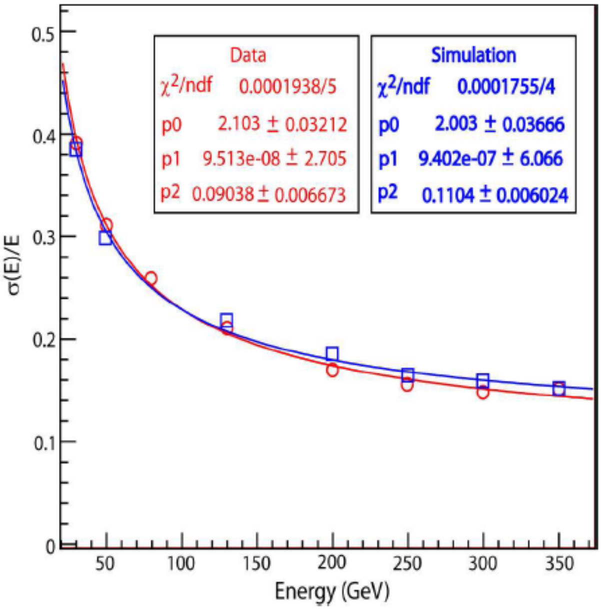

Fig. 10. Hadronic energy resolution for the calorimeter prototype.

B. Using UV Absorbing Wavelength Shifting Fibers

Based on our Cerenkov light collection optimization studies using the UV absorbing WLS fibers [13], we built a 20 layer quartz plate calorimeter prototype. Since the Cerenkov radiation produces a spectrum that is inversely proportional to square of wavelength these UV absorbing WLS fibers improve the light collection substantially. The prototype was tested at Cern H2 area, and the measured hadronic resolution of the calorimeter is shown in Figure 11.

This model's success depends on a radiation hard WLS fiber, which does not exist commercially. Our new study focuses on developing radiation hard WLS fibers by using quartz and pTp. We built and tested a prototype using quartz fiber cores covered with pTp (see Figure 12). We got promising results with this unit, and working on possible improvements.

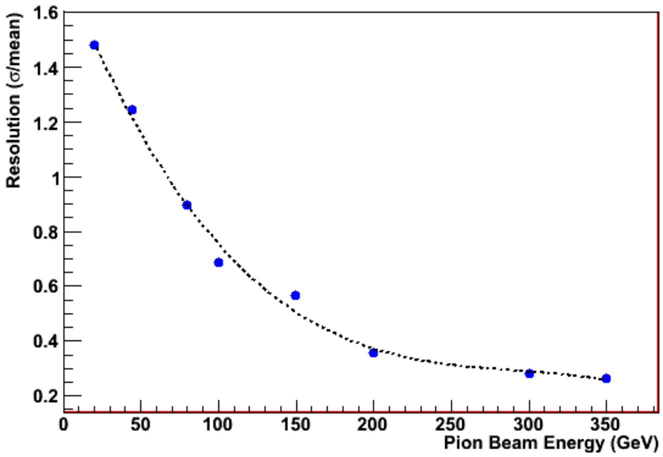

Fig. 11. Hadronic energy resolution for the calorimeter prototype with WLS fibers.

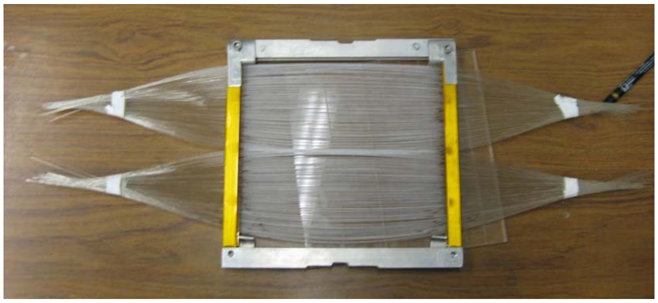

Fig. 12. The ribbon built with radiation hard WLS fiber prototype.

IV. CONCLUSION & DISCUSSION

The LHC is going to start running in November 2010, and the CMS experiment is ready to take data. However we are still working on short and long term detector improvement studies. Here, we discussed two possible solutions for PMT events observed in CMS HF calorimeters. Our beam test results show that replacing the current Hamamatsu R7525 PMTs with 4 anode high quantum efficiency PMTs, like R7600U-200-M4, would solve the problem. The thin glass and 4 anode signal capability would minimize the signal size and give us opportunity to discriminate the PMT events immediately. The higher quantum efficiency of these PMTs also improves the energy measurement capability of the HF calorimeter and helps on new physics discovery.

On the other hand, the timing properties of the HF PMT events are very distinct that a simple additional circuit on HF calorimeter would also help to discriminate these events. Our tests show that the pulse width of the PMT events is less than 2 ns, and the pulse shape is symmetric. However, the Cherenkov light collected at the HF quartz fibers has an asymmetric pulse shape with 4-5 ns width.

The LHC luminosity is planned to increase in coming years. The resulting radiation damage problems will require upgrades on many detectors in LHC experiments. CMS HE calorimeter is one of them. Here we propose to replace the existing scintillators with quartz plates. We developed two separate models, based on quartz plates. The first model uses pTp to improve the light collection on quartz, and reads signal form the edge of the plate. On our tests we used regular pmts, but at HE calorimeter we are proposing to use micro channel pmts due to their radiation hardness and magnetic field independence.

The second model uses UV absorbing WLS fibers to improve the light collection. Since we carry the signal away from high radiation and magnetic field areas, the existing HE readout can be used with this model. But the success of the second scenario depends on developing radiation hard WLS fiber, which we started to work. The prototype, with quartz fibers and pTp, yielded very promising results.

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