***Final Technical Report – CMS FAST OPTICAL CALORIMETRY
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Fairfield University

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Abstract/Summary:

This is the final report of CMS FAST OPTICAL CALORIMETRY, a grant to Fairfield University for development, construction, installation and operation of the forward calorimeter on CMS, and for upgrades of the Forward and Endcap calorimeters for higher luminosity, performance, and radiation damage amelioration.

Task A: HF in CMS

CMS Operation: During 2009-10 the HF calorimeter arms made fully operational in CMS, and in early 2010, operations commenced at up to 3.5 TeV beams (7 TeV). Below are figures show jet activity in the HF at 2.36 TeV and 7 TeV during this period.

(Left) *The HF was the first detector to see 7 TeV collisions!* The scatter plot of the observed energy in the HF- arm vs HF+ arm (Right) Reconstructed HCAL MET compared with MC for 7 TeV.

In 2009 we also had good results in advance of beam during the CRAFT (Cosmic Rays At Full Field) Run in 2009:

Figure 3: Ratio of Calibration Fibers (Field On) to (Field Off).

Figure 4: Cosmic Ray Event with energy in HF, triggered by CMS trigger processing. Magnetic Field Operation Conclusions:

- Fringe field at HF RO Boxes up to ~ 100 Gauss
- Stability of $\text{LED}(B)/\text{LED}(0) (\approx 1) \rightarrow$ PMT shielding GOOD
- Stability of $\text{RADDAM}(B)/\text{RADDAM}(0)$ test fibers GOOD

Cosmic (and a few beam-induced) triggers were taken in 2009 using CMS, demonstrating the full readout chain. An HF display is shown of a cosmic event, one part of which shows the difficulties in HF as described below.

Large Energy Events in HF: Problem and Solution: In 2008-9, we (re-)identified a serious flaw in the apparatus from muons or mips travelling through the glass of the HF readout PMT, which cause large spurious energy, and we have developed and are testing a modest upgrade to correct this problem, which has now been approved by CMS. Although HF detectors are shielded hermetically (~ 40 cm of concrete, and 5 cm of polyethylene), a fraction of the muons produced by the pp collisions or by the cosmic rays in the atmosphere are likely to reach to the readout region and register signal in the form of very high energy events (referred as PMT events). The PMT events occur when a muon interacts with the PMT window glass, resulting in large number of Cherenkov photons. The PMT events can also be produced (see Figure 5,6) by charged particles

from late showering hadrons in HF that can also produce Cherenkov light in the PMT glass window effect at a rate of when the pion impacts the HF at the readout box region. These events can be tagged and rejected off-line analysis with, on average, $\sim 80\%$ efficiency (which may be too low for sensitive searches for new particles). The efficiency depends on the particle. The PMT events may cause some problems in trigger rates by producing fake missing transverse energy. Also, luminosity monitoring and minimum bias event triggering are affected by PMT events. The real impact on physics is being investigated by using detailed Monte Carlo simulation based on GEANT4 and CMS Simulation Software (CMSSW).

Figure 6: Examples of PMT background events. (Left) Apparent HF Energy (color – red highest) versus x-y position for test beam muons incident on the calorimeter. The position of the PMT is clearly seen as a red circular area of high light (p.e.) deposition in the PMT, along with some noise generated in the fibers (green). (Right) Muon Response (GeV) when aimed towards the location of the PMT. The enhancement at ~ 130 GeV is due to PMT direct excitation (Cerenkov in PMT glass window and body) instead of true energy deposit in the calorimeter fibers as shown below. Not apparent is the high tail to the right which extends up to a few TeV, unacceptable for operations

Fig. Sources of punchthrough noise in the HF PMT.

(Left) Histogram of energy in HF with 300 GeV pions incident. The large energy deposits are consistent with punch-through into the PMT, as in the red circle in the figure above from the muon beam. Troublesome are the events which correspond to fake events above 1 TeV (Right) Energy in short fibers versus long fibers for 300 GeV pions. Shower leakage causing excitation in the PMT is seen in the uncorrelated tails. Although one can make cuts by comparing the energy in the long fibers (a full hadron+em calorimeters) vs short fibers (like an hadron only section) to help eliminate this problem, this is an imperfect process and we propose hardware solutions.

A correction algorithm was found using the long (L) and short (S) fibers to reject the events, the basic cuts of which can be imagined from the above figures above. The outline of the algorithm is shown in the Figures below:

- Polynomial energy threshold (PET) algorithm is based on the following two variables:
 - $R = (L - S) / (L + S)$ where L and S are the RecHits energies of the long and short fibers in a given HF tower, respectively
 - $E > E_{\text{Threshold}}(i\eta)$ where $E_{\text{Threshold}}(i\eta)$ is a polynomial in $i\eta$ optimized using 900 GeV collision data (more on the next slide)

PET Algorithm Performance:

PET algorithm and $R < -0.98$ cuts are reasonably safe for the short fiber reconstructed events. This is expected from the physics point of view – it is unlikely that a hadron will deposit all its energy only in the short fibers (i.e. the hadron compartment). The amount of the real energy flagged as fake by the PET algorithm in the short fibers is very small. We show MC for QCD, minbias and photon events, the spike near -1-0.98 being cut.

The histogram of the R variable for the Short Fibers on QCD, minbias and Photon MC events.

The PET algorithm flags some real energy as fake in the long fibers. This is expected based on the HF geometry, especially for direct photons and electrons, but also for jets that fluctuate mainly into electrons. The impact on physics, however, still has to be fully evaluated and is part of our ongoing studies. T

The histogram of the R variable for the Long Fibers on QCD, minbias and Photon MC events.

Rate of PMT hits was extrapolated to 7 TeV based on HF energy

The filter will reject most of PMT hits in high ET region and it will reject only small fraction of real signals at low ET
Final filter choice and optimization will be done with real 7 TeV collisions

Both ECAL and HF cleaning applied on the fly following the latest recipe from DPG.

Energy Dependence of hits: Number of identified PMT hits per event

900 GeV Collisions	$(5.8 \pm 0.2) \times 10^{-3}$
2360 GeV Collisions	$(7.4 \pm 0.8) \times 10^{-3}$
7 TeV Collisions	$(13.2 \pm 0.3) \times 10^{-3}$

The anomalous PMT hits are energy dependent, and exceed 1% at 7 TeV and are expected to exceed 2% at 14 TeV

While this algorithm has been used to clean the existing data, it is dangerous to rely on this alone to reject fake events. An energetic QCD or minbias event that deposits much of its energy in the long fibers and also has a background pulse in the short fiber PMT of that tower will reconstruct as a very high energy jet. As one can see, these are not out of

the realm of possibility. The number of such events grows with energy as shown by the events flagged using this algorithm in existing data.

We have therefore embarked on a search for a hardware solution to back-stop the L/S algorithms to reduce the potential for false MET (missing ET) and especially tagging jets.

2008-9 Proposed HF PMT System Upgrade to Correct mip-PMT Background +

Improve σ_E/E : The Fairfield Group first proposed in 2008-9, as an HF upgrade, to replace the present R7525 in HF with ~ 1800 quad-anode metal envelope PMT with 45% peak QE photo-cathodes, and windows thinner than 1 mm. We asserted the following logic:

- Two or more photosensors (preferably PMT's, at the time of this writing, but SiPMT's are

also a possibility if they are sufficiently rad-hard.) view each light guide.

- The photosensors should have a QE of 45% peak or more

- They should also have a thin glass window, less than 1 mm thick, and walls that cannot generate Cerenkov light (for PMT, a metal envelope).

The properties of the new photocathode is compared with existing HF PMT below.

Left: QE of recent photocathodes from Hamamatsu. **Right:** The QE of the HF PMT R7525 now in use peaks at 23% at 410 nm, whereas the UBA is 44%. The HF PMT has QE~20% at 350 nm, where the UBA is x2 more (42%). **Using this new photocathode we would expect 1.8-2x more p.e. per GeV.** We indeed see a factor of 2 or more in performance as described below.

Reduction in PMT-induced Background: The ultrathin window and metal envelop immediately reduce background compared to the exiting HF PMT. In the square quad anode PMT, the four anodes will be brought out as 2 channels, and the 2 “kitty-corner”/chess-board square anodes would be ganged together, forming 2 separate “bow-tie”-shaped phototube channels (future higher segmentation possible), each viewing half of the same fully mixed light (the crosstalk can be minimal; adiabatically adapting the round light guide to the square PMT is not a serious issue). When this PMT (or a pair of

single channel PMT) views the fully mixed light from an air light guide, a muon traversing it will light up only 1 anode. When one signal is significantly larger than the other (example: when the % difference between the 2 anode signals is greater than $\sim 6/\sqrt{N_{pe}}$), as could be the case with a mip in one of the 4 cathode window sections, then we would use the lower PH channel to calculate the energy in that tower.

Energy Resolution Improvement: The electromagnetic energy resolution is almost entirely dominated by photoelectron statistics, parameterized as $a=198\%$ and $b=9\%$ for stochastic and constant terms, resp. The asymptotic hadronic energy resolution is largely determined by the fluctuations in the neutral pion content of the showers, but we emphasize that at lower energies, photoelectron statistics also contribute. When parameterized as $a = 280\%$ and $b = 11\%$, we would anticipate the stochastic terms to reduce to $\sim 145\%$, and $\sim 205\%$ respectively, with new high-QE PMT. The properties of this new photocathode are shown above. Moreover, our marginal muon response would improve from ~ 1 p.e./muon (a mip is about 4 GeV in an 8.3 lambda HF) to close to 2 p.e./muon – considering Poisson statistics, this is a non trivial improvement in the energy scale/calibration point, and would increase the efficiency to above 80%. Any added ability to remove vertical muons caused by inelastic muon interactions in 1 or 2 towers (and which produce a string of low energy deposits in a stack of towers), would be helpful, as these produce rare spurious high-energy events.

There are many variants of this theme of:

- Thin Glass/Metal Envelope for background signal size and rate reduction +
- Dual PMT for background elimination and correction +
- High QE for resolution

We have proposed a very simple upgrade, as a start. This upgrade is a matter of modifying the PMT boxes and HV, and providing an adaptor to the air light guides – in HF, all these are accessible by design, without taking the detector radically apart.

The proposed PMT below were acquired and tested in 2008-9;

Figure 8: (Left) Photograph of the Hamamatsu 16-Anode version of the Quad-Anode PMT as in the drawings (Center), with area similar to existing HF PMT, as a proposed replacement of the R7525 (right). Note the metal envelope, which eliminates Cerenkov light in the walls. The window is 0.6 mm thick. (Right) The R7525 in CMS HFCal. The window thickness grows to $\sim 6-7$ mm on the edge from ~ 1 mm in the center.

Test Beam setups to test a variety of PMT background solutions. (Top) CERN summer 2008 test beam setup, used both for PMT background investigations and HE SLHC upgrades. Various tests were performed with electron, pion, and muon beam at 30, 50, 80, 150, 225, 300 GeV. Note that the absorber thickness was 165cm as in real HF geometry. Bottom: Test Beam Setup in April, 2009 at FNAL, testing both HF PMT upgrades and HE upgrades for SLHC. 120 GeV proton beam for 5 days, 32 GeV muons for one day.

The HF upgrade project tested PMT properties. The QE peaks at ~ 380 nm with 35-45% within the range of 300-650 nm. The metal envelope and thin window (less than 1 mm) eliminates the production of Cerenkov light in the walls. The figures below show the results of tests showing that indeed the induced background is reduced with the new PMT compared to the present HF tube as shown below. The tubes were tested in a variety of configurations and incident radiation angles as shown below.

Different thickness, different window response!

- ⦿ Four anode and single anode gives very similar signal
- ⦿ HF PMT gives highest signal ($> 2 \times$ Four Anode)
- ⦿ Mini-PMT has the smallest signal.

Figure 12: Reduction of the size of Background Pulses: Muon induced backgrounds in the present HF PMT (purple) compared to the proposed HF upgrade PMTs (green). *Note the large reduction in background of the new PMT – the peak is about half, which, because of the doubled QE on the fiber Cerenkov light, corresponds to a reduction of the peak energy from 130 GeV of muons transiting the existing PMT to ~25-30 GeV equivalent of the new tube.*

Response of Proposed High QE PMT (green) to quartz fiber calorimeter Cerenkov light generated by 100 GeV electrons. The proposed high QE PMT with 4 anodes has x2.2 more response than the HF PMT. This corresponds to an e-m energy resolution improvement by a x1.5!.

Comparing the 4 photocathodes viewing the same calorimeter channel indeed enabled the near complete elimination of background pulses, a process as shown in the cartoon below.

Tagging/Recovery of PMT Events

When PMT sees light from the fibers all anodes shares the light roughly.

When PMT sees a muon, only 1 anode produce signal.

$$\max(\text{dev}_i) = |S_i - \frac{1}{4} \sum_{j=1}^4 S_j|$$

Can reject event, even recover signal.

(Left) After applying the algorithm of the above figure, 98% of events are removed, 2.5% are lost. (Right) Particularly dramatic is the reduction of very high energy events – events above ~19,000 fC are equivalent to >1 TeV

Not only can the background events be rejected, but the real energy can be recovered simply by eliminating the hit quadrant and increasing the remaining sum of 3 by a factor 4/3:

Effect of Recovery Algorithm on Real Fiber Cerenkov Light Signals

PMT is not in beam line

PMT is in beam line

The quad anode PMT in muon test beam through a fiber bundle - left: the muons do not traverse the PMT and the algorithm has at most a few percent effect on the resulting Cerenkov signal– right: the muons pass through the PMT. The recovery algorithm preserves real signals within a few percent.

The April 2009 FNAL and summer 2009 CERN test beam results for the new PMT prototypes for HF are summarized as the following:

- Metal envelop thin window PMT with quad cathode/anodes (R9880U series PMT and R7600U series PMT) indeed have lower PMT event rates and lower induced signals than the all glass tube used presently in HF R7525-HA by factors of 5-10, and a p.e yield/GeV ~2x that of the present PMT. This is a huge success for Fairfield, which first proposed this in 2008.

- Metal envelop thin window PMT with quad cathode/anodes (R9880U series PMT and R7600U series PMT) can be used to reject background events.

- Metal envelop thin window PMT with quad cathode/anodes (R9880U series PMT and R7600U series PMT) can be used to recover the true calorimeter energy despite a muon or punchthrough on one of the 4 photocathodes.

Summary:

We proposed the following upgrades to HF for LHC:

- (i) Implementation of thin window, high QE, metal envelop, dual channel PMT system on each tower, preserving sub 2ns rise time and sub-12 ns transit time.

- (ii) Implementation of PMT last dynode circuit for timing studies using commercial waveform digitizers and including a CF or other type of fast timing discriminator with a multi-hit TDC.

- (iii) If our test beam analysis shows that the quartz plate veto is effective for tagging PMT events we can implement this behind PMT box, preferably to two wedges.

- (iv) Continuing CMSSW simulation studies of the above proposals and effects of the PMT effect on CMS physics signals from the HF Cal.

Implementing the dual PMT system could begin nearly immediately with existing or trivially modified multichannel PMT (at least from Hamamatsu). It would likely require:

- small HV changes;
- relatively easy optical matching element,
- modified or new PMT boxes with dynode taps and double outputs, and
- double the readout electronics (as the easiest manpower and time route).

Conclusions from other HF work 2008-2010:

- QP fibers will be fine for LHC (up to 1 Grad)
- For SLHC (10^{35}) all QP fibers should be replaced with QQ
- With recovery during shutdowns QQ fiber will work for SLHC.
- HF PMTs will not have any radiation problem during LHC due to neutrons.
- Replacing HF PMTs with smaller/high Q.E. PMTs will reduce muon interactions.
- We outlined a plan to replace HF PMTs in 2 years.
- PMTs have “half gain lifetime” of 3000 C.
- Starting from lower HV values will help to compensate fiber and PMT signal degradation with HV increase.

Report Task B: SLHC HE:

We have proposed replacing the damageable plastic scintillator plates of HE with quartz plates and quartz plates coated thin-film scintillator/WLS, in order to operate HE at SLHC radiation levels. During 2008-10, Fairfield with U. Iowa and U. Mississippi made major progress for the SLHC upgrade of endcap calorimeter HE in showing:

a) Quartz Cerenkov Plates: that Cerenkov light could be efficiently and sufficiently collected from grooved quartz plates using WLS fibers, in 2 test beam runs at Fermilab (Nov 08, April 09), and one at summer CERN 2008. We finished this first phase of the R&D proposed in our grant. The results have shown that it is possible to use quartz plates

to replace the plastic scintillator in HE. One example of the reconfigurable calorimeter is shown below; absorber plates are steel or PB, depending on the test. The QPCAL-I prototype showed very good potential as a Hadronic, and Electromagnetic calorimeter.

Figure 13: Reconfigurable plate calorimeter to test SLHC endcap calorimeter upgrade technologies, as used in the test beams at FNAL and CERN 2007, 2008, 2009 as part of this grant.

As discovered 2008-10, pTP (pTerphenyl) and ZnO:Ga(3%) thin films were shown to have an increase in light yield. In the summer 2008 CERN (H2) test beam, the calorimeter prototype consisted of:

- 20 layer quartz plates 20cm x 20cm x 5 mm coated with pTP
- Direct Readout via the HF PMT Hamamatsu R7523-HA from one edge.
- Hadronic configuration 7 cm iron absorbers
- EM configuration 2 cm iron absorbers

The results are summarized by the following Figures:

Pion Resolution and Linearity and Electron Resolution vs E

300 GeV pion 100 GeV Electron 225 Muons

Figures 14: Signals in QPCAL-II - Results of test beams of quartz plate with WLS fiber readouts for a rad-hard replacement of the HE endcap calorimeter plates for the SLHC upgrade.

We have thus shown a feasible scheme to upgrade the HE calorimeter for rad-hard and fast operation at the SLHC, pending the results of improving the readout and some of the light output.

b) Progress on Scintillation Film Coated Quartz Plates: A suggestion by Fairfield to use ZnO(Ga), a very high speed scintillator (0.7 ns decay) with high light output (near NaI) and radiation hard (used as a phosphor), and also pTP (p-terphenyl) as a scintillator (it also WLS) could indeed be coated onto quartz plates and read out using WLS fibers has proved very successful. Below we show the first ZnO coated plates made by Fairfield (PVD - e-beam evaporation), and also the plates made in Lab 7 at FNAL, where we were able to obtain Ga doped PVD sputtering targets (ZnO:Ga 3%-4% ~0.6-0.7 ns decay constant, ~40,000 photons per MeV per ns). With the FNAL RF-sputtering, we covered quartz plates with ZnO (3%-4% Ga doped) 0.3 micron and 1.5 micron. We are currently working on 100 micron thick quartz plates, depositing ZnO films on each layer and bundle the plates together, for a radiation hard scintillating plate of 2-3 mm thickness with a large light output. We also investigated other possibilities of MOCVD using a metal-organic Zn precursor to make thin films on quartz plates, but did not do so successfully. At Fermilab Lab7, we covered quartz plates with PTP by thermal evaporation. We deposited 1.5, 2, 2.5, and 3 micron thickness of PTP.

Figures 15: ZnO plate (undoped – e-beam evaporation) produced by Fairfield (left) and assembly with WLS(wavelength shifting) readout fibers at test beams 2008-2009.

Figure 16 (L): ZnO(Ga) film coated quartz plate made for Fairfield/Iowa at FNAL Lab 7 shown in Fairfield readout package. **(M):** Fairfield packaged ZnO(Ga) film scintillator plate for tests at CERN **(R)** Quartz plate calorimeter with ZnO(Ga) coated quartz plate in front at CERN test beam

Figure 19: Quartz plate calorimeter QPCAL-2 (pTP film quartz plates) with a ZnO(Ga) coated quartz plate in front at CERN test beam. *The PI is shown on the extreme right adjusting the boxes with prototype scintillator films on quartz plates and prototype PMT.*

Figure 20: ADC spectra at CERN Test beam of HE SLHC scintillator plate upgrade technologies. Note the remarkable x4 improvement in light yield with the thin film coatings.

Figure 21: ADC spectra at CERN Test beam of HE SLHC scintillator plate upgrade technologies. Note that the thin film of ZnO is only 0.3 micron thick; a trebling of the thickness to 1 micron may give a light yield x10 over the bare quartz.

The ZnO is known to be very radhard, as it is used as a TV phosphor. We are currently manufacturing a stack of several 0.3-0.6 micron ZnO(Ga) coated 100 micron thick quartz plates in lab 7, to replace the single 3 mm plates. This should allow us to obtain at least a factor of 12-16 in light output, a considerable breakthrough for this application, and many others.

As shown above, we have constructed and tested the QPCAL-II, with PTP deposited quartz layers. The 20cmx20cmx5mm, GE-124 quartz plates are used. 2 μm PTP is evaporated on every quartz plate at Fermilab Lab 7. The readout has been performed with Hamamatsu R7525 PMTs. For hadronic configuration 7cm iron absorbers used between layers. No WLS fiber! This is the second prototype “QPCAL-II”, and more results will be forthcoming in 2010.

Remarkably, the very thin films of PTP and ZnO:Ga (4% Gallium doped) coated quartz plates enhance the light production almost 4 times over the bare quartz plates, and we have proved it is mainly scintillation, beyond wavelength shifting (WLS) of the Cerenkov light. This is a huge success, and will have implications for other high energy instrumentation.

Publications and Reports Progress is shown in the following publications and reports, available upon request:

- "pTerphenyl Deposited Quartz Plate Calorimeter Prototype", Akgun, U. Bilki, B. Albayrak, E. A. Bruecken, P. Cankocak, K. Clarida, W. Cremaldi, L. Duru, F. Moeller, A. Mestvirishvili, A. Onel, Y. Ozok, F. Sanders, D. Sonmez, N. Wetzel, J. Winn, D. Yetkin, T.; IEEE - 2008 Nuclear Science and Symposium and Medical Imaging Conference, Dresden, Germany, 19-25 October 2008 and Nuclear Science Symposium Conference Record, 2008, NSS '08, IEEE, 2228-2233 (19-25 Oct. 2008) ISSN: 1082-3654 ISBN: 978-1-4244-2714-7

- Design, performance, and calibration of CMS forward calorimeter wedges. The CMS-HCAL Collaboration S. Abdullin et al., Eur. Phys. J. C 53, 139–166 (2008) DOI 10.1140/epjc/s10052-007-0459-4

- "CMS Hadronic EndCap Calorimeter Upgrade Studies for SLHC - Cerenkov Light Collection from Quartz Plates", F. Duru et al., IEEE Transactions on Nuclear Science, Vol 55, Issue 2, 734-740, Apr 2008.

- "Quartz Plate Calorimeter as SLHC Upgrade to CMS Hadronic Endcap Calorimeters", U. Akgun et al., XIII International Conference on Calorimetry in High Energy Physics, CALOR 2008, Pavio, Italy, May 2008 CMS-CR-2008-056 and J.Phys.Conf.Ser.160:012015, 2009.

- "CMS Hadronic EndCap Calorimeter Upgrade Studies for SLHC - Cerenkov Light Collection from Quartz Plates", F. Duru et al., IEEE Trans Nuclear Science, Vol 55, No2, 734, April 2008.

"Quartz Plate Calorimeter as SLHC Upgrade to CMS Hadronic Endcap Calorimeters", U. Akgun et al., XIII International Conference on Calorimetry in High Energy Physics, CALOR 2008, Pavio, Italy, May 2008 CMS-CR-2008-056 and J.Phys.Conf.Ser.160:012015, 2009.

- The CMS barrel calorimeter response to particle beams from 2-GeV/c to 350-GeV/c. By USCMS Collaboration and ECAL/HCAL Collaboration (S. Abdullin *et al.*). Eur.Phys.J.C60:359-373,2009. **Cited 2 times**

- The CMS experiment at the CERN LHC. CMS Collaboration (R. Adolphi *et al.*). 2008. 361pp. JINST 0803:S08004, 2008, JINST 3:S08004, 2008. TOPCITE = 50+, **Cited 100 times**