CMS Hadron Endcap Calorimeter Upgrade Studies for Super-LHC

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Abstract. When the Large Hadron Collider approaches Super-LHC conditions above a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$, the scintillator tiles of the CMS Hadron Endcap calorimeters will lose their efficiencies. As a radiation hard solution, the scintillator tiles are planned to be replaced by quartz plates. In order to improve the efficiency of the photodetection, various methods were investigated including radiation hard wavelength shifters, p-terphenyl or 4% gallium doped zinc oxide. We constructed a 20 layer calorimeter prototype with pTp coated plates of size 20 cm x 20 cm, and tested the hadronic and the electromagnetic capabilities at the CERN H2 beam-line. The beam tests revealed a substantial light collection increase with pTp or ZnO:Ga deposited quartz plates. Here we report on the current R&D for a viable endcap calorimeter solution for CMS with beam tests and radiation damage studies.

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). Current luminosity upgrade plans are divided into two 5-year phases. Phase 1 covers the period from 2013 to 2018 when the peak luminosity will increase from $10^{34}\text{cm}^{-2}\text{s}^{-1}$ to $4\times10^{34}\text{cm}^{-2}\text{s}^{-1}$. Phase 2 covers from 2018 to 2023 when the peak luminosity reaches to $10^{35}\text{cm}^{-2}\text{s}^{-1}$.

Coverage between pseudorapidities of 1.3 and 3.0 is provided by the endcap hadron calorimeter (HE). The HE is composed entirely of brass absorber plates in an 18-fold $\phi$-geometry matching that of the barrel calorimeter. The thickness of the plates is 78 mm while the scintillator thickness is 3.7 mm, hence reducing the sampling fraction. There are 19 active plastic scintillator layers. In the high $\eta$-region, above $|\eta| = 1.74$, the $\phi$-granularity of the tiles is reduced to $10^\circ$ to accommodate the bending radius of the WLS fiber readout. For the purpose of uniform segmentation in the Level-1 calorimeter trigger, the energies measured in the $10^\circ$ $\phi$-wedges are artificially divided into equal shares and sent separately to the trigger. The $\Delta\eta \Delta\phi$ tower size matches that of the barrel in the range $1.3 < |\eta| < 1.74$. For $|\eta| > 1.74$, the $\eta$ size increases [2].

2. Upgrade Requirement
Light generated in the HE scintillators (Kuraray SCSN81) is carried to hybrid photodiodes by Kuraray Y-11 double clad wavelength shifting (WLS) fibers. Both scintillators and WLS fiber have been shown to be moderately radiation hard up to 2.5 MRad [3]. The simulation studies
show that the expected radiation levels have strong $\eta$ dependence and they predict radiation levels up to 10 MRad in high $\eta$ towers after 10 years of LHC operation at $10^{34} \text{ cm}^{-2} \text{s}^{-1}$ luminosity [4][5]. This value reaches up to 30 MRad for the front towers of the $2.9 < |\eta| < 3.0$ region, where the Endcap Electromagnetic (EE) calorimeter does not shield the HE calorimeter.

With the increasing luminosity plan for LHC, we expect the scintillator tiles and plastic WLS fibers to face higher radiation levels than these reports. Hence, the resolution of the HE calorimeter will deteriorate faster, starting from high $\eta$ towers. As a solution to this radiation damage problem, we propose to substitute the scintillators with quartz plates. Results show that quartz can withstand the radiation doses up to 1.25 GRad [6][7][8].

However, with the quartz plates, the detected photons come from Čerenkov radiation, which yields 100 times less light than the scintillation process. To improve the number of generated photons we tested different light enhancement tools, including p-Terphenyl (pTp), 4% Gallium dopped - ZincOxide (ZnO:Ga), α-Terphenyl (αTp), m-Terphenyl (mTp), and p-Quarterphenyl (pQp). The light enhancement tool on the quartz has to be radiation hard as well.

3. Selection of Light Enhancement Tool

To improve the light production inside the quartz plates, we considered various light enhancement tools: pTp, ZnO:Ga, oTp, mTp, and pQp. Other than ZnO:Ga, all of them can be evaporated in a vacuum chamber to be applied on quartz. The molecular properties of ZnO:Ga do not allow evaporation, so RF sputtering was used for this case. After the beam tests at the Fermilab Meson Test Beam Facility and at the Cern H2 beamline, the one sided coatings with 2 $\mu m$ thickness of pTp and 0.2 $\mu m$ of ZnO:Ga yielded the best results in pion, proton, and electron beams at various energies. Figure 1 shows that in both cases, we have increased the light yield for minimum ionizing particles at least four times compared to plain quartz plates. Since ZnO:Ga requires a more expensive and delicate deposition process, we decided to focus on pTp for the rest of our studies.

![Figure 1](image.png)

Figure 1. Light yield from 2 $\mu m$ thickness of PTP (red) and 0.2 $\mu m$ thickness of Ga:ZnO (green) deposited quartz plates, and clean quartz plate (blue).

Figure 2 shows the absorption and emission spectra of pTp. As the number of created Čerenkov photons increases with $1/\lambda^2$ having the pTp absorption spectra positioned in UV range helps us to enhance light production.

As the next step, we tested pTp radiation hardness with proton beams at the Indiana University Cyclotron Facility (IUCF) and CERN beam lines. The $^{90}\text{Sr}$ activated scintillation light outputs of pTp samples both before and after irradiation were compared in the University
of Mississippi CMS Laboratories. We also employed the liquid scintillation technique in which the pTp samples were mixed in a saturated toluene solution with a standard tritium beta source and scintillation light analyzed for dosed and standard samples. The toluene yields negligible scintillation light in the tests. The dosed pTp samples were also sent for chemical analysis showing slight breakdown of the tri-ring pTp molecule into simpler benzene ring forms. The results of different irradiation levels are reported in Fig.3. After 20 MRad of proton irradiation, the light output drops to 84% of the initial level. But the initial radiation damage rate slowly flattens, and after 40 MRad of radiation we still observe less than 20% loss of light production.

![Figure 2. Absorption (blue) and emission (red) spectra of p-Terphenyl.](image1)

![Figure 3. Light output from PTP sample after proton irradiation versus proton irradiation level with simple fitted line.](image2)

4. Construction and Tests of the Prototype
We have built a quartz plate calorimeter prototype with 0.2 \( \mu m \) pTp deposited on one side of the quartz tiles. The prototype consists of 20 layers of quartz plates (15 cm x 15 cm x 5 mm) with 7 cm iron absorbers between each layer making it a good representation of the small solid angle of the upgraded HE calorimeter. GE-124 quartz from GE Quartz Company was used as the material for the plates. After 2 \( \mu m \) pTp was deposited on every quartz plate via evaporation
at Fermilab Thin Film Laboratory, one inch section on the side of each plate was polished at the University of Iowa CMS Laboratories for better PMT coupling. The light generated in the quartz plate was read out by Hamamatsu R7525-HA photomultiplier tubes from the edge of the polished side.

The quartz plates were wrapped with mylar for good reflectivity, especially in the UV range, and then with Dupont Tyvek for a robust light tight structure. Every quartz plate and PMT system was prepared to be a standalone unit. Having our prototype constructed as a collection of standalone units allowed us to change the absorber thickness between layers for a possible electromagnetic configuration.

The prototype was tested at the CERN H2 beam-line with two different configurations: a hadronic configuration with 7 cm iron absorbers between each layer and an electromagnetic configuration with 2 cm iron absorbers. Hadronic configuration was tested with 20, 30, 50, 80, 130, 200, 250, 300, and 350 GeV $\pi^-$ beams and the electromagnetic configuration was tested with 50, 80, 100, 120, and 200 GeV electrons [9].

Figure 4 shows the longitudinal shape of the hadronic showers. Solid curves are the Geant4 [10] simulation results. The calibration between simulation and data was done using 80 GeV $\pi^-$ data by matching the response layer by layer. Slight variations between layers are understood to be due to alignment and optical matching differences.

![Figure 4](image.png)

**Figure 4.** Longitudinal shower shape for hadronic showers. Solid curves are the Geant4 simulation results that were calibrated with 80 GeV $\pi^-$ data.

Figure 5a shows the detector linearity for hadronic response. There is good agreement with the data and simulation at all energies. Figure 5b shows the energy resolution of the calorimeter. At lower energies, the hadronic resolution is better than 40% and it reaches 13% at 350 GeV. The agreement between data and simulation is better at lower energies. The main limiting factor of the prototype in terms of resolution is its small lateral size.

Although the purpose of these studies is to find a solution for radiation hardness problems of the CMS HE calorimeter, we took this opportunity to test the similar radiation hard configuration on an electromagnetic calorimeter. Figure 6 shows the longitudinal shape of the electromagnetic showers. For the calibration of the simulation results (solid curves) 80 GeV electron data was used. Figure 7a shows the detector linearity in response to electromagnetic showers and the energy resolution is shown in Fig. 7b. At energies higher than 120 GeV, both resolution curves converge to a value around 5.6%.
Figure 5. Hadronic response linearity (a) and energy resolution (b) of the calorimeter.

Figure 6. Longitudinal shower shape for electromagnetic showers. Solid curves are the Geant4 simulation results that were calibrated with 80 GeV e\(^-\) data.

5. Conclusions
As the peak luminosity of the LHC increases, detector upgrades are required for LHC experiments. The CMS experiment HE calorimeter consists of moderately radiation hard scintillator tiles, and they are not going to survive the high radiation environment of the SLHC. Here, we show that p-Terphenyl (pTp) deposited quartz plates are a perfect candidate to replace the scintillator tiles of the CMS HE calorimeter. Both quartz and pTp are radiation hard and cost effective options.

We have demonstrated that with one sided coatings of 2 \(\mu m\) pTp and 0.2 \(\mu m\) ZnO:Ga (4% gallium doped zinc oxide), the light production can be enhanced at least 4 times. We also report that pTp loses only 16 % of the light production after 40 MRad proton irradiation. This is well above the predicted SLHC radiation levels for most of the HE towers.

To test the calorimeter capabilities of this replacement option, we constructed a 20 layer...
Figure 7. Electromagnetic response linearity (a) and energy resolution (b) of the calorimeter.

pTp deposited quartz plate calorimeter prototype. Overall, the hadronic energy resolution of the calorimeter can be expressed as \( \sigma(E) = 211% \sqrt{E} + 8.8% \) with a negligible noise term, and the electromagnetic energy resolution can be expressed as \( \sigma(E) = 26% \sqrt{E} + 4.5% \) \( E \). Particularly hadronic resolution suffers significantly from lateral leakage but a hadronic resolution of 11% is achievable at higher energies.

pTp deposited quartz plates sandwiched between thinner absorbers can be used as a radiation hard electromagnetic or hadronic calorimeter option for future collider experiments. Considering the radiation damage issues of the CMS Endcap Electromagnetic calorimeter, we propose that pTp deposited quartz plates constitute a viable option for all CMS endcap regions.

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