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Quartz plate calorimeter prototype with wavelength shifting fibers


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ABSTRACT: The quartz plate calorimeters are considered as hadronic calorimeter options for upgrading Large Hadron Collider experiments. Previous studies have shown that quartz can resist up to 12 MGy of proton irradiation. Using uniformly distributed wavelength shifting fibers embedded the quartz plates are shown to solve the problem of low visible light production on Cherenkov process. Here, we report the performance tests of a 20-layer quartz plate calorimeter prototype, which is constructed with this approach. The calorimeter prototype was tested at CERN H2 area in hadronic and electromagnetic configuration, at various energies of pion and electron beams. We report the beam test and simulation results of this prototype, we also discuss future improvement directions on manufacturing radiation hard wavelength shifting fibers for this type of hadronic calorimeter design.

KEYWORDS: Calorimeters; Cherenkov detectors; Calorimeter methods

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1 Introduction

The Large Hadron Collider (LHC) completed the first year of physics runs at 7 TeV center of mass energy with lots of promises. However, the LHC is designed to provide 14 TeV proton-proton collisions every 25 ns, and this energy level is planned to be reached in 2012. The integrated luminosity is planned to increase by a factor of 10 in 2022 \[1-3\]. The high luminosity runs will require substantial upgrade on some of the detector systems, such as the Hadronic Endcap (HE) calorimeters of the Compact Muon Solenoid (CMS), which are positioned at both ends of the detector. These calorimeters are especially essential on jet and missing transverse energy reconstruction in pseudorapidity region of 1.8–3 \[1\].

The CMS HE calorimeters use 19 layers of plastic Kuraray SCSN81 scintillator tiles to detect the showering particles through 70 mm brass absorber at every layer. Light generated in Kuraray SCSN81 plastic scintillators is collected by Kuraray Y-11 double clad wavelength shifting (WLS) fibers, and readout with hybrid photodiodes. The Kuraray SCSN81 scintillators and Kuraray Y-11 wavelength shifting (WLS) fibers have been shown to be moderately radiation resistant up to 25 kGy. The simulation studies on high luminosity runs predict radiation levels up to 10 kGy in high \(\eta\) towers. Moreover, this value reaches up to 30 kGy for the front towers where the Electromagnetic Endcap (EE) calorimeter does not shield the HE calorimeter \[4-8\].

As a solution to this radiation damage problem, it is proposed to substitute the scintillators with quartz plates \[9-11\]. The major advantage of such replacement is the radiation hardness of quartz material. Although there are some variations between different types, quartz shows robust performance under electron and proton irradiations \[12, 13\]. On the other hand light production within quartz is through Cherenkov process, in which the number of generated photons is inversely proportional to the wavelength, and increases in deep UV. The number of photons that a charge particle creates within 5 mm thick quartz plate is 2 orders of magnitude less than the same size plastic scintillator. Currently we are pursuing two different approaches to overcome this discrepancy: \(i\) covering the surface of the quartz plates with various radiation hard, UV absorbing, wavelength shifter chemicals (such as pTp, or ZnO) and readout the signal from the edge of the plate \[14\]. \(ii\) carrying the signal away from high radiation and magnetic field region by using WLS fibers. Duru et al. outlined an effective way of collecting the Cherenkov light within quartz by using WLS fibers in a bar-shape geometry \[15\]. However, the performance of such a calorimeter was not reported. This report follows up the idea using WLS fibers, and summarizes the beam test and simulation results of the quartz plate calorimeter prototype prepared with UV absorbing WLS fibers.
2 The design and test results

The WLS fiber type and design are crucial on improving the light collection efficiency. The Saint Gobain BCF-412 plastic WLS fibers [18], which can absorb photons down to 280 nm, and emit at 435 nm are good candidates to collect the maximum amount of Cherenkov light within quartz plates. The current fiber design of the CMS HE calorimeter plastic scintillators, collect the scintillation photons from the edges of the plates with WLS fibers. This simple fiber geometry works well for the scintillators since the scintillation photons are generated in random directions. However, the Cherenkov photons have fixed angle with respect to the momentum of the charged particle. Since Cherenkov photons are already scarce, scattering the photons all the way to the edges would yield small amount of photons. That is why we investigated the geometry options where the fibers are placed uniformly in quartz plates. Various fiber embedding geometries were studied at test beams and Geant4 simulations; Bar-shape, HE-shape, Y-shape, and S-shape. Eventually, the bar-shaped geometry proved to be the best option with the light collection of 70% of the original HE plastic scintillator tile [15].

The calorimeter prototype is prepared with bar-shaped fiber geometry embedded into the wedge shaped grooves of 5 mm thick GE-124 quartz plates. Polymicro Company grooved the quartz plates. Saint Gobain BCF-12 WLS fibers were inserted into each groove. Each quartz plate — WLS fiber combination was readout via Hamamatsu R7525-HA photomultiplier tubes (PMTs) [16, 17]. These 8 stage, head-on, 1 inch diameter PMTs have a peak quantum efficiency at 425 nm, and are very good fit for this application. Each layer is a stand-alone unit with 20 cm × 20 cm × 0.5 cm quartz plate, embedded WLS fibers, and a Hamamatsu R7525 PMT. The quartz plate and fiber combination wrapped with aluminized Mylar for specular reflection. Afterwards whole unit was wrapped with Tyvek for light tightness. By changing the absorber thickness we utilized the prototype as an Electromagnetic (EM) and Hadronic calorimeter. In EM configuration, the iron absorber thickness was to 2 cm. For Hadronic configuration 7 cm thick iron absorbers were used.

The calorimeter prototype was tested at Cern H2 test beam facility. 20 GeV, 50 GeV, 80 GeV,
Figure 2. 100 GeV electron response of the calorimeter prototype in EM configuration. One QIE count corresponds to 2.7 fC.

Figure 3. The hadronic resolution of the quartz plate calorimeter prototype is shown for data (solid red line - circles) and Geant4 simulations (black dashed line - squares) in hadronic configuration.

100 GeV, 150 GeV, 200 GeV, 300 GeV, and 350 GeV energy pion beams were used during the hadronic calorimeter tests. Prototype’s response to 300 GeV pion beam can be seen in figure 1. The EM configuration was tested with 20 GeV, 50 GeV, 80 GeV, and 100 GeV electron beam. The 100 GeV electron response of the prototype is shown in figure 2. During each run the PMT gain was set to $10^6$ (1500 V). On each case the total calorimeter response was constructed by adding the signal from all individual layers. The signal is also corrected for PMT gain differences and ADC pedestals. The Geant4 simulation of the model utilized LHEP physics package. The simulation model counted every photon reaching to PMT surface. In order to find the resolution the data were fit to:

$$\frac{\sigma(E)}{E} = \frac{A}{\sqrt{E}} + \frac{B}{E} + C$$  \hspace{1cm} (2.1)
where $A$ is the stochastic term, $B$ is noise term, and $C$ is the constant term. The hadronic resolution yields $235 \pm 4\%$ stochastic term, negligible ($0.03\%$) noise term and $10.9 \pm 0.4\%$ constant term (see figure 3). The calorimeter prototype hadronic response linearity is within $0.1\%$ up to $350$ GeV pion energy (see figure 4). The Electromagnetic configuration resolution (see figure 5) fit yields $A = 31 \pm 2$, $B = 7.5 \pm 0.5$, and $C = 6.7 \pm 0.2$. The electromagnetic response linearity of the calorimeter prototype is also found to be within $0.01\%$ (see figure 6).

3 Discussion and conclusion

The LHC luminosity is planned to increase in coming years. The resulting radiation damage problems will require upgrades on many detectors in LHC experiments. For this purpose, it has been
Figure 6. The electromagnetic linearity of the quartz plate calorimeter prototype in EM configuration. \( R^2 \) of the fit yields 0.99999, which means it shows 99.99\% correlation with linear fit.

proposed to replace the existing scintillators of CMS HE calorimeter with quartz plates. On previous reports we outlined two separate upgrade scenarios, 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 [15]. However, this approach requires the light to be collected by a light detector from the edge of the plate. The 9 mm gap between current HE calorimeter absorbers, the radiation level as well as the high magnetic field strength at HE location requires a special light detector, which is commercially not available. The second approach, which uses UV absorbing WLS fibers eliminates the radiation and magnetic field problems by carrying the light out of the region. This study shows that by using Saint Gobain BCF-412 WLS fibers, a very effective Hadronic and Electromagnetic calorimeter can be built. On discussion of upgrading CMS HE calorimeter, the WLS fiber embedded quartz plate calorimeter is a promising option in terms of achieving the current HE calorimeter performance, which is around 8\% in hadronic energy resolution at a 300 GeV pion beam energy. This upgrade option also yields better than 0.1\% linearity, which is within the CMS HE Calorimeter requirements of 1\%. Considering the Endcap Electromagnetic (EE) calorimeters, which are located in front of the HE, are exposed to same radiation levels, quartz plates can be answer for the whole EndCap region. However, the WLS fibers used in this study are only moderately radiation hard [19, 20] and cannot be long-term solution for the future of LHC. Therefore, the success of this scenario depends on developing radiation hard WLS fiber, which will shape the future of this R&D study. We have recently built a radiation hard WLS fiber prototype by using quartz fibers and pTP, both known to be radiation hard [12–14]. We obtained promising results with this unit, and we are working on possible improvements.

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