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Physics Procedia 37 (2012) 238 – 243

Physics Procedia

TIPP 2011 - Technology and Instrumentation in Particle Physics 2011

CMS Hadronic Endcap Calorimeter Upgrade R&D Studies

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Abstract

Due to an expected increase in radiation damage in LHC, we propose to transform CMS Hadronic EndCap calorimeters to radiation hard quartz plate calorimeters. Quartz is proved to be radiation hard by the radiation damage tests with electron, proton, neutron and gamma beams. However, the light produced in quartz comes from Cerenkov process, which yields drastically fewer photons than scintillation. To increase the light collection efficiency we pursue two separate methods: First method; is to use wavelength shifting (WLS) fibers, which have been shown to collect efficiently the Cerenkov light generated in quartz plates. A quartz plate calorimeter prototype with WLS fibers has been constructed and tested at CERN to show that this method is feasible. Second proposed solution is to treat the quartz plates with radiation hard wavelength shifters, p-terphenyl, or doped zinc oxide. Another calorimeter prototype has been constructed with p-terphenyl deposited quartz plates, and showed superior calorimeter capabilities. Here, the test beam, bench test and simulation efforts on these methods are reported. We also outline the future directions on these possible upgrade scenarios for the CMS HE calorimeter.

Keywords: cms upgrade; cerenkov; p-terphenyl; hadronic calorimeter

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 doi:10.1016/j.phpro.2012.02.370

1. Introduction

The Hadronic Endcap (HE) calorimeters of the Compact Muon Solenoid (CMS) [1], at the CERN Large Hadron Collider (LHC), cover the $1.4 < \eta < 3$ region. The HE calorimeters are positioned at the both ends of the CMS detector and are vital tools on high Pt physics discoveries. The HE calorimeters are essential on jet and eventually missing transverse energy reconstruction in this high pseudorapidity region [2]. Although is still running at 7 TeV center of mass energy, the Large Hadron Collider (LHC) is designed to provide 14 TeV with p-p collisions every 25 ns. The starting peak luminosity of the accelerator is planned to increase gradually to $10^{35}cm^{-2}s^{-1}$ in 2020s [2, 3]. These high luminosity runs will require substantial upgrade on current design of the HE calorimeters.

The Hadronic EndCap calorimeters use 19 layers of plastic Kuraray SCSN81 scintillator tiles to detect the showering particles through 70mm 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 WLS fibers have been shown to be moderately radiation hard up to 2.5 Mrad. However the simulation studies on high luminosity runs 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 [4, 5, 6, 7]. As a solution to this radiation damage problem, we propose to substitute the scintillators with quartz plates [8, 9, 10]. The results from radiation hardness tests on various types of quartz material show that quartz can withstand extremely high radiation doses [11, 12]. Here, we summarize the studies performed on two scenarios based on quartz plates: ***i)*** Using UV absorbing WLS fibers to carry the signal to readout box. ***ii)*** Covering the quartz plates with radiation hard scintillators and reading the signal from the plate.

2. Radiation Hard Quartz

The radiation damage studies on quartz have been performed with electron, proton, gamma and neutron beams separately. In all of these studies, the light transmission of the quartz has been studied in fiber form.

The quartz radiation damage test with an electron beam has been tested on nine different high OH^- quartz fibers, with hard plastic cladding (qp) and quartz cladding (qq) using 500 MeV electrons from the Linac Injector of LEP (LIL) at CERN. The transmission of Xe light was measured *in-situ* in the 350-800 nm range. The induced attenuation at 450 nm found to be 1.52±0.15 dB/m for a 100 Mrad absorbed dose. We observed some darkening on the fibers, but the radiation did not change the tensile strength of the quartz fibers. Three bands of luminescence have been observed in fused silica at 280, 470 and 650 nm with lifetimes around 4 ns; 2–10 ms; and 20 ms; respectively. The characteristics of the luminescence, mainly in the 470 nm band, in the fibers have to be further measured in order to fully evaluate the effects of this band on the performance of the quartz plate calorimeter [11].

The proton radiation damage studies on quartz have been performed with 24 GeV protons at CERN. About 10^{16} protons/cm^2 were sent onto 1.20 m of quartz fibers, corresponding to a dose of 1.25 Grad. The fiber radiation damage induced by protons exhibited the same well known behavior as with electrons: high light attenuation below 380 nm and in the band 550–680 nm, moderate attenuation in the band 400–520 nm and practically no attenuation above 700 nm. The damage varies exponentially with dose; fast in the first hours and slow after. Above 0.6 Grad we observe a new phenomenon: the radiation damage is not recoverable in the range 580–650 nm and below 380 nm.

As in electron irradiations we did not observe significant differences in proton irradiation between qq and qp fiber up to 1 Grad. Near 450 nm the observed difference appears in the fits at high dose and above 1 Grad there is a steep decrease of the transmitted signal in qp fiber. For a 2 m qp fiber we observed a decrease of 30% in light transmission resulting from a dose accumulation of 20 Mrad, as well as an increase in light transmission by 22% 10 days after an irradiation of 100 Mrad in 200 days [12].

The radiation damage tests to measure the degradation of quartz optical fibers under neutron and gamma radiation has been performed at Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory. A set of seven different types of quartz material in the form of fiber from Polymicro Technologies have been tested; FVP 300-315-345, FSHA 300-330-350, FDP 300-315-345, FBP 600-660-710, FVP 600-660-710, FVP 600-660-710 UVM, and FSHA 600-630-800 [5]. The fibers were bombarded with pulses of high-energy neutrons produced by the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory for 313 hours. The fibers were exposed to a total of 17.6 MRad of neutron and 73.5 MRad of gamma radiation. The optical transmission of the fibers was then measured and compared to the baseline measurements. The tests show that a special radiation-hard solarization resistant quartz fiber (FBP 600-660-710) gives the best results with within 10% variation between before and after irradiation.

3. Quartz Plate Calorimeter Using Wavelength Shifting Fibers

The use of quartz plates instead of plastic scintillators improves the radiation hardness of the calorimeter, however the light produced in quartz plates is coming from Cherenkov process, and drastically lower than that of scintillation process in visible region. To increase the collected photons we decided to go deep into UV range, 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. For this purpose we selected Saint Gobain BCF-12 WLS fibers, which can absorb photons down to 280 nm, and emit at 435 nm. In the current design of the HE plates, fibers collect the scintillation photons from the edges of the plates. This simple fiber geometry works well for the scintillators since the scintillation photons are generated in random directions. However, the Cherenkov photons are generated at a fixed angle with respect to the momentum of the charged particle. Since the photons are scarce we cannot afford to make them propagate to the edges of the plates. The fibers should be placed close to the photons for efficient light collection. We investigated the most uniform and efficient fiber embedding geometry to collect the Cherenkov photons. For this purpose, various fiber embedding geometries were investigated at test beams and Geant4 simulations; Bar-shape, HE-shape, Y-shape, and S-shape (see Fig.1) [13]. All of the plates were wrapped with Tyvek, which is a very strong, synthetic material. The University of Iowa bench tests showed that Tyvek is as good a reflective material as aluminum and Mylar in both the UV and visible wavelength region. In all the tests reported below Hamamatsu R7525-HA photomultiplier tubes (PMTs) [14, 15] were used to measure the light at the end of the fibers.

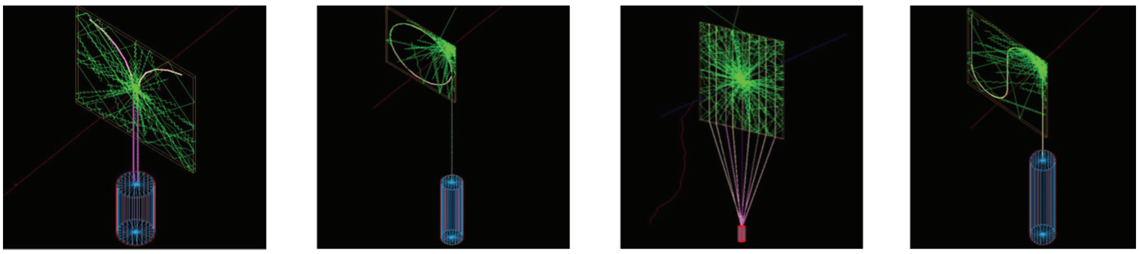

Fig. 1. The different geometries of wavelength shifting fibers tested, constructed and simulated during the R&D studies. From left to right Y-shape, HE-shape, Bar-shape, and S-shape.

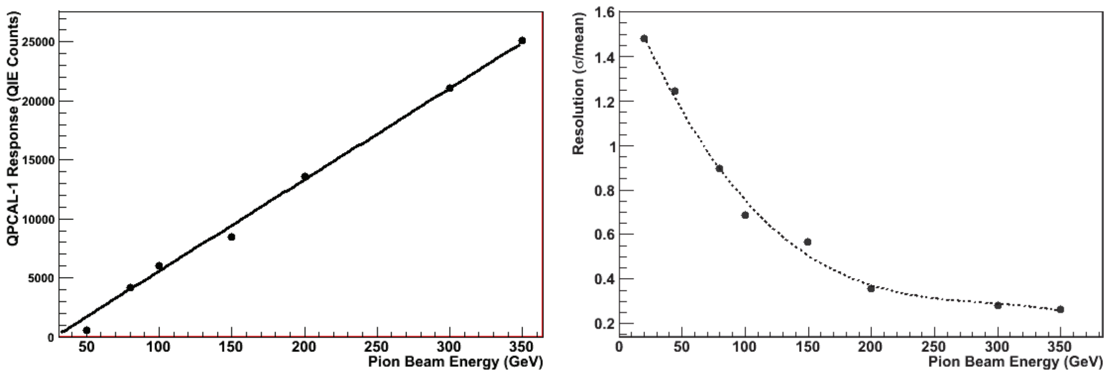

Fig. 2. Hadronic linearity (Left) and resolution (Right) of quartz plate calorimeter versus beam energy.

The calculations and simulated model for our system show that the amount of Cherenkov radiation in a quartz plate is around 1% of the scintillation photons from the same size scintillator tile. To collect the light in a more efficient way, we worked on different plates with different sizes and with different fiber geometries embedded in them. After many beam tests and bench tests we came to the conclusion that by using a quartz plate with the bar-shape fiber geometry, we can collect almost 70 percent of the light that the original HE tile would yield [13].

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 linearity and hadronic resolution of the calorimeter is shown in Fig. 2.

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. We got promising results with this unit, and working on possible improvements.

4. Quartz Plate Calorimeter Coated With Inorganic Scintillators

The lack of commercially available wavelength shifting fibers pushed us to investigate alternative solutions. For this purpose we coated the surface of the quartz plates with various inorganic scintillators (pTp, ZnO:Ga, oTp, mTp, and pQp) and readout the signal directly from the edge of the plate. The ZnO:Ga was sputtered on the quartz via RF guns, all the other scintillators were evaporated in a vacuum chamber. The light readout was performed with the Hamamatsu R7525-HA photomultiplier tubes (PMTs). The coating thickness optimization and comparison of the materials were done at beam tests at Fermilab and Cern H2 area. 2 μm thickness of pTp and 0.2 μm of ZnO:Ga yield the best results, by improving the light production by a factor of at least 4 times. With evaporation capabilities of the University of Iowa HEP laboratories we decided use pTp for the calorimeter prototype. Our collaborators at University of Mississippi, tested the radiation hardness of pTp at the Indiana University Cyclotron Facility (IUCF) and CERN beam lines. After 400 kGy of radiation less than a 20 % loss of light production has been observed [16].

To test the capabilities of a calorimeter based on pTp and quartz plate technology we constructed a prototype. The prototype has 20 layers of pTp deposited quartz plates calorimeter prototype with 7 cm iron absorbers between each layer. The prototype was tested at the CERN H2 test area with various energies of pion and electron beams. The calorimeter linearity is within 1% up to 350 GeV pion energies and the hadronic resolution yields stochastic term 210.3% with 8.8% constant term.

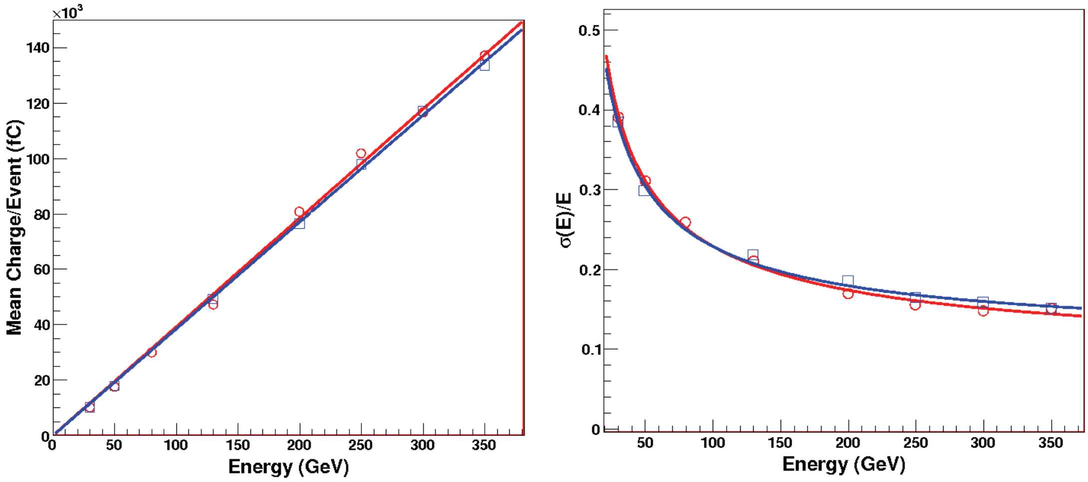

Fig. 3. Detector linearity (LEFT and hadronic resolution for the calorimeter prototype. Blue lines are Geant4 simulations, the red lines are data from beam tests.

5. **Conclusion & Discussion**

The CMS experiment is currently taking data, and on its way to first exciting physics results. On the other hand considering the long lifetime of LHC machine, the detector improvement studies continue. Here, we discussed two possible solutions for radiation damage problem of the CMS Hadronic Endcap (HE) calorimeter. We propose to replace the existing scintillators with quartz plates. Two separate models were studied extensively and the related prototypes tested at beam tests. The first 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. The second 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.

Acknowledgements

The author would like to thank CERN H2, and Fermilab Meson beam test, and Indiana University Cyclotron facilities. The authors especially would like to thank Eileen Hahn from Fermilab Thin Film laboratory for her amazing efforts on pTp, and ZnO:Ga depositions. The authors are indebted to our CMS HCAL Collaborators for their support and encouragement, the QUARKNET students for their help during the construction of the prototypes. This research is funded by DOE (DE-FG02-91ER40644), Iowa-

Fermilab MOU for CMS construction and M&O projects, and The University of Iowa office of VP of Research and Graduate College.

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