P-Terphenyl Deposited Quartz Plate Calorimeter Prototype

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***Abstract*–Due to an expected increase in radiation damage under super-LHC conditions, we propose to substitute the scintillator tiles in the original design of the CMS hadronic endcap (HE) calorimeter with quartz plates. Quartz is proved to be radiation hard by various tests, but the light produced by quartz comes from Cerenkov process, and it is 100 times less than scintillation photons. To enhance the light production we treated the quartz plates with p-Terphenyl, and constructed a 20 layers calorimeter prototype. Here, we report the test beam results for hadronic and electromagnetic capabilities of the calorimeter prototype as well as radiation damage results for p-Terphenyl.**

I. Introduction

THE current design of "soon starting" Large Hadron Collider (LHC) provides 14 TeV center of mass energy with p-p collisions every 25 ns, and peak luminosity of L = 10^{34} cm^{-2} s^{-1}. In the current design this number is limited by beam dumping, machine collimation and protection systems, as well as electron cloud effects.

The life expectancy of LHC IR quadrupole magnets are expected to be less than ten years due to high radiation doses. So around the year of 2015, the LHC will be upgraded to a super-LHC (SLHC), that will operate at 10 times higher luminosity (L = 10^{35} cm^{-2} s^{-1}), thereby allowing new physics discoveries. There are two possible upgrade paths: "early separation" (ES) scenario and "Large Piwinski angle" (LPA) scenario [1].

TABLE I
LHC AND SLHC SCENERIOS COMPARISON

Parameter	Symbol	Nominal	Ultimate	ES	LPA
Number of bunches	N_b	2808	2808	2808	1404
Protons per bunch	$N_b[10^{11}]$	1.15	1.7	1.7	4.9
Bunch spacing	Δt_{sep}[ns]	25	25	25	50
Peak luminosity	L[10^{34} cm^{-2}s^{-1}]	1.0	2.3	15.5	10.6
Events per crossing		19	44	294	403

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The early separation scenario proposes installation of early separation dipoles at about 3 m from interaction points of ATLAS and CMS detectors. In the Large Piwinski angle scenario the bunch spacing is doubled, and bunches are proposed to be longer, more flat, and intense. Table 1 compares the main features of these upgrade scenarios with the current LHC limits.

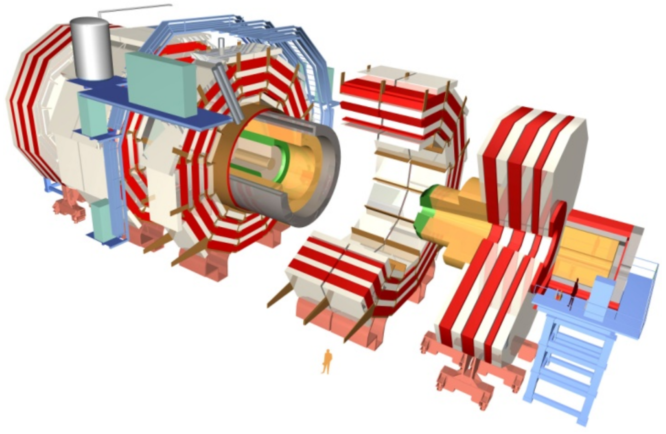

Fig. 1. CMS Detector general view.

If as widely predicted, the LHC discovers Higgs boson, the accumulated luminosity will only be enough to study mass and couplings, but not to measure the Higgs self couplings. SLHC high will provide high statistics to study the topics like Higgs self coupling, massive MSSM Higgs, Higgs coupling ratios for bosons and fermions.

This accelerator upgrade will require detectors to be modified for higher radiation conditions as well. For the Compact Muon Solenoid (CMS) experiment (see Fig.1) Hadronic Endcap (HE) calorimeter is one of these detectors. In the current design the CMS HE calorimeter consists of 19 layers of scintillator tiles sandwiched between 70mm brass absorbers (see Fig.2). Light generated in these scintillators (Kuraray SCSN81) are 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 [1]. Under SLHC conditions the lifetime radiation dose in the HE calorimeter region will increase from 2.5 MRad to 25 MRad. The scintillator tiles used in the current design of the HE calorimeter will lose their efficiency due to radiation damage.

As a solution to the radiation damage problem in the SLHC era, we propose to substitute scintillators by quartz plates. We performed radiation hardness tests on various types of quartz material in the form of fiber, under electron, proton, neutron, and gamma radiation. Results show that quartz will not be affected by the radiation dose at the SLHC [2,3,4].

However, when quartz plates are used, the detected photons come from Cherenkov radiation, which yields 100 times less light than the scintillation process [5,6]. For this purpose we tested different light enhancement tools, including p-Terphenyl (PTP), %4 Gallium dopped - ZincOxide (Ga:ZnO), o-Terphenyl (OTP), m-Terphenyl (MTP), and p-Quarterphenyl (pQP). Among these PTP and Ga:ZnO deposited on one side of a quartz plates gave the most promising results by improving light production at least four times.

Fig. 2. Constructed CMS Hadronic EndCap Calorimeter.

II. PRELIMINARY TESTS

In our preliminary tests we used PTP [7] and Ga:ZnO to enhance the light yield from quartz plates. The molecular properties of Ga:ZnO do not allow evaporation, but RF sputtering was used to deposit Ga:ZnO on to the quartz plates. It is a more expensive and delicate process. Depositions of PTP and ZnO over quartz were made at the Fermilab Thin Film Laboratory facility (see Fig.3). Different thicknesses of coatings were tested for an optimum result; 2µm thickness of PTP and 0.2 µm of Ga:ZnO deposited on one side of quartz plates yielded best results. In both cases we have improved the light yield for minimum ionizing particles at least four times (see Fig.4). Since the number of created Cherenkov photons increases with $1/\lambda^2$, having PTP absorption spectra positioned in UV range helps us to enhance light production.

Beam tests have been performed at Fermilab Meson Test Beam Facility and CERN H2 area. We have confirmed the light enhancement property with various energy pion, proton, and electron beams.

As part of the R&D project we tested PTP for radiation damage due to protons at the Indiana University Cyclotron Facility (IUCF) and CERN beam lines. Two comparisons were made. We compared the Sr^{90} activated scintillation light output of PTP samples both before and after radiation. The PTP samples were also tested by liquid scintillation technique in which the PTP samples were mixed in a saturated toluene solution with a standard tritium beta source and scintillation light analysed 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 in to simpler forms benzene ring forms.

The results of different irradiation levels are reported in Fig.5. 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 observed less than 20% loss of light production.

Fig. 3. PTP evaporation setup in Fermilab Thin Film Laboratory.

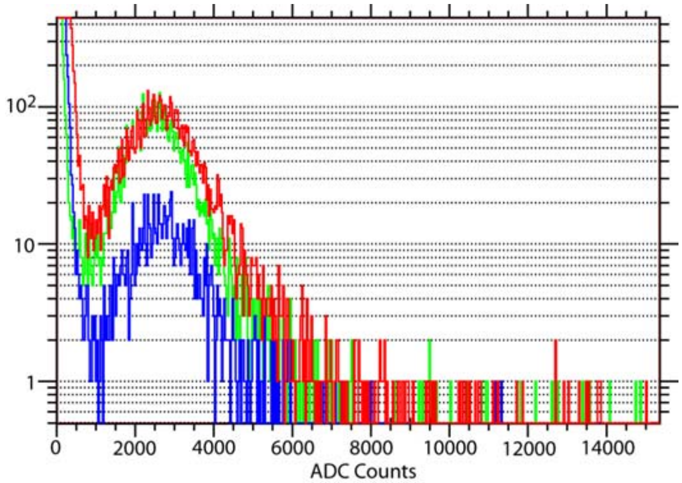

Fig. 4. Light yield from 2µm thickness of PTP (red), 0.2 µm thickness of Ga:ZnO (green) deposited quartz plates, and clean quartz plate (blue).

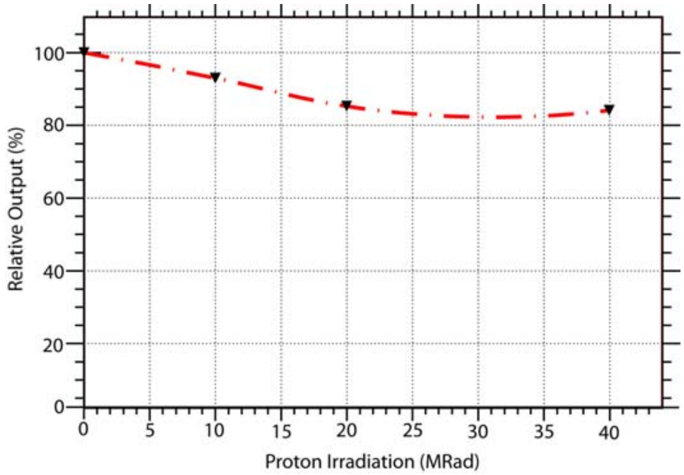

Fig. 5. Light output from PTP sample after proton irradiation versus proton irradiation level with simple fitted line.

III. CONSTRUCTION AND TESTS OF THE PROTOTYPE

In light of the preliminary test results, we have built a quartz plate calorimeter prototype which consists of 20 layers of quartz plates (20 cm x 20 cm x 5 mm) with 7 cm iron absorbers between them. 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 "upgraded" HE calorimeter (see Fig.6). Though preliminary results showed that 0.2 µm 4% Gallium doped ZnO and 2 µm PTP yield very similar results, we have selected to use PTP as the light enhancement tool on our prototype since it was easier to apply on the quartz plate.

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GE-124 quartz from GE Quartz Company has been used for plates. After 2 µm PTP deposited on every quartz plate via evaporation at Fermilab Thin Film Laboratory, one inch length of area at the side of every plate was polished in University of Iowa CMS Laboratories for better PMT coupling. The light generated in the quartz plate was readout by Hamamatsu R7525-HA photomultiplier tubes [8,9,10] from the polished side at the edge. The R7525-HA PMTs' sensitivity range matches well with emission spectrum of PTP (see Fig. 6).

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

The prototype was tested at the CERN H2 test area with 2 different configurations; Hadronic configuration with 7 cm iron absorbers between each layer, and electromagnetic (EM) configuration with 2 cm iron absorbers. In the Hadronic configuration 50,000 events were collected at π^- beam with 20 GeV, 30 GeV, 50 GeV, 80 GeV, 130 GeV, 200 GeV, 250 GeV, 300 GeV and 350 GeV energies. In EM configuration 50,000 events were recorded for electron energies of 50 GeV, 80 GeV, 100 GeV, 120 GeV, and 200 GeV energies.

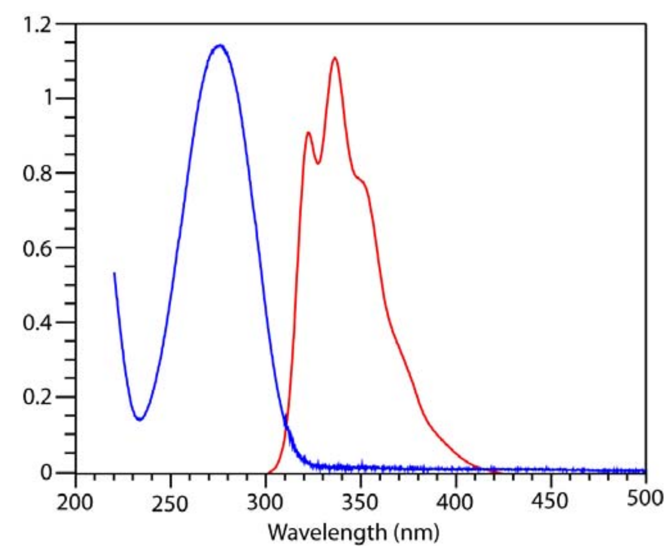

Fig. 6. Absorption and emission spectrums of PTP.

At every beam energy data sample, the signals from all layers were added to find the total calorimeter response. Fig. 7 shows such total calorimeter response at 300 GeV pion beam. The hadronic shower maximum peaks at layer 5 (35 cm of iron), and yield superior hadronic response good linearity (see Fig. 8).

The PTP deposited quartz plate calorimeter prototype's hadronic resolution is plotted in Fig. 9. Even for low energy beam the hadronic resolution is better than 40% and it reaches to 13% at 350 GeV pion beam. The extrapolation to higher energies gives very good hadronic resolution. It is obvious that this hadronic resolution would be better if we could eliminate the leaking shower from the edges of the calorimeter.

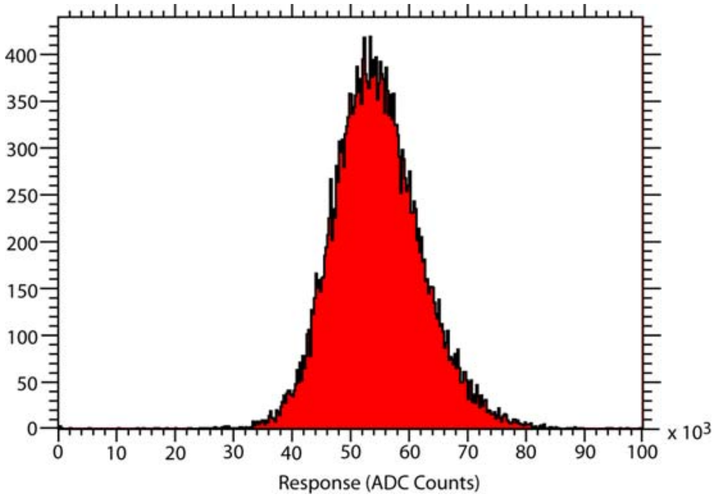

Fig.7. 300 GeV pion response of the calorimeter prototype on Hadronic configuration.

Although the purpose of this R&D studies is to find a solution on radiation hardness problems of CMS HE calorimeter we took this opportunity to test the similar radiation hard configuration on an electromagnetic calorimeter. The Electromagnetic shower peaks at the fourth layer (8 cm of iron) and gives very high resolution signal. 100 GeV electron signal from prototype is given in Fig. 10. The electromagnetic response is very linear until 120 GeV (see Fig. 11), after this point we only had 200 GeV beam and the response shows a little saturation. With more data points it would be easier to elaborate on signal linearity.

Fig.12 shows the Electromagnetic resolution of the prototype at various beam energies. The calorimeter yields 5% electromagnetic resolution at 200 GeV electron beam energy.

GEANT4 simulations were also performed on the simulated model of quartz plate calorimeter prototype (see Fig. 13, and Fig. 14). Absorption and emission spectrums from Fig. 6 are used. As beam energies; 20, 50, 80, 100, 120, 150, and 175 GeV electrons, and 30, 130, 200, 250, 300, and 350 GeV pion beams were simulated. Simulated 300 GeV pion response of the calorimeter is very similar to real data (see Fig. 15 and Fig. 16). The same agreement is also exist on electron response (see Fig. 17).

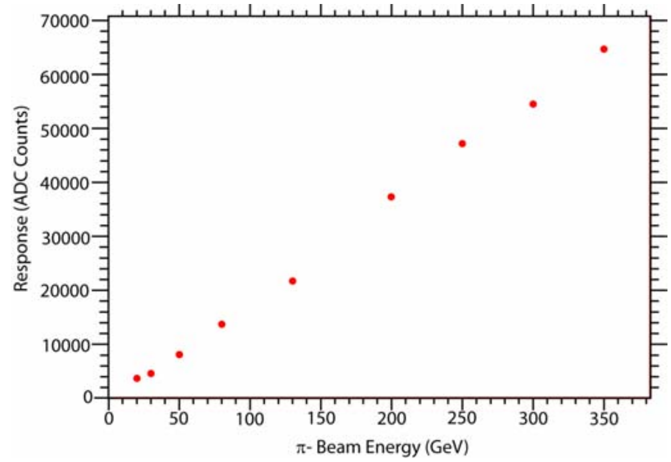

Fig.8. Hadronic response linearity of the calorimeter prototype for various pion beam energies.

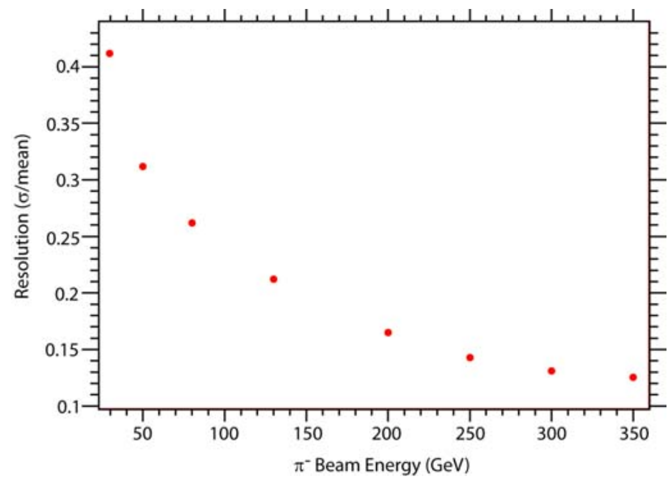

Fig.9. Hadronic energy resolution of the calorimeter prototype at various pion beam energies.

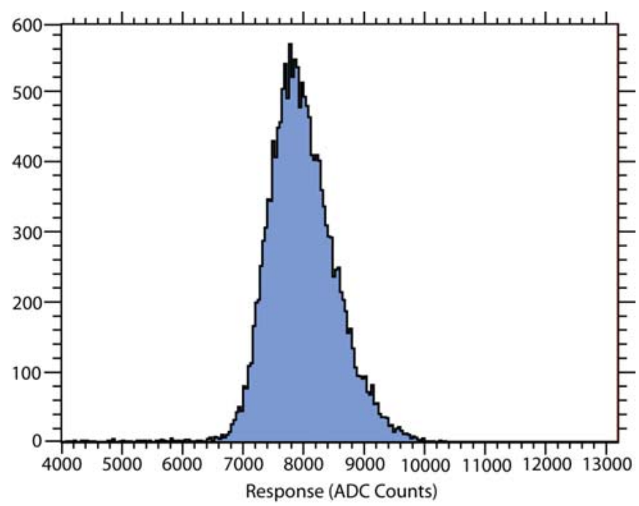

Fig.10. 100 GeV electron response of calorimeter prototype at E configuration.

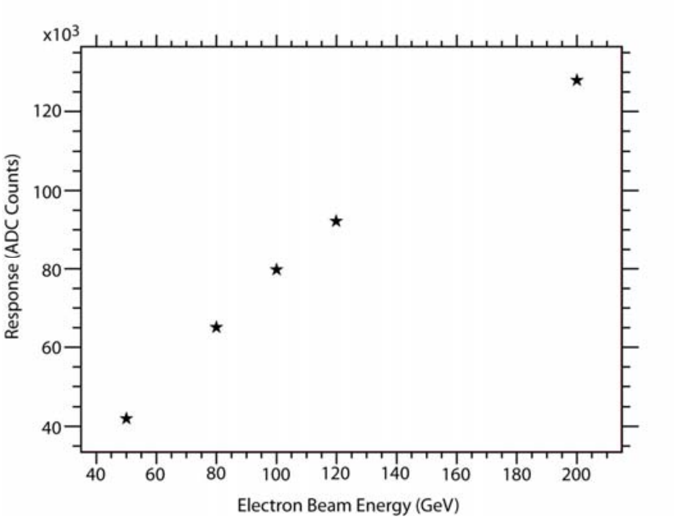

Fig. 11. Electromagnetic response linearity of the calorimeter prototype for various electron beam energies.

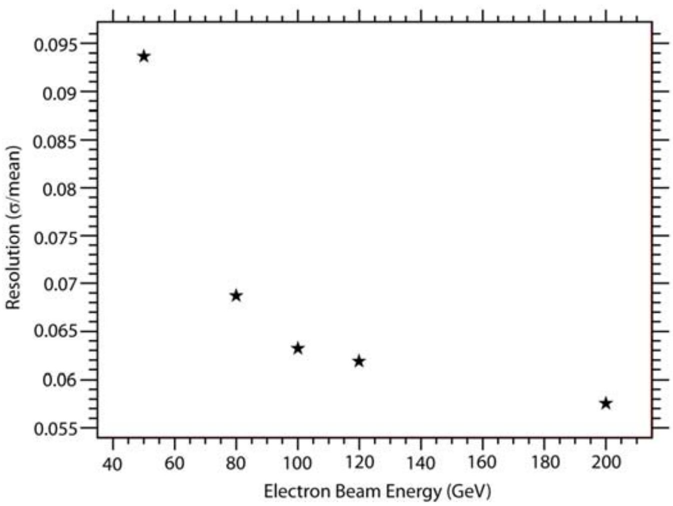

Fig.12. Electromagnetic resolution of the calorimeter prototype for various pion beam energies.

IV. CONCLUSION

A possible upgrade to the LHC (SLHC) is going to require detector upgrades to LHC experiments. CMS experiment Hadronic Endcap calorimeter consists of moderately radiation hard scintillator tiles, and they are not going to survive the high radiation environment of SLHC. This report shows that, PTP deposited quartz plates are very good candidate to replace the scintillator tiles of CMS HE calorimeter. Quartz and PTP are very radiation hard, and cost effective option.

Since using just quartz plates alone will yield very low light levels, we have shown that with PTP and Ga:ZO the light production can be enhanced at least 4 times. We have tested PTP under proton irradiation up to 40 MRad. This is well above the predicted SLHC radiation level of 25 MRad.

To test the calorimeter capabilities we have constructed a 20 layer PTP deposited quartz plate calorimeter prototype, and tested at various pion and electron beams. The test beam results show that 20 cm X 20 cm prototype can reach up to 13% of hadronic resolution. Considering the energy leakage from the undersize prototype, this is very promising result. On a bigger scale we believe a PTP deposited Quartz plate calorimeter can easily reach the current HE calorimeter performance, which is 8% hadronic resolution at 300 GeV energy pion beam.

Although it is out of context we reconfigured the prototype as an electromagnetic calorimeter and tested it at various electron beam energies. We got very promising results, which suggests a very radiation hard EM calorimeter option for future collider experiments.

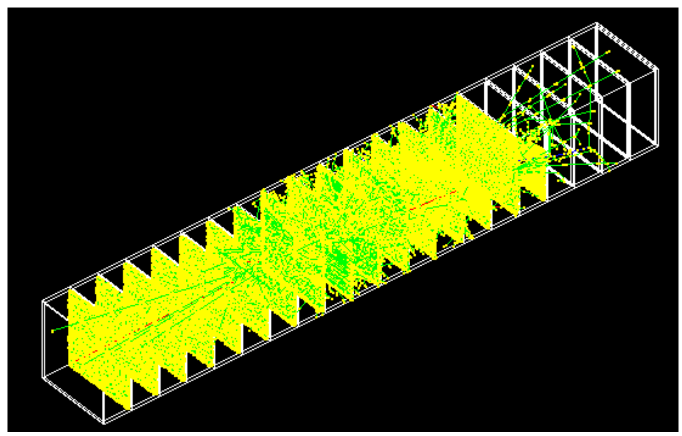

Fig. 13. Geant4 simulation of the calorimeter prototype.

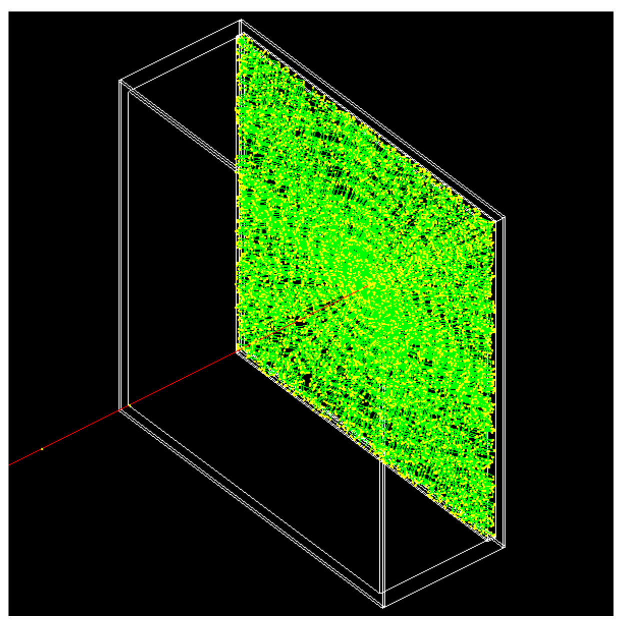

Fig. 14. Geant4 simulation of the single PTP deposited quartz plate.

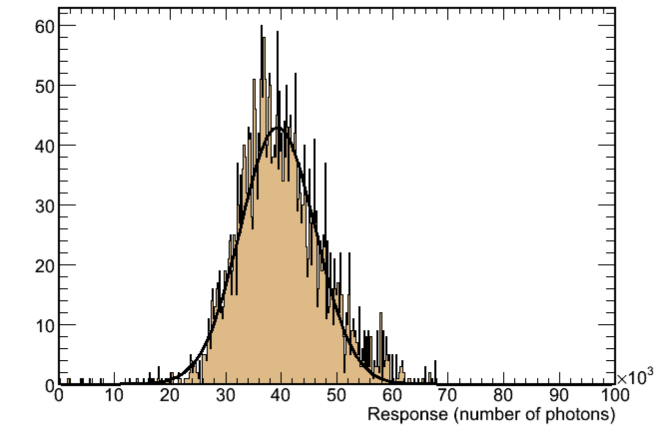

Fig. 15. Geant4 simulated response of 300 GeV pion beam on quartz plate calorimeter prototype.

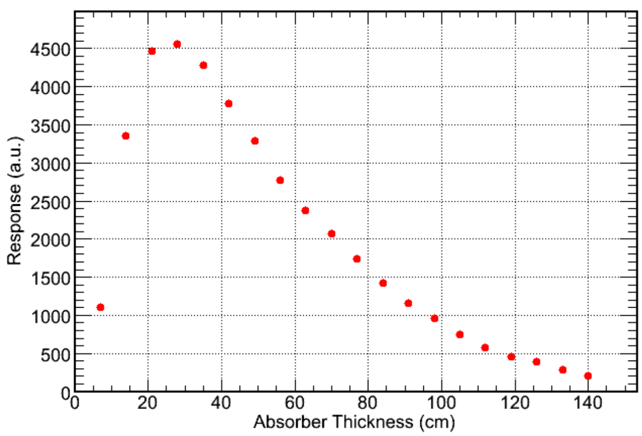

Fig. 16. Geant4 simulated shower profile of 300 GeV pion beam on quartz plate calorimeter prototype.

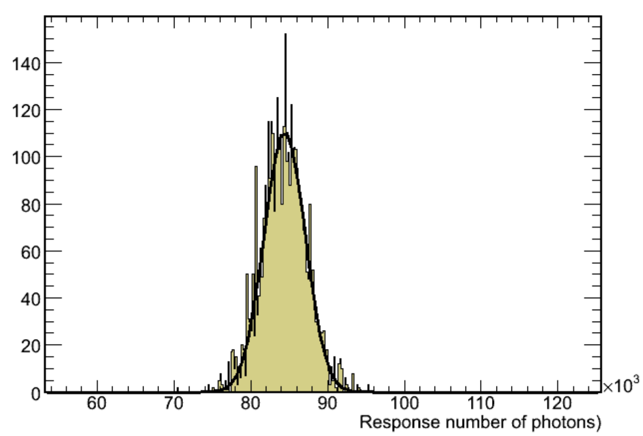

Fig. 17. Geant4 simulated response of 100 GeV electron beam on quartz plate calorimeter prototype.

Acknowledgment

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