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# CMS Hadronic EndCap Calorimeter Upgrade Studies for SLHC "Čerenkov Light Collection from Quartz Plate"

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## Abstract

Due to an expected increase in radiation damage under SuperLHC conditions, we propose to substitute the scintillator tiles in the original design of the HE Calorimeter with quartz plates. Quartz is shown to be radiation hard. Using wavelenght shifting fibers, it is possible to collect efficiently the Čerenkov light generated in quartz plates. This note summarizes the results from various test beams, bench tests, and Geant4 simulations done on methods of collecting light from quartz plates, as well as radiation hardness tests on quartz material.

# 1 Introduction

The Large Hadron Collider (LHC) is designed to provide 14 TeV center of mass energy with proton proton collisions every 25 ns. After a few years of running, the conditions of LHC will be upgraded to SuperLHC (SLHC), which will operate at 10 times higher luminosity (L = $10^{35}$ $cm^{-2}$ $s^{-1}$) allowing new physics discoveries. In the current design,the Hadronic Endcap (HE) Calorimeter of the Compact Muon Solenoid (CMS) detector uses Kuraray SCSN81 scintillator tiles, and Kuraray Y-11 double clad wavelength shifting (WLS) fibers. These materials have been shown to be moderately radiation hard up to 2.5 MRad [1]. The scintillation photons are collected by wavelength shifting fibers which have the geometry shown in Figure 1.

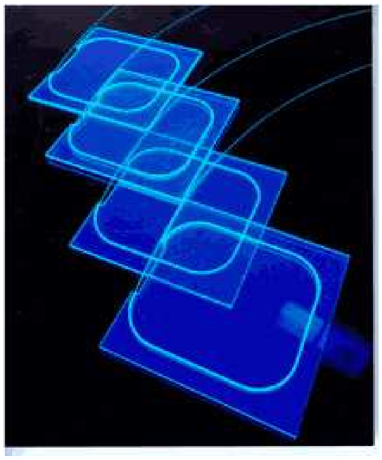

Figure 1: CMS HE Calorimeter Design for LHC [1]

Whereas, under the 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 HE Calorimeter will lose their efficiency due to high radiation. As a solution to the radiation damage problem at the SLHC era, we propose to substitute scintillators by quartz plates and carry out the light via UV absorbing, blue emitting WLS fibers. We performed radiation hardness tests on seven different types of quartz material. Results show that quartz will not be affected by the radiation at the dose of SLHC condition. However, when quartz plates are used, the detected photons come from Čerenkov radiation which yields 100 times less light than the scintillation process. Čerenkov photons are created when a charged particle passes through a medium with refractive index bigger than 1/$\beta$=c/v. The focus of this study is to find an efficient way to collect light from quartz plates. At the University of Iowa and Fermilab, we tested and simulated different sizes of quartz plates with different fiber geometries embedded in them to obtain maximum light. To make up the big deficit of light production, we chose the strategy of going deep in the UV region to collect Čerenkov photons since the number of generated Čerenkov photons increase as $1/\lambda^2$ [2]. In this report we present the results from the studies done on radiation hardness of the quartz material, and on finding an efficient way to collect light from quartz plates.

# 2 Radiation Hardness Tests

Quartz is known to be radiation hard in general. However, not all the quartz types have the same amount of radiation hardness. Among the different types of quartz it is important to find the best option to replace the CMS HE calorimeter tiles. For this purpose we selected seven different types of quartz material in the form of fiber from Polymicro Technologies. The selected quartz types were 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 [3]. The fibers were tested for light transmission degradation under a high background radiation. They were bombarded with pulses of high-energy neutrons produced by the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory for 313 hours. Seven sets, with five fibers each, were placed in an irradiation tube about 25 cm away from the IPNS target. These fibers were irradiated for a two-week period during which the integrated current delivered to the IPNS target was 4456 A-hrs. Fibers were exposed to 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. A light source and a spectrometer were used for these measurements. The light was sent into a bifurcated optical fiber and was split into two channels. The test setup is shown in Figure 2.

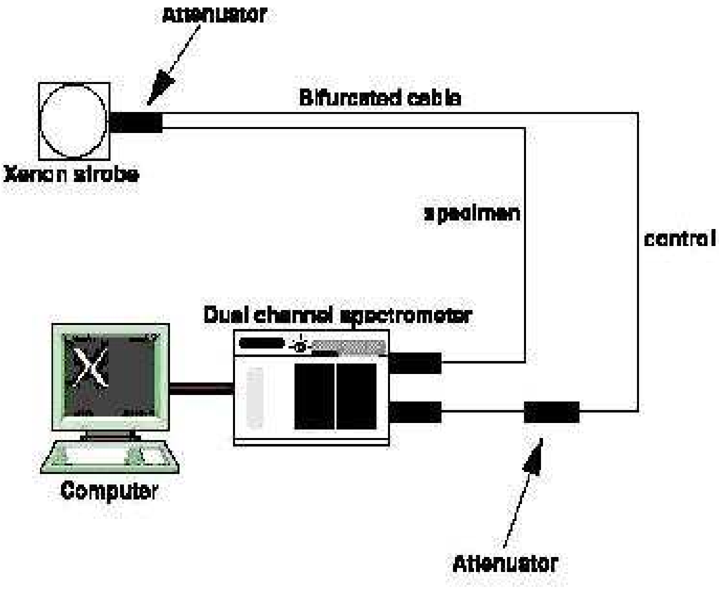

Figure 2: Optical transmission measurement setup the University of Iowa CMS Laboratories.

Tests show that a special radiation hard solarization resistant quartz fiber (FBP 600-660-710) gives the best results. The response of this fiber to the radiation can be seen in Figure 3, where the blue line is the response of the plate before being subject to the radiation and red line is the response after radiation.

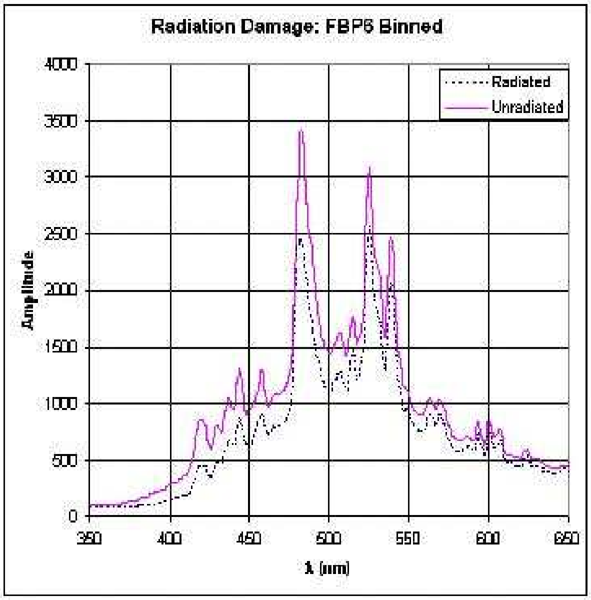

Figure 3: Light transmission test results for FBP 600-660-710 which was found to be very radiation hard.

## 3 Light Collection Tests

Our proposal is to collect the Čerenkov photons from the deep UV range to help to make up for the deficiency against scintillators. 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 Čerenkov 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 the edges of the plates.

We investigated the most uniform and efficient fiber embedding geometry to collect the Čerenkov photons. For this purpose, various fiber embedding geometries were considered. Here we report the result for the following geometries: Bar-Shape, HE-Shape, Y-Shape, S-Shape (see Figure 4).

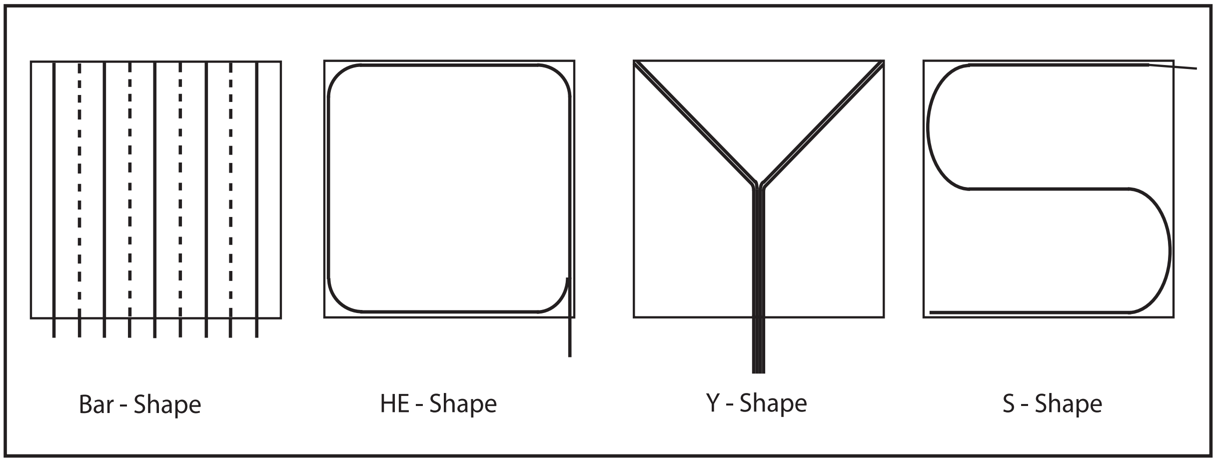

Figure 4: Fiber geometries embedded into quartz plates

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 of a reflective material as aluminum and Mylar in the UV and visible wavelength region. In all the tests reported below Hamamatsu R7525-HA photomultiplier tubes (PMTs) [4] were used for signal read-out from plates.

Light collection efficiencies and uniformities of the quartz plates were compared to that of the original HE scintillators at Fermilab test beams, and the bench tests in the University of Iowa. We also confirmed the results with GEANT4 simulations that will be discussed in the last section.

## 3.1 Light Collection Test Beams and Results

In the span of 18 months we performed three independent beam tests at the Fermilab M-Test facility.

The August 2004 run tested (20 cm x 20 cm x 3 mm) UV transmitting (UVT) acrylic plates, with different fiber geometries (HE-Shape, Y-Shape, S-Shape). The WLS fibers used were 0.6 mm diameter BCF-12. The UVT acrylic has the same refractive index as quartz (1.45), and other than not being radiation hard, it is the same as quartz for creating Čerenkov photons. Although the tests showed fewer Čerenkov photons compared to quartz, due to the fact that UVT absorbes more in the UV, being inexpensive and easy to machine make the UVT plates a good test tool. The light collection efficiencies of these plates were compared to two (20 cm x 20 cm x 4 mm) original HE scintillators with the original HE WLS fibers. The 120 GeV proton beam hit the center of 20 cm x 20 cm iron blocks. The shower was sampled at 1 inch increments from 5” to 13” of absorber depths for all plates. The original HE geometry quartz yielded only around 1% as much light as the scintillator plates, while the Y-Shape and S-Shape yielded 5%. This first test beam showed us that by varying the fiber geometries we can efficiently increase the Čerenkov light collection. Also, due to the fixed angle nature of the Čerenkov photons, it is not suitable to locate the WLS fibers at the edges of the plates. Instead we should place the fibers close to the photons for efficient light collection.

In January 2005, we perfomed tests on two sets of (10 cm x 10 cm x 3 mm) Polymicro quartz plates; 6 plates with high OH and 4 plates with low OH content. These quartz plates were grooved with S-Shape, HE-Shape and Y-Shape fiber geometries. Again, the BCF-12 WLS fibers of 0.6 mm diameter were embedded into these grooves. These quartz plates, and two (20 cm x 20 cm x 4 mm) original HE scintillators with original HE WLS fibers embedded in them, were exposed to 120 GeV and 64 GeV proton beams. Showers were created with iron absorbers and sampled at different shower depths. The amount of charge obtained from each geometry was compared to that of the original HE scintillator. The results from this second test beam show that the low OH quartz is slightly more efficient than the high OH quartz. The amount of light collected with the quartz increased dramatically compared to UVT plates. Also, with smaller plate sizes, the probability that Čerenkov photons would be captured by WLS fibers inside the plates was increased. As a result, the signal from the quartz plates was as much as $50\%$ of that from the light that original HE plate. Again the HE-Shape yielded the worst charge collection efficiency compared to the others. Also, we modified S-Shape and HE-Shape plates to read the signal from both ends of the WLS fibers, which increased the light collection by almost $25\%$.

From the two previous test beams and the surface uniformity studies, we concluded: a) For uniform Čerenkov light collection we need to distribute the fibers uniformly over the quartz plate. b) Efficient light collection requires an increase in (i) the number of Čerenkov photons created by using thicker quartz plates (ii) the cross section of Čerenkov photons to be captured by WLS fibers by using larger diameter WLS fibers.

To answer these efficiency and uniformity needs we designed a geometry called "Bar-Shape" (see Figure 4), in which the fibers are uniformly distributed on both sides of the quartz plate. In January 2006, we tested 6 Polymicro quartz plates with (20 cm x 20 cm x 6 mm) dimensions which were grooved in Bar-Shape to hold 1 mm diameter WLS fibers. Figure 5 shows the light collection comparison between the HE scintillator and the quartz plate with the Bar-Shape fiber geometry. Most of the points lie on the diagonal of the plot implying that the light collection abilities of the two plates are about the same.

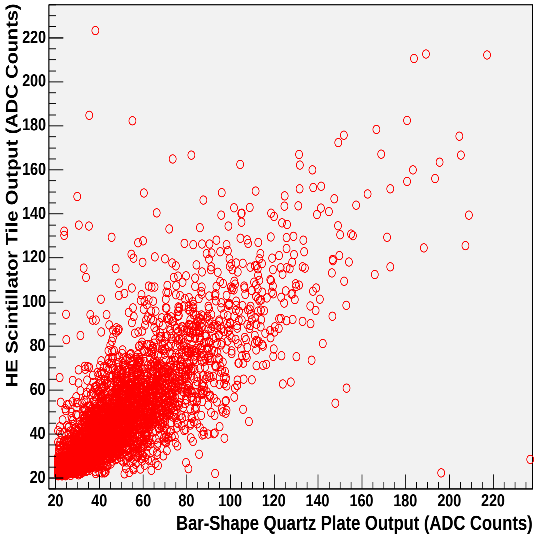

Figure 5: Comparison of Bar-Shape to HE scintillator: event by event ADC outputs from each plate. Weighted linear fit gives a slope of 1.42.

The test beam results are summarized in Figure 6. The light collection percentages of the quartz plates with four different fiber geometries with respect to the original HE scintillator are shown. It should be noted that, the percentage goes up to 70 percent with the bar shape.

# 4 Surface Uniformity Tests

At the University of Iowa CMS laboratories, we performed bench tests on all quartz fiber geometries for surface light collection non-uniformities.

UV-LED (380 nm), nitrogen laser (337 nm), and mercury lamp were used as light sources to imitate Čerenkov radiation, of various wavelengths, in quartz plates. The mercury lamp has 3 emission wavelenghts (253.65 nm, 365 nm, 404.7 nm). However, the absorption spectrum of BCF-12 WLS fiber is from 280 nm to 435 nm, which

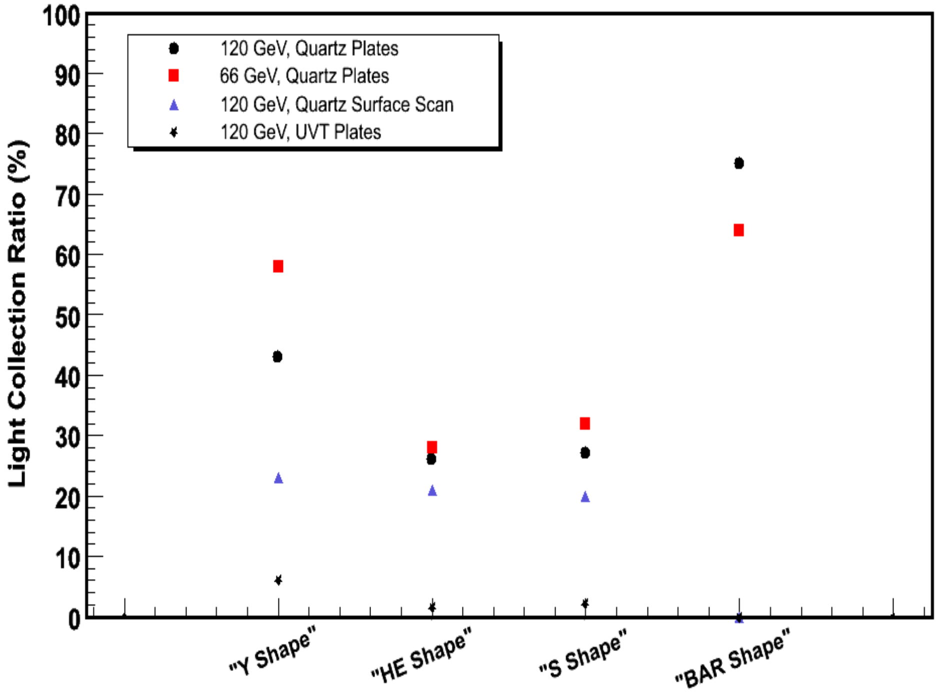

Figure 6: The light collection ratios of quartz plates with different fiber geometries to the original HE scintillator

eliminates the possibility of detecting the 253.65 nm photons with this setup. Quartz plates with four different fiber geometries (S-Shape, Y-Shape, HE-Shape, and Bar-Shape) were tested for light collection uniformity

Two dark boxes were used for these tests (see Figure 7) The light was generated in the first box and then carried to the second box by a quartz fiber of 600 $\mu$m diameter [5]. Only one surface of the quartz plates was wrapped with Tyvek. The light coming out of quartz fiber was directed onto the open surface of the plate from a 2 mm distance. The quartz plates were attached to a computer controlled X-Y scanner that has the capacity to scan the surfaces with 1/4000 inch step size. The light shined onto the surface was absorbed by WLS fibers and shifted/carried to Hamamatsu R7525 PMTs. For pulsing light sources (UV-LED and Laser), the PMT signal was processed by a data acqusition system that included a CAMAC and a LeCroy 2249A ADC. For DC light source (mercury lamp) the PMT current was read by a picoammeter. For both cases the DAQ is monitored online by LabView software. The pulse frequency was 20 Hz for the Nitrogen laser and 10 kHz for the UV-LED. Neutral density filters were used to make the light intensities same for all sources.

The current test design allows a comparison of the light collection uniformities of the different fiber geometries. The test results are in good agreement with GEANT4 simulations from which we can get absolute light collection uniformity values.

The bench tests show that Bar-Shape is the most uniform geometry. This fiber geometry yields an even more uniform light collection than the original HE scintillator. The ratio of the Bar-Shape nonuniformity to that of the HE scintillator is measured to be around 0.75. All the other fiber geometries have a surface nonuniformity around twice the nonuniformity of the Bar-Shape. The surface uniformity plot for the Bar-Shape is shown in Figure 8.

## 5 GEANT4 Simulations

We performed GEANT4 [6] simulations to study photon production, collection efficiencies and surface non-uniformities in a quartz plate and WLS fiber system. As in the real plate samples, in the simulated model the WLS fibers are embedded in the quartz plate. The Čerenkov photons created in the quartz plates are wavelength shifted in the fiber and detected by the photocathode of the photomultiplier tube. We studied four different fiber

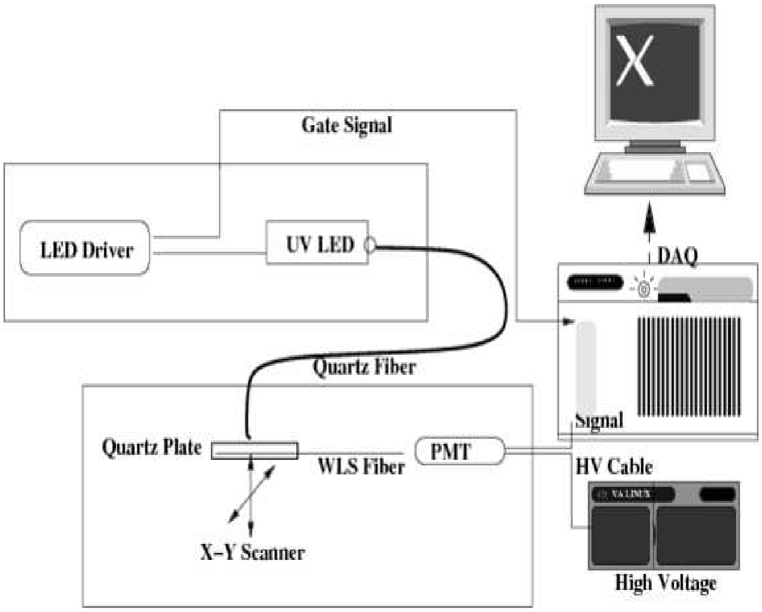

Figure 7: Surface uniformity tests setup in the University of Iowa CMS Laboratories

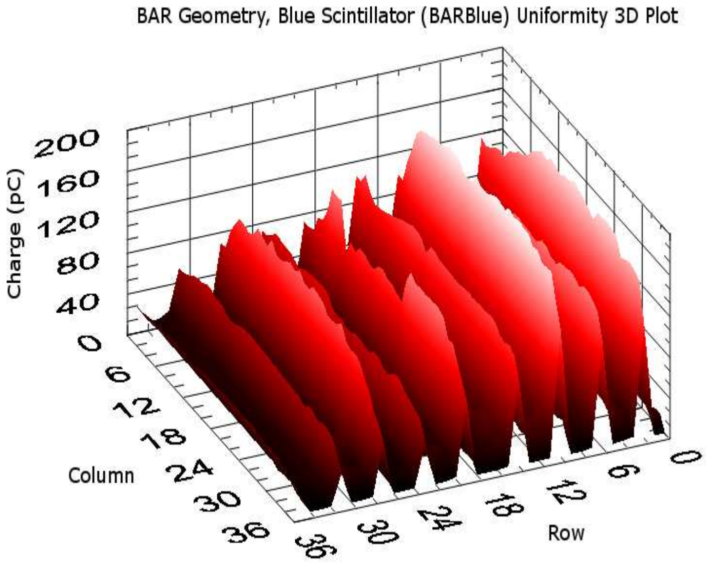

Figure 8: The charge collected by bar-shape

geometries: the Bar-Shape, Y-Shape, S-Shape and HE-Shape (see Figures 9,10,11, 12).

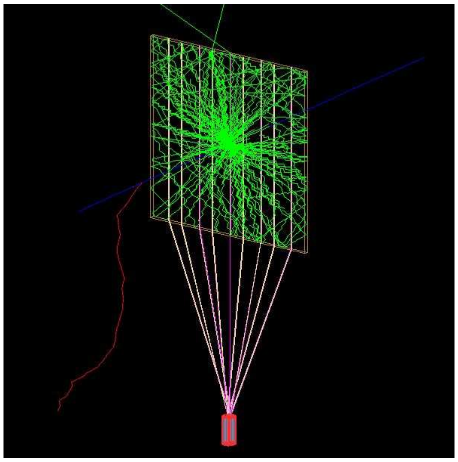

Figure 9: Bar-shape

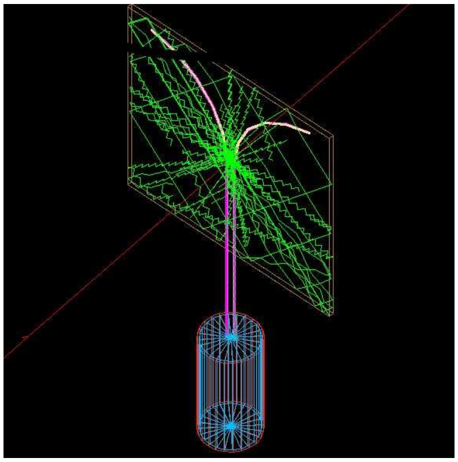

Figure 10: Y-shape

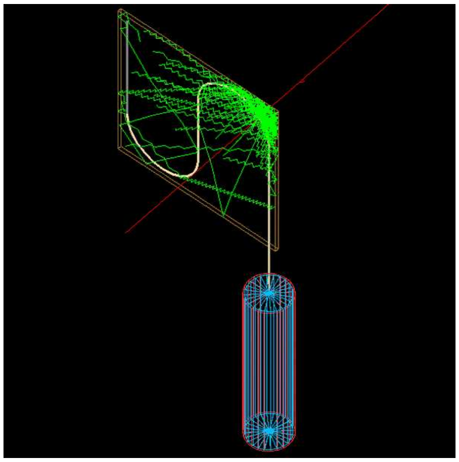

Figure 11: S-shape

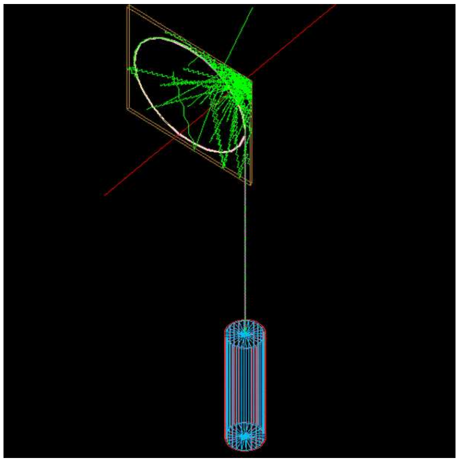

Figure 12: O-shape

The model quartz plates are 2 mm thick and have a cross sectional area of 10 cm x 10 cm. The WLS fibers have a core diameter of 600 $\mu$m. Quartz plates are wrapped with a reflecting material that has a 95% reflection efficiency to imitate the effect of Tyvek. The quartz and WLS fiber attenuations are included in the simulation, as well. The absorption and emission spectra of Bicron 91 WLS fiber is used in the simulations. As shown in Figure 13, the absorption peaks around 425 nm, and below 390 nm the relative amplitude is less than 50%. The emission spectra maximum is around 495 nm and falls below 50% after 510 nm. Wavelength shifted photons reaching the PMTs are counted.

Some of the Čerenkov photons go into the core of WLS fibers. Among those photons the ones with energies within the absorption spectrum of the WLS fiber are absorbed and then emitted at a shifted energy.

In order to compare the light collection efficiencies and surface nonuniformities of different fiber configurations, we have simulated a surface scan with a 4 GeV electron beam. The scan was carried out in a grid with 1 cm increments in the x and y directions. For each (x,y) point, a total of 1000 4 GeV electron events were recorded. For each event the total number of photons reaching to the PMT cathode and their arrival time were recorded to be analyzed offline. The photon arrival time is defined as the time interval between the creation of Čerenkov photons and the detection of wavelenght shifted photons by the PMT.

In Figures 14, 15, 16 and 17, the profiles of the number of photons reaching the PMT as a function of the beam position are shown. The figures show that the PMT signals are larger when the beam is closer to the WLS fibers. As can be seen, bar-shape geometry has a more uniform charge collection since the fibers are more uniformly distributed throughout the plate.

According to the simulations of the surface scan, the light collection non uniformities are 62%, 36%, 52%, and

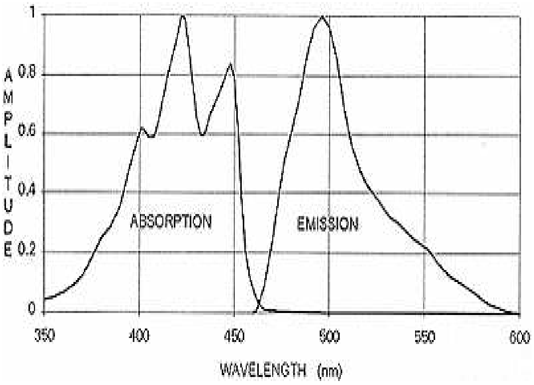

Figure 13: The absorption and emission spectra of Bicron 91 wave length shifting fiber.

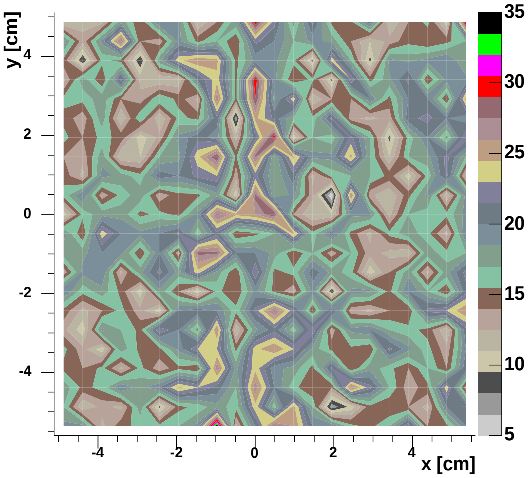

Figure 14: Bar-shape

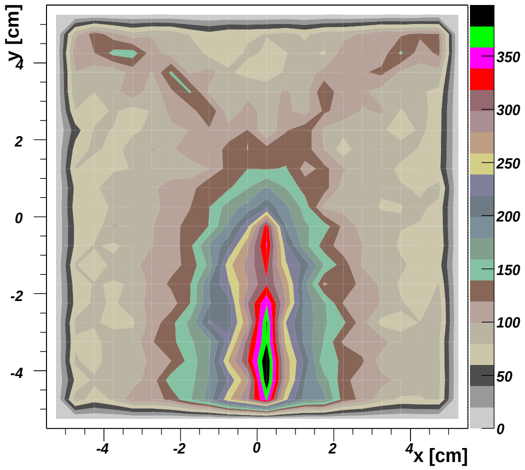

Figure 15: Y-shape

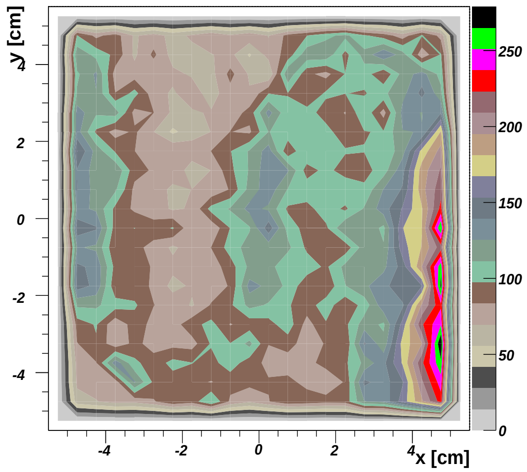

Figure 16: S-shape

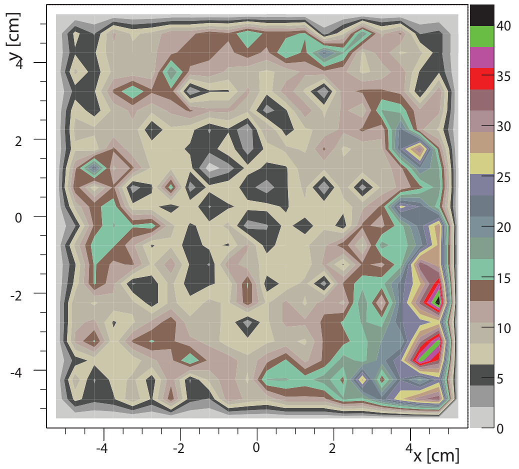

Figure 17: O-shape

26% for HE-Shape, S-Shape, Y-Shape and Bar-Shape, respectively. These results are in excellent agreement with the bench tests. Bar-shape has the most uniform light collection ability.

The comparison of the light collection efficiencies between different fiber geometries was done by taking the ratios of the mean number of photons collected at each beam position. Bar-Shape has the highest light collection efficiency. The simulated light collection ratios can be normalized with respect to Bar-Shape. The values are as follows: Bar-Shape: 100%, Y-Shape: 90%, S-Shape: 85%, and HE-Shape: 70%. The same efficiency order is also observed at the test beams.

Another important parameter is the arrival time of the photons to the PMT as there will be finite amount of time that a gate will be opened to measure the signal. Simulations show that mean arrival time of photons to the PMT cathode is less than 5 ns for all fiber geometries.

## 6 Conclusion

The current scintillator design of the CMS HE Calorimeter is not adequate for the high radiation environment of the SLHC era. We propose to replace the scintillator tiles by quartz plates where we will collect photons from Čerenkov process which will yield much less light than scintillation.

Radiation damage tests at Argonne Laboratories showed that Polymicro FBP 600-660-710 solarization resistant quartz is the most radiation hard of the tested quartz types.

Simulations show that the amount of Čerenkov radiation in quartz plates is around 1% of the scintillation photons from the same size scintillator tiles yield. To collect the more light in an efficient way, we worked on different plates with different sizes and different fiber geometries embedded in them.

After many test beams and bench tests we came to the conclusion by that 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. The plate with the Bar-Shape fiber geometry is shown to be very uniform since the fibers are distributed uniformly throughout the surface.

To improve the light collection, thicker quartz plate with smaller size, and more WLS fibers embedded in it should be used. It should be remembered that the space between the absorber layers of HE calorimeter (9 mm) limits the thickness of the quartz plates.

Elaborate simulations show that the surface nonuniformity is around 26% for the Bar-Shape and the ratio of collected light with respect to HE scintillator is around 70%. The analyses of the mean arrival time showed that the light collection is extremely fast ($< 5$ ns) which makes quartz a good candidate in the SLHC era. Even if the 10 times higher luminosity is obtained by decreasing the bunch crossing to 12.5 ns, the photon arrival time for quartz plates will be well within the gate.

## 7 Acknowledgement

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# References

[1] **The HCAL Technical Design Report**, CERN/LHCC 97-31, CMS TDR 2, 20 June 1997

[2] G. F. Knoll, **Radiation Detection and Measurement**, 1989

[3] P. Bruecken et al, **Radiation Damage in Quartz Fibers Exposed to Energetic Neutrons**, CMS Internal Note 2006/014, http://cmsdoc.cern.ch/doc/notes/docs/IN2006-014

[4] U. Akgun et al., **Complete Tests of 2000 Hamamatsu R7525HA Phototubes for the CMS-HF Forward Calorimeter**, CMS-NOTE-2004-019, Jul 2004. 18pp. Published in Nucl.Instrum.Meth.A550:145-156,2005

[5] U. Akgun et al., **Radiation Damage and Light Transmission Studies on Air Core Light Guides**, IEEE Trans.Nucl.Sci.53:1547-1550,2006

[6] S. Agostinelli et al, Nuclear Instruments and Methods in Physics Research, NIM A 506 (2003), 250-303.