Available on CMS information server

CMS CR -2009/051

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

22 January 2009 (v2, 02 April 2009)

THE SLHC PROGRAM AND CMS HADRON CALORIMETER UPGRADES

Y. Onel

Abstract

The Large Hadron Collider (LHC) is designed to provide 14 TeV center of mass energy with proton-proton collisions every 25 ns. After several years of running, the LHC will be upgraded to the super-LHC (SLHC), which will operate with 10 times higher luminosity (L = $10^35cm^-2s^-1), therebyallowingnewphysicsdiscoverie$

Presented at *International Conference on Particle Physics ”In Memoriam” Engin Arik and Her Colleagues,October 27-31, 2009,Istanbul,Turkey,16/01/2009*

BALKAN PHYSICS LETTERS

27-31 October 2008
BPL, **8** (2), pp. 1 - 13 (2008)

THE SLHC PROGRAM AND CMS HADRON CALORIMETER UPGRADES

Y. ONEL
Department of Physics and Astronomy, The University Of Iowa,
Iowa City, Iowa, U.S.A.

Abstract. - The Large Hadron Collider (LHC) is designed to provide 14 TeV center of mass energy with proton-proton collisions every 25 ns. After several years of running, the LHC will be upgraded to the super-LHC (SLHC), which will operate with 10 times higher luminosity (L = 10^{35} cm^{-2}s^{-1}), thereby allowing new physics discoveries. The impact of the LHC luminosity upgrade on the CMS detector is discussed.

The Large Hadron Collider (LHC) [1], at the CERN Laboratory, the European Laboratory for Particle Physics, outside Geneva, Switzerland, will start running in 2009. The LHC will collide two proton beams, circulating in opposite directions, at an energy of 7 TeV each (centre of mass energy $\sqrt{s} = 14$ TeV). The accelerator has been designed to run at a peak luminosity of L = 10^{34} cm^{-2} s^{-1}. The CMS experiment is a general purpose detector designed to explore physics at the TeV energy scale [2]. It is expected that the data produced at the LHC will reveal the electroweak symmetry breaking mechanism (EWSB) and provide evidence of physics beyond the standard model. The detector and the accelerator were designed for a physics program which would deliver several hundred fb^{-1} of integrated luminosity at a peak luminosity of L = 10^{34} cm^{-2} s^{-1} Continued running of the LHC much beyond 500 fb^{-1} without upgrades of the machine and detectors will not be profitable due to;

- elements of the machine reaching their radiation damage lifetime,
- radiation damage to the central tracker,
- very long time required to further accumulate a sufficiently large data sample to significantly increase the desired statistical precision.

The current plan to upgrade the LHC has two phases:

- Phase 1: LHC luminosity will be upgraded to $L = 2 - 4 \times 10^{34}$, keeping 25 ns bunch crossing. For this phase there will not be any changes to IR inside CMS and only a short downtime will be required. The CMS experiment will be ready for Phase 1 in 2013, at the earliest.
- Phase 2: The details will be decided in 2011, the luminosity is expected to reach $L = 8 - 10 \times 10^{34}$. The bunch crossing will be 25 or 50 ns. Phase 2 will possibly require changes to inside CMS, and a long shutdown. The CMS experiment could be ready as soon as 2017 (see Figure 1).

CMS is designed to perform at 10^{34} luminosity. Increase in luminosity will require some issues to be addressed. These are radiation damage, high occupancy affecting reconstruction or triggering, high occupancy that leads to buffer overflows and to problems with link bandwidth and pileup creating dead time or affecting trigger performance. Figure 2 summarizes the upgrade path for detector components. CMS is designed to be opened and accessed, so these upgrades should be easy to install.

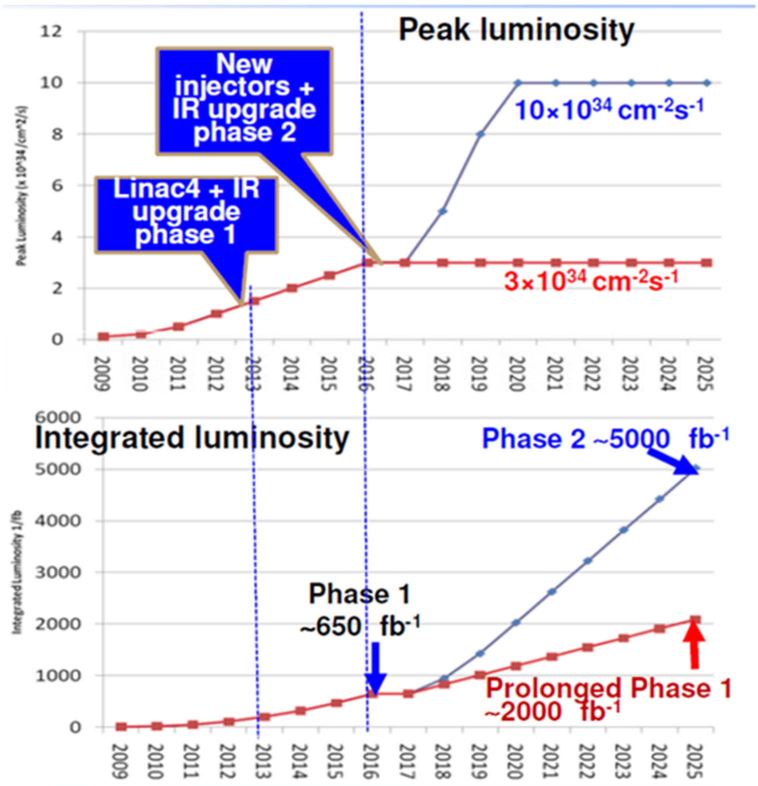

Figure 1: LHC to SLHC physics evolution [3].

Component	10^{34}	$3x10^{34}$	10^{35} or prolonged phase 1
TRACKER Pixel	OK	Rad/Occ: Replace/Add layers/disks	Rad/Occ: Full Replacement
TRACKER Strip	OK	OK	Rad/Occ: Full Replacement
ECAL Barrel	OK	OK	OK
ECAL Endcap	OK	OK	Rad high η: replace
HCAL Barrel	OK	Performance: Upgrade readout X4	No further action
HCAL Endcap	OK	Rad: Upgrade readout X4	Rad high η: new scintillators
HCAL Forward	OK	Rad: Upgrade readout X2	Rad/Occ: replace
HCAL Outer	HPD upgrade	No further action	No further action
MUON Drift Tube Barrel	OK	Change minicrates	Occ: upgrade electronics
MUON Cathode Strip chambers Endcap	OK	Occ: Add planes	Occ: upgrade electronics
MUON Resistive chambers Endcap	OK	Occ: Add planes	Occ: upgrade electronics
TRIGGER	OK	Enhancements	Occ: tracking in L1 trigger

Figure 2: The list of CMS components that will be affected from LHC upgrade radiation and occupancy increase. Red: Severe degradation, blue: Reduced performance.

The CMS Detector

The CMS detector measures roughly 22 meters in length, 15 meters in diameter, and 12,500 metric tons in weight. Its central feature is a 4 Tesla solenoid, 13 meters in length, and 6 meters in diameter. Along with the silicon microstrip tracking detector, the electromagnetic and hadronic calorimeters are contained within the solenoid coil. Muon detection is embedded in the flux return iron of the magnet. A drawing of the detector can be seen in Figure 3 and a detailed description of the construction and performance of its detector systems can be found in [2]. The innermost tracking for the barrel region (BPIX) is accomplished with a three layer (4.4 cm, 7.3 cm, 10.2 cm) silicon micro pixel detector and with two disks of pixels (FPIX) in each forward region (34.5 cm and 46.5 cm from the IP) with a total area of approximately 1m^2 composed of 66 million 100×150 μm^2 area pixels. These detectors are designed to withstand the high occupancy and fluence of the LHC. The remaining tracking layers are composed of 11 million channels of silicon microstrip detectors. In total nearly 200m^2 of detectors organized in an inner barrel (TIB) 4 layers occupying a radius 20 cm - 50 cm, an outer barrel (TOB) 6 layers occupying a radius 55 cm - 120 cm, and two endcap detectors (TEC,TID). At nominal luminosity, the expected occupancy of the strips in the TIB at LHC is 2-3% while the occupancy in the TOB should be $\approx$ 1%. As described above, the SLHC machine upgrade scenarios could increase these expected occupancies by up to a factor of 20. A combination of increasing the area of the pixel detector, and shortening the strip length will be required to cope with the increased occupancy. In addition new technologies may be required for the innermost layer where the radiation effects will be extreme.

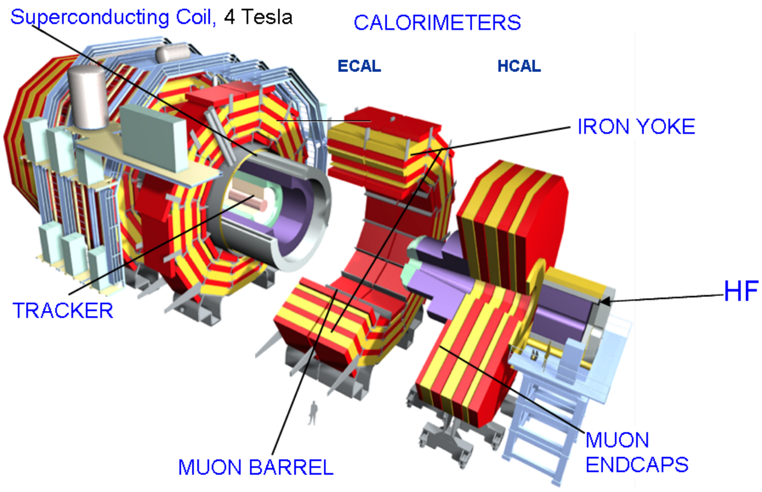

Figure 3: CMS Detector general view.

The electromagnetic calorimeter has a barrel section covering the region $|\eta| < 1.479$ and two endcaps completing the coverage up to $|\eta| < 3.0$. The barrel consists of 61200 lead tungstate crystals read out by silicon avalanche photodiodes (APDs). The two endcaps contain a total of 14648 crystals read out by vacuum phototriodes (VPTs). Hadronic calorimetry is achieved with scintillator embedded in brass absorber, where the light is read out using hybrid photodiodes (HPDs). The barrel sections of these calorimeters are expected to operate even in the extreme environment of the SLHC, while the forward regions HE and HF may require replacement or modification. The CMS muon detection system uses three technologies. Drift tubes (DT) are used in the CMS barrel. Cathode Strip Chambers (CSC) are used in the endcaps, and Resistive Plate Chambers (RPC) are used in parallel with the other detectors in both the barrel and endcap. The muon system is well shielded by the CMS iron yoke, and it is expected that the detectors should continue to operate in the SLHC regime, with only a potential need for changes in the shielding in the forward regions ($2 < |\eta| < 4$) and possible upgrades for the on-detector electronics required. The CMS trigger takes input from the calorimeters and muon systems to form a Level-1 decision. At each Level-1 trigger, the data are sent to a higher level software trigger (Level-3) processing farm where the full event data are available for making a trigger decision. The current maximum rate for Level-1 triggers is 100 kHz. It is proposed that any upgrade continue to respect that limit, but this implies a required increase in the bandwidth of the data acquisition system. In addition it appears that the current muon and calorimeter triggers may not have sufficient capability to reject background at high luminosity. In order to greatly increase the rejection power of the Level-1 trigger, it is proposed to bring in information from the upgraded tracking detector. This requires substantial new developments in the tracking system, and a complete replacement of the central trigger, but offers the possibility of much more information in the trigger decision taken at the SLHC.

Physics Case

The SLHC, with its order of magnitude greater luminosity, will extend the discovery reach of the LHC for new particles such as those arising from Supersymmetry, or new forces and will allow for detailed measurements of Standard Model processes and any new phenomena discovered during LHC operations. The precision measurement of electroweak parameters is a tool to look indirectly for physics beyond the Standard Model. One such measurement is that of multiple gauge boson production. The luminosity of the SLHC will provide for improvements on the limits of anomalous triple and quartic gauge boson couplings by a factor of about two, depending on the coupling. Even measurements of events with four gauge bosons in the final state will become accessible at the SLHC. The Standard Model Higgs, if it exists, will have been discovered by the time the SLHC starts its operation. It will however remain important to measure its properties more precisely. If Supersymmetry (SUSY) has not yet been discovered in data samples collected during LHC running, inclusive searches may continue with the larger integrated luminosity of the SLHC. For example, in the minimal Supergravity model (mSUGRA), a search for an excess of events in the high-E_T jets and large Miss-E_T signature can extend the discovery reach by an additional 0.5 TeV in squark and gluino mass (from 2.5 to 3.0 TeV/c^2) in going from 100 fb^{-1} to 1000 fb^{-1}. Such a search is based on measurements made by the calorimeters, where the jet energy deposition (and thus the jet E_T threshold) scales with the SUSY mass scale. For inclusive searches involving leptons, we note that the lepton p_T is less correlated with the SUSY mass scale since many leptons originate from the cascade decays of SUSY particles. In order to disentangle the particle spectrum for the mass reach of SUSY, E_T jet measurements will be especially important up to 3 TeV.

SLHC Triggers and DAQ

The CMS trigger and data acquisition systems (TRiDAS) will need significant modifications to operate at the SLHC design luminosity up to ten times the LHC design luminosity of 10^{34} cm^{-2} s^{-1}, possibly with a crossing frequency half the present 40 MHz. Due to the increased occupancy of each crossing, at the SLHC Level-1 trigger systems would experience degraded performance of the LHC algorithms presently planned to select the 100 kHz of crossings from the input rate of 40 MHz. The electron isolation algorithms would experience reduced rejection at fixed efficiency and the muon trigger would experience increased background rates from accidental coincidences. The DAQ system would experience larger event sizes due to greater occupancy. If new, higher channel-count trackers replace the existing ones, then the

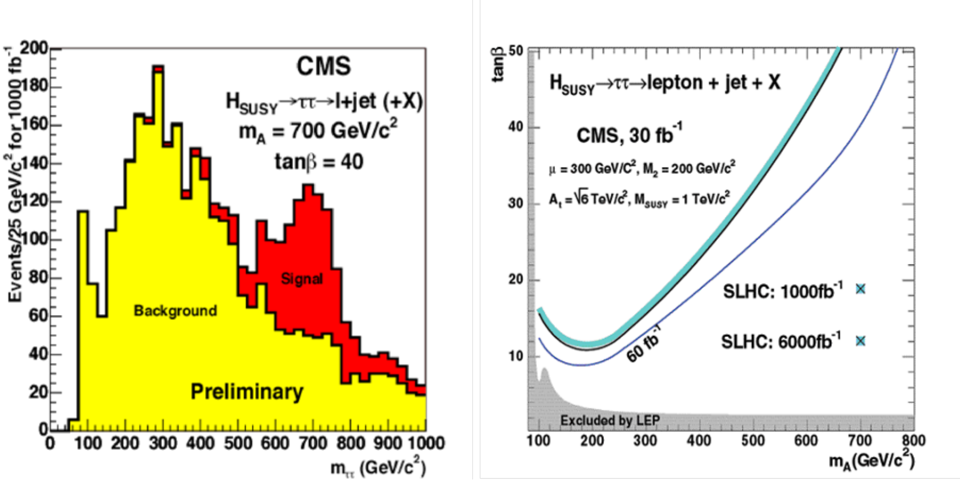

Figure 4: (left) Peak at 5σ limit of observability at LHC greatly improves at SLHC (fast simulation). (right) Order of magnitude increase in statistics with SLHC should allow tanβ to go down to 20.

increase would be greater. This would reduce the maximum Level-1 trigger rate for a fixed readout bandwidth.

The goal of the CMS SLHC TriDAS system is to enable a physics program with integrated luminosity roughly ten times that of the LHC or about 3000 fb^{-1}. The priority for the CMS SLHC TriDAS system is to capture the physics of the SLHC with the highest efficiency possible at acceptable detector readout and data storage rates.

In order to meet the challenges of SLHC operation the suggested approach is to hold the overall Level-1 trigger rate at the LHC value of 100 kHz while increasing the readout bandwidth. This approach avoids rebuilding front-end and readout electronics as much as possible since these were designed for an average readout time of less than 10 μsec. The additional layer of processing for combination of tracking information, increased algorithm complexity and larger trigger data volume due to finer trigger granularity suggest an extension of the present CMS 3.2 μs L1 latency. A longer latency would also be needed for use of FPGA embedded serializers and deserializers, the addition of more serialization and deserialization steps to use high speed serial links or the use of buffers to incorporate commercial serial links running asynchronously with respect to the LHC clock. The CMS L1 latency is limited by the front-end analog storage capacity of the tracker and preshower electronics. Since it is expected that these detectors will be replaced for the SLHC, it is reasonable to assume that their electronics will also be replaced and that this limitation can be removed. The next limitation is the ECAL digital memory depth of 256 40 MHz samples corresponding to time of 6.4 μs. This is proposed as the CMS SLHC L1 latency baseline.

The Barrel region of HCAL is largely immune to the changes in environment between the LHC and the SLHC. The high eta region of the endcap hadronic calorimeter (HE) will suffer extensive radiation damage requiring replacement. Improvements in MIP recognition in the outer hadronic calorimeter (HO) will be desirable. Finally the HCAL readout electronics need to accommodate higher bandwidth in readout and finer trigger primitive granularity. In the current design, HE uses plastic scintillator tiles and wavelength shifting fiber. These materials have been shown to be moderately radiation hard up to the 2.5 Mrad limit expected from 10 years operation of the LHC. Under the SLHC conditions the lifetime radiation dose at the HE will increase from 2.5 Mrad to 25 Mrad. The scintillator tiles used in the current design of HE will lose their efficiency due to high radiation. They will need to be replaced with new devices that fit in the geometric constraints of the existing absorber structure. There are several possible solutions, including new scintillators, parallel plate chambers, silicon sensors, and quartz plates that generate Cerenkov light rather than scintillation light. Each of these solutions is being pursued.

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. To investigate different fiber radiation damage properties under various radiation types the following tests have been performed;

Quartz Radiation Damage with Electrons

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 [4].

Quartz Radiation Damage with Protons

To complete our knowledge of radiation damage in quartz fibers and to investigate their possible use at the Super LHC (SLHC) we initiated high level irradiation 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 [5]. 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. The attenuation measurements were performed in-situ. We tested quartz fibers with quartz cladding (qq) and with plastic cladding (qp). Radiation damage due to protons and damage recovery are in agreement within errors with our previous results of electron irradiations with the same type of quartz used by Polymicro Technology Inc. The two types of irradiation were quite different: 24 GeV protons compared to 0.5 GeV electrons, in different geometries. 1.25 Grad with protons compared to 50Mrad with electrons.

Quartz Radiation Damage with Neutron and Gamma

We also performed radiation damage tests to measure the degradation of quartz optical fibers under neutron and gamma radiation, which is expected to be present in the CMS hadronic calorimeters at the LHC and even more during SLHC. 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 [6]. The fibers were tested for light transmission degradation after a large radiation dose. 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, of 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 μA-hrs. 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. An Ocean Optics PX-1 Xenon flash lamp and an Ocean Optics SD2000 spectrometer were used for these measurements. The light was sent into a bifurcated optical fiber and was split into two channels. The tests show that a special radiation-hard solarization resistant quartz fiber (FBP 600-660-710) gives the best results. Solarization is defined as a phenomenon where a temporary change occurs to a material due to exposure to high energy electromagnetic radiation. The response of this fiber to the radiation can be seen in Figure 5, where the solid line is the response of the quartz fiber before being subject to the radiation and the dotted line is the response after irradiation.

Cherenkov light and a quartz plate calorimeter

To collect the Cherenkov photons from the far-UV range BCF-12 WLS fibers, which can absorb photons down to 280 nm and emit at 435 nm, will be used. 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 considered. Here we report the results for the following geometries: Bar-shape, HE-shape, Y-shape, and S-shape (see Figure 6). 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 [7,8]. In all the tests reported below Hamamatsu R7525-HA photomultiplier tubes (PMTs) [9,10,11] were used to measure the light at the end of the fibers.

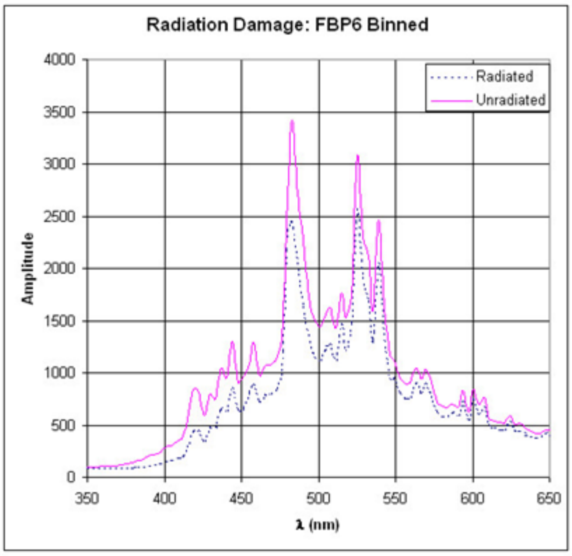

Figure 5: FBP 600-660-710 spectra before (red) and after (black) radiation.

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.

The plate with the barshape fiber geometry is shown to be very uniform since the fibers are distributed uniformly throughout the surface. To improve the light collection, a thick quartz plate with a small area, and many 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. Simulations

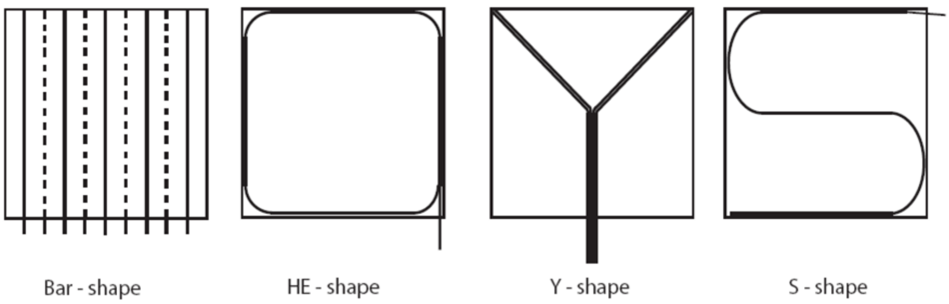

Figure 6: Fiber geometries embedded into quartz plates. The dotted lines of the bar-shape represent the fibers on the other side of the plate.

show that the surface non-uniformity of light output is around 26% for the bar-shape and the ratio of collected light with respect to HE scintillator is about 70%. The analyses of the mean arrival time showed that the light collection is extremely fast (< 5 ns) which makes quartz a good candidate for the SLHC era.

However, when quartz plates are used, the detected photons come from Cherenkov radiation, which yields 100 times less light than the scintillation process [6,7]. 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.

In our preliminary tests we used PTP [12] 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 Figure 7 left). 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 Figure 8 right). 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.

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 $\times$ 20 cm $\times$ 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. Though preliminary results showed that

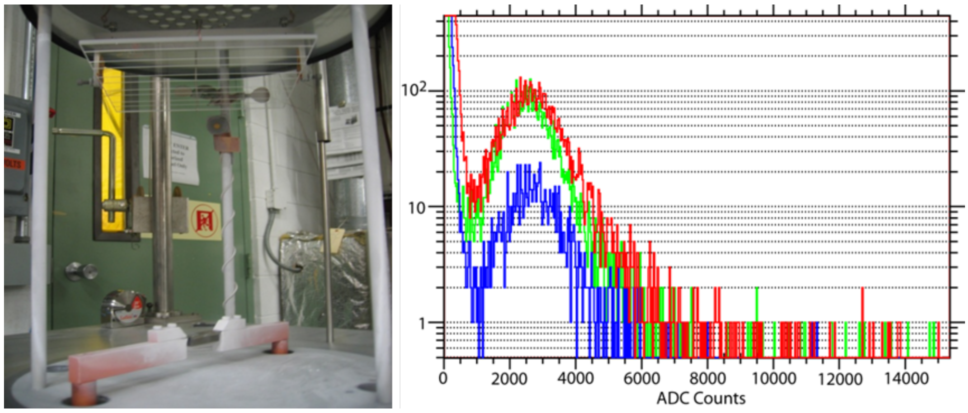

Figure 7: (left) PTP evaporation setup in Fermilab Thin Film Laboratory. (Right) Light yield from 2m thickness of PTP (red), 0.2 μm thickness of Ga:ZnO (green) deposited quartz plates, and clean quartz plate (blue).

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.

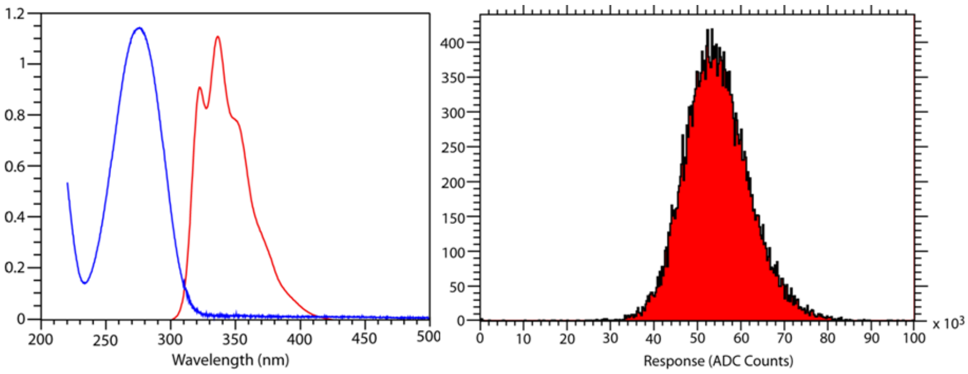

Figure 8: (Left) Absorption and emission spectrums of PTP. (Right) 300 GeV pion response of the calorimeter prototype on Hadronic configuration.

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. At every beam energy data sample, the signals from all layers were added to find the total calorimeter response. Figure 8-right 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 Figure 9-left). The PTP deposited quartz plate calorimeter prototype's hadronic resolution is plotted in Figure 8-right. 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.

GEANT4 simulations were also performed on the simulated model of quartz plate calorimeter prototype. Absorption and emission spectrums from Figure 8-left 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 Figure 10-left). The same agreement is also exist on electron response (see Figure 10-right).

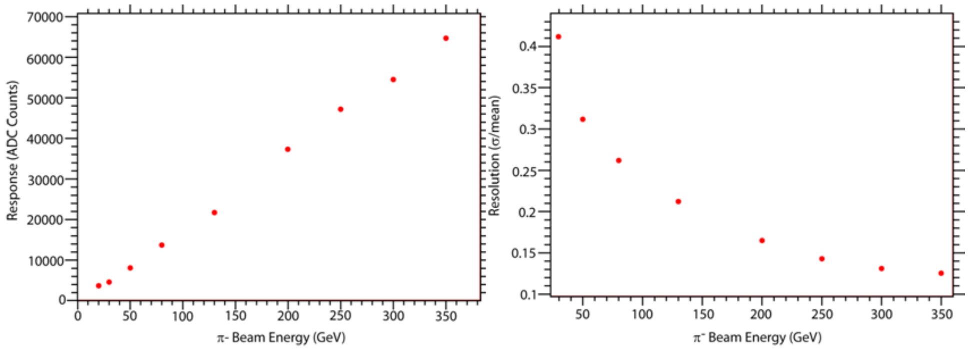

Figure 9: Hadronic response linearity (left) and energy resolution (right) of the calorimeter prototype for various pion beam energies.

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 candidates to replace the scintillator tiles of CMS HE calorimeter. Quartz and PTP are very radiation hard and cost effective options. 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 × 20 cm prototype

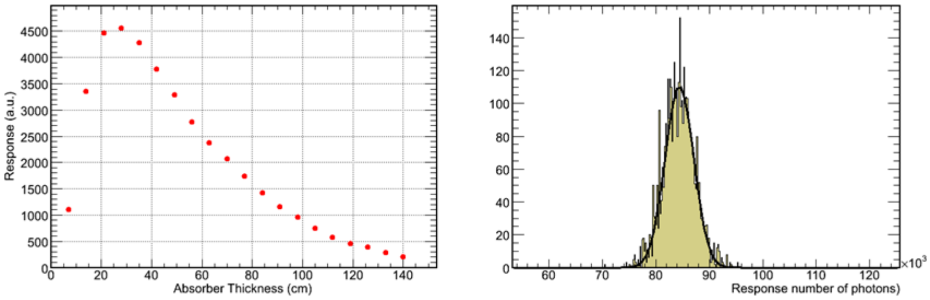

Figure 10: (Left) Geant4 simulated shower profile of 300 GeV pion beam on quartz plate calorimeter prototype. (Right) Geant4 simulated response of 100 GeV electron beam on quartz plate calorimeter prototype.

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.

REFERENCES

[1] De Roeck, Ellis, Gianotti, hep-ph/0112004; Gianotti et al, hep-ph/0204087, Eur. Phys. J. C39, 293(2005).

[2] CMS Collaboration, "The CMS experiment at the CERN LHC," J. Inst. 3, 2008 JINST 3 S08004 (2008).

[3] W. Scandale, F. Zimmermann, "Scenarios for sLHC and vLHC", Nucl. Phys. B (Proc. Suppl.) 177-178 (2008), 207-211.

[4] Dumanoglu et al., "Radiation-hardness studies of high OH- content quartz fibres irradiated with 500 MeV electrons", Nucl. Instr. Meth. A 490, 444-455, 2002.

[5] K. Cankocak et al., "Radiation-hardness measurements of high OH- content quartz fibres irradiated with 24-GeV protons up to 1.25-Grad.", Nucl. Instrum. Meth. A 585, 20-27, 2008.

[6] U. Akgun and Y. Onel, "Radiation-Hard Quartz Cherenkov Calorimeters", AIP Conf.Proc.867:282-289,2006. Also in "Chicago 2006, Calorimetry in high energy physics" 282-289, 2006.

[7] U. Akgun et al., "Quartz Plate Calorimeter as SLHC Upgrade to CMS Hadronic Endcap Calorimeters", XIII International Conference on Calorimetry in High Energy Physics, CALOR 2008, Pavio, Italy, 2008.

[8] F. Duru et al., "CMS Hadronic EndCap Calorimeter Upgrade Studies for SLHC - Cerenkov Light Collection from Quartz Plates", IEEE Trans. Nucl. Sci., Vol 55, Issue 2, 734-740, 2008.

[9] U. Akgun et al., "Afterpulse Timing and Rate investigation of Three Different Hamamatsu Photomultipler Tubes", Journal of Instrumentation, 3 T01001, 2008.
[10] U. Akgun et al., "Complete tests of 2000 Hamamatsu R7525HA Phototubes for the CMS-HF Forward Calorimeter" Nucl. Instrum. Meth. A 550, 145-156, 2005.
[11] U. Akgun et al., "Comparison of PMTs from three different manufacturers for the CMS-HF Forward Calorimeter", IEEE Trans. Nucl. Sci. Vol 51, 1909-1915, 2004
[12] D. Bartlett et al. "Performance of the Cherenkov counters in the fermilab tagged photon spectrometer facility", Nucl. Instrum. Meth. A 260, 55-75, 1987.