R and D on Radiation Hard Active Media Based on Quartz Plates

Yasar Onel for the CMS Collaboration

Abstract

The need for radiation-hard active media in particle detectors is prominently dictated by the future colliders and the future operations of the Large Hadron Collider. The areas of implementation range from calorimetry to beamline instrumentation to specialized forward detectors e.g. luminosity monitors. In this context, we developed the idea of utilizing quartz plates with various surface coating properties as the active medium for such detectors. Plain quartz is a pure Cerenkov radiator which has quite limited photostatistics. In order to improve the efficiency of the photodetection, various methods were investigated including radiation hard wavelength shifters, p-terphenyl or 4pct gallium doped zinc oxide. The readout options include direct coupling of the photodetector to the quartz plate, or fibers. We have studied various geometries and readout options and constructed calorimeter prototypes. Here we report on the results of the previous tests, and the recent developments, which enable several factors of performance improvements on MIP detection and shower response with simple geometrical modifications such as multi-layer tiles.

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I. INTRODUCTION

Modern colliders have been imposing unprecedented challenges on the radiation hardness of particle detectors that are being/will be used for specific purposes e.g. forward calorimeters, beam and luminosity monitors. Quartz Čerenkov radiators have implementations in beam and luminosity monitors, however, they were never considered as active media in calorimetry in the form of quartz plates in a sampling calorimeter. One particular reason is that the Čerenkov radiation yields 100 times less light than the scintillation process from a moderate performance scintillator. To improve the number of generated photons, we tested different light enhancement coatings, including p-Terphenyl (pTp), 4% Gallium doped Zinc Oxide (ZnO:Ga), o-Terphenyl (oTp), m-Terphenyl (mTp), and p-Quarterphenyl (pQp). The light enhancement coating on the quartz has to be radiation hard as well.

The Compact Muon Solenoid (CMS) [1] is a general-purpose detector designed to run at the highest luminosity provided by the Large Hadron Collider (LHC) at CERN. The CMS detector calorimeter has been designed to detect cleanly the diverse signatures of new physics through the measurement of jets with moderate precision and by measuring missing transverse energy flow. The CMS experiment has a 4 T superconducting solenoidal magnet of length 13 m and inner diameter 5.9 m. The barrel and end-cap calorimeters are located inside this magnet.

The HCAL (hadron calorimeter) is used to measure the energy of hadronic showers, as well as their angle and position, needed for the generation of the calorimeter trigger, and offline reconstruction of jets and missing transverse energy. The CMS HCAL contains 9072 readout channels organized into four subsystems: barrel (HB, 2592 channels), endcap (HE, 2592 channels), outer (HO, 2160 channels) and forward (HF, 1728 channels). The performance of the HB, HE, HO, and HF were also extensively investigated and are reported in [2], [3], [4], [5], [6].

The predictions based on the measurements during Run I of the LHC indicate that the scintillator tiles of the hadron endcap calorimeter will not withstand the radiation levels and will need to be replaced during Long Shutdown 3, projected to be between 2023 and 2025. The quartz plates with various radiation-hard wavelength shifter coatings as well as intrinsically radiation-hard scintillating tiles are among the options of replacement tiles for the hadron endcap calorimeters.

II. CALORIMETRY WITH pTP COATED QUARTZ PLATES

At the initial stages of the R&D, we studied the radiation hardness of quartz in detail with electron [7] and proton [8] irradiations as well as neutron and gamma. Once it was validated that quartz, as the baseline of the R&D, has a radiation hardness that is beyond expectations for calorimetry in hadron colliders, we studied efficient ways of collecting the Čerenkov light using different wavelength shifting fiber geometries. Figure 1 shows the simulation of the Čerenkov light collection in plain quartz with Y (a), bar (b), sigma (c) and S-shaped (d) fiber geometries. Due to the nature of the Čerenkov light production, it was found that the highest packing fraction option for the fibers, namely the bar shaped fiber geometry provides the best solution for light collection. A calorimeter stack constructed with quartz plates with bar-shaped fiber geometry yielded valuable results [9], [10].

To improve the light production inside the quartz plates, we considered various light enhancement coatings: pTp, ZnO:Ga, oTp, mTp, and pQp. Other than ZnO:Ga, all of them can be evaporated in a vacuum chamber to be applied on quartz. The molecular properties of ZnO:Ga do not allow evaporation, so RF sputtering was used for this case. Figure 2 shows the pictures of the RF sputterrer (left) and the vacuum chamber (right).

After the beam tests at the Fermilab Test Beam Facility [11] and at the CERN H2 beamline [12], the one sided coatings with 2 µm thickness of pTp and 0.2 µm of ZnO:Ga yielded the best results in pion, proton, and electron beams at various energies.

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Yasar Onel is with University of Iowa, Iowa City, IA 52242 USA (e-mail: yasar-onel@uiowa.edu).
As the next step, we tested pTp radiation hardness with proton beams at the Indiana University Cyclotron Facility and CERN beam lines. The Sr90 activated scintillation light outputs of pTp samples both before and after irradiation were compared in the University of Mississippi Laboratories. We also employed the liquid scintillation technique in which the pTp samples were mixed in a saturated toluene solution with a standard tritium beta source and scintillation light analyzed for dosed and standard samples. The toluene yields negli-gible scintillation light in the tests. The dosed pTp samples were also sent for chemical analysis showing slight breakdown of the tri-ring pTp molecule into simpler benzene ring forms. 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 observe less than 20% loss of light production.

We have built a quartz plate calorimeter prototype with 0.2 \( \mu \)m pTp deposited on one side of the quartz tiles succeeding the calorimeter prototype with plain quartz plates and wavelength shifting fibers. The prototype consists of 20 layers of quartz plates (15 cm x 15 cm x 5 mm) with 7 cm iron absorbers. GE-124 quartz from GE Quartz Company was used as the material for the plates. After 2 \( \mu \)m pTp was deposited on every quartz plate via evaporation at Fermilab Thin Film Laboratory, one inch section on the side of each plate was polished for better PMT coupling. The light generated in the quartz plate was read out by Hamamatsu R7525-HA photomultiplier tubes from the edge of the polished side. The quartz plates were wrapped with mylar for good reflectivity, especially in the UV range, and then with Dupont Tyvek for a robust light tight structure. Every quartz plate and PMT system was prepared to be a standalone unit.

Figure 3 shows the response of the calorimeter prototype to hadrons and the hadronic energy resolution. The response was sufficiently linear up to 350 GeV and the stochastic term of the energy resolution for hadrons was 211% with negligible noise term and \( \sim 10 \% \) constant term. The Monte Carlo simulations were in sufficient agreement with the data.
with 2 cm iron absorbers instead of 7 cm. The calorimeter in the electromagnetic configuration had acceptable energy resolution and response linearity that were also in agreement with the Monte Carlo predictions. Details about these measurements and simulations can be found in [13].

We recently constructed two multi-layer structures: Two quartz plates with pTp coatings on single side that are optically coupled to an array of wavelength shifting fibers - the so-called “sandwich pTp” setup; and seven layers of thin quartz plates with ZnO coating stacked together. We tested one sandwich pTp setup with MIPs and in electromagnetic showers and observed a factor of around 3.5 improvement in the shower response compared to quartz plate with single-side coating. Figure 4 shows the response of the sandwich pTp and the HE tile to MIPs and electromagnetic showers. The prediction of performance of a prototype similar to the one with single pTp plates yields a stochastic term of 112 %, which is comparable to e.g. CMS hadron endcap calorimeter performance (102 %).

![Figure 4](image1.png)

**III. Search for Radiation-Hard Scintillator Tiles**

As readily-available solutions of radiation-hard scintillators, we investigated the performance of HEM sheets, Polyethylene-2,6-Naphthalate (PEN) and Polyethylene Terephthalate (PET). These samples demonstrate intrinsic blue scintillation peaking at 425 nm and 10500 photons/MeV light yield. They were recently proven to be radiation-hard [14].

In the progress of validating the idea of using HEM and PEN as an active medium in calorimetry, we assembled a test tile with alternating layers of HEM sheets and quartz plates. The tile measured 8 cm x 10 cm and was 4 mm thick. It was read-out by a directly coupled photomultiplier tube and the response was compared with a megatile of 4 pTp coated quartz plates also read out with a directly coupled photomultiplier tube. Figure 5 shows the comparison of the responses of these tiles. The light output of the intrinsic scintillation of the HEM is manifestly evident.

![Figure 5](image2.png)

**IV. R&D on Radiation-Hard Wavelength Shifting Fibers**

We investigated options for radiation-hard wavelength shifting (WLS) fibers. As a first prototype, we built radiation hard WLS fibers by depositing pTp on the stripped region of quartz...
fibers on both faces. The whole ribbon is then sandwiched between quartz plate to form a test assembly. Figure 7 shows a picture of the assembly in progress.

Fig. 7. pTp deposited quartz fibers in the test assembly.

The radiation-hard WLS fiber assembly was then tested in the CERN test beam with 80 GeV electron beam close to its shower maximum at around 5 radiation lengths. Figure 8 shows the response of the WLS fibers (green) as well as the pedestal (red). With this simple prototype, a substantial amount of signal was collected.

Fig. 8. Response of the WLS fibers to 80 GeV electron shower (green) and the pedestal (red).

We also tested quartz capillaries filled with anthracene and 3HF as radiation-hard fiber candidates. A small bundle of 7 250 \( \mu \)m core capillaries filled with anthracene was exposed to 80 GeV electron beam. The results prove that the anthracene filled capillaries are promising options as radiation-hard WLS fibers. A bundle of 5 100 \( \mu \)m core 3HF filled capillaries was exposed to 120 GeV protons and despite the size of the capillaries, the results are highly encouraging. Currently 750 \( \mu \)m core capillaries are investigated to better suit the calorimetry implementations.

V. CONCLUSIONS

The development of radiation-hard wavelength shifting fibers produced promising results for further implementations. Currently, in-situ measurements are being performed with real tiles.

We explored the possibility of utilizing the quartz plates as active media of radiation-hard detectors. Plain quartz was studied extensively to understand the best ways of utilizing the generated Čerenkov light. After obtaining a reasonably good performance with plain quartz, we explored radiation-hard coating options that would enhance the light-collection capability. We considered various light enhancement coatings including pTp, ZnO:Ga, oTp, mTp, and pQp, and converged on the best two solutions: pTp and ZnO:Ga. The calorimeter prototype constructed with pTp coated quartz plates demonstrated the concept of quartz plate calorimetry. Further R&D on the individual tiles showed that calorimeters with performance comparable to the currently operational ones can be constructed using quartz plates.

In addition to the quartz plates with wavelength shifting coatings, we also investigated tiles that are intrinsically scintillating and are radiation-hard. The samples tested so far include PEN, PET and HEM. The initial performance is beyond expectations and current R&D concentrates on optimizing various parameters of these tiles e.g. timing and uniformity.

The development of radiation-hard wavelength shifting fibers produced promising results for further implementations. Currently, in-situ measurements are being performed with real tiles.

The development of the active media mentioned in this note is of utmost importance for future LHC upgrades in high radiation regions. As of today, there is no equivalent to quartz-based active media in terms of radiation-hardness.

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REFERENCES