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A Very Compact Crystal Shashlik Electromagnetic Calorimeter for Future HEP Experiments

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Abstract. A very compact crystal based shashlik calorimeter is proposed for future HEP experiments in an extreme harsh radiation environment, such as the proposed HL-LHC. Thin crystal plates are used as the sensitive medium to reduce the light path length and thus the radiation damage effects and the calorimeter cost. A design of such a calorimeter uses tungsten as absorber, LYSO crystals as active medium, and liquid scintillator filled quartz capillaries as WLS to transport scintillating light to photodetectors. Initial calorimeter design and performance of prototype modules are presented. Possible optimizations are discussed.

1. Introduction

In high energy physics (HEP) and nuclear physics (NP) experiments, total absorption electromagnetic calorimeters (ECAL) made of inorganic crystals are well known for their superb energy resolution and detection efficiency for photon and electron measurements [1]. The CMS PWO ECAL, for example, played a crucial role in the discovery of the Higgs boson [2]. One crucial issue is crystal's radiation damage in the severe radiation environment at the LHC, which requires precision monitoring to correct variations of crystal transparency [3]. Figure 1 shows up to 70% loss of light output as well as partial recovery during the shutdown periods in the CMS PWO crystals observed in high rapidity when the LHC was running at different energies with a luminosity of up to 7×10^{33} cm^{-2}s^{-1} [4].

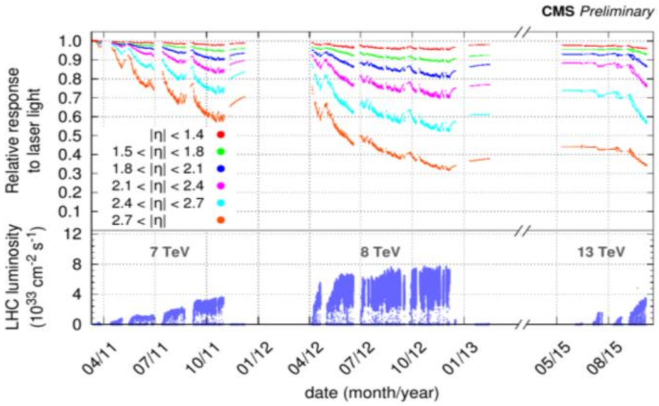

Figure 1. History of monitoring response is shown as a function of rapidity for CMS PWO crystals since LHC starts in 2011.

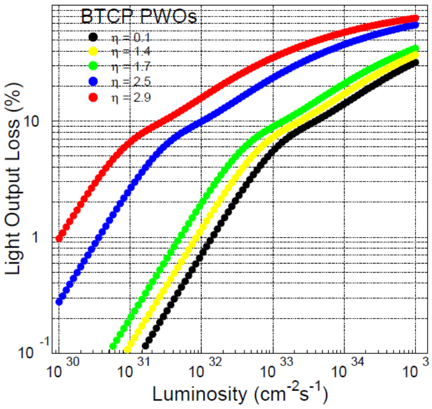

Figure 2. Predicated LO loss as a function of the luminosity and rapidity.

The dose rate dependent damage and recovery in PWO crystals are well understood [5, 6]. Figure 2 shows the expected light output loss as a function of luminosity for PWO crystals at different rapidity, predicted in 2010 before LHC running by using γ-ray induced radiation damage data [7]. It agrees well with Figure 1, indicating that the radiation damage in PWO crystals observed in Figure 1 is mainly caused by ionization dose. Radiation damage caused by charged hadrons was also studied [8]. Because of these damages the CMS endcap ECAL is planned to be replaced by more radiation hard technologies. An LYSO crystal based very compact Shashlik sampling calorimeter was proposed as one option [9].

2. A very Compact Crystal Shashlik Sampling Calorimeter

Figure 3 shows a photo of an LYSO/W Shashlik tower with four Y-11 wavelength shifter (WLS) fibers to transport scintillation light in LYSO to a PMT. This detector concept improves the overall radiation hardness of the calorimeter because of the much reduced light path length in the sensitive medium. An initial design consists of 30 LYSO plates of 14×14×1.5 mm and 29 W plates of 14×14×2.5 mm. Each tower has a depth of 25 X_0 to accommodate electrons and photons up to the TeV range. The sampling fraction was chosen to be 20% to provide a stochastic term at a level of 10% for the energy resolution. Because of the high density of both LYSO and W, the average radiation length (0.51 cm) and Moliere radius (1.3 cm) are much smaller as compared to commonly used heavy crystal scintillators. It thus provides fine granularity to reduce the pile-up effect at the HL-LHC.

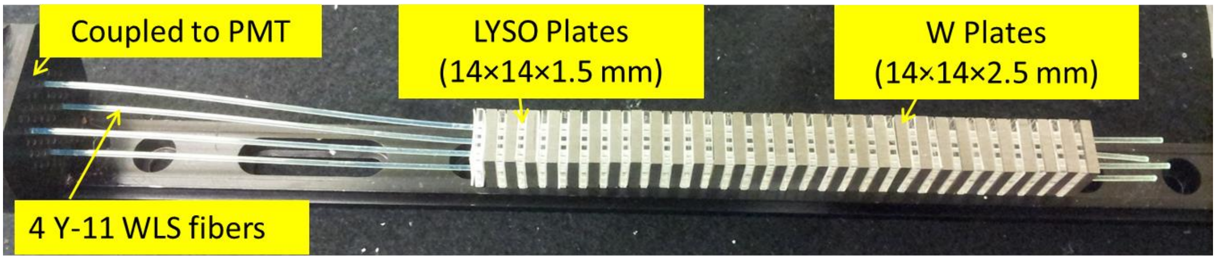

Figure 3. A photo showing an LYSO/W Shashlik tower with four Y-11 WLS fibers inserted.

Beam tests were carried out at Fermilab and CERN for an LYSO/W Shashlik matrix consisting of sixteen towers with Y-11 and SiPM readout. Figure 4 shows an energy resolution of 1.5% observed for 100 GeV electrons. Figure 5 shows an LYSO crystal based Shashlik calorimeter detector concept with four quartz capillaries filled with liquid scintillator serving as WLS and a quartz monitoring leaky fiber at the center [10]. The quartz capillaries allow light transportation in quartz so greatly enhance radiation hardness of the WLS and the entire calorimeter [11].

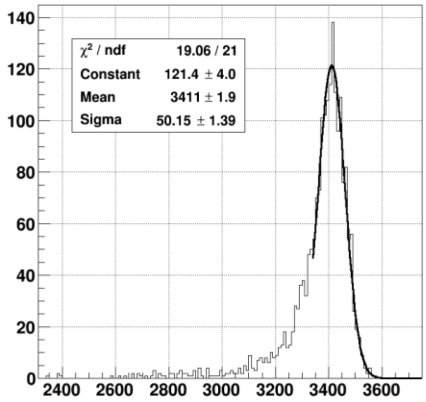

Figure 4. Energy resolution measured by a LYSO/W Shashlik matrix with 16 towers for 100 GeV electrons.

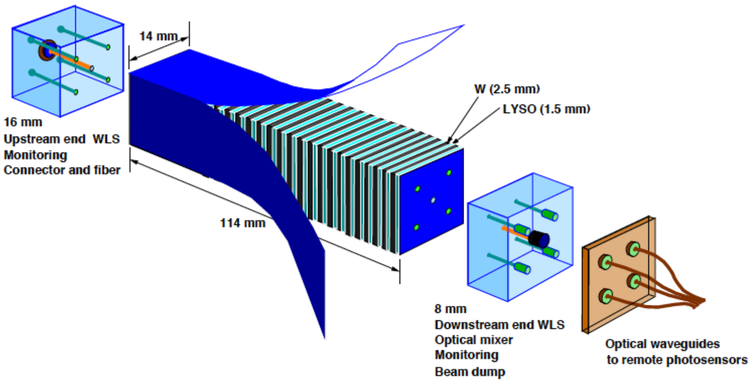

Figure 5. The LYSO/W Shashlik calorimeter concept consisting of 1.5 mm LYSO plates, 2.5 mm tungsten plates, four quartz capillaries as WLS and one quartz leaky fiber for light monitoring.

3. Bright, Fast and Radiation Hard LYSO Crystals and LYSO/W/Quartz Capillary Tower

Because of their high density (7.4 g/cm^3), short radiation length (1.14 cm), fast (40 ns) and bright (4 times BGO) scintillation, cerium doped lutetium oxyorthosilicate (Lu_2SiO_5:Ce, LSO) and lutetium yttrium oxyorthosilicate ($Lu_{2(1-x)}Y_{2x}SiO_5$:Ce, LYSO) crystals have attracted a broad interest in the high energy physics community. Their excellent radiation hardness against γ-rays [12], neutrons [13] and charged hadrons [14] also makes them a preferred material for the HL-LHC.

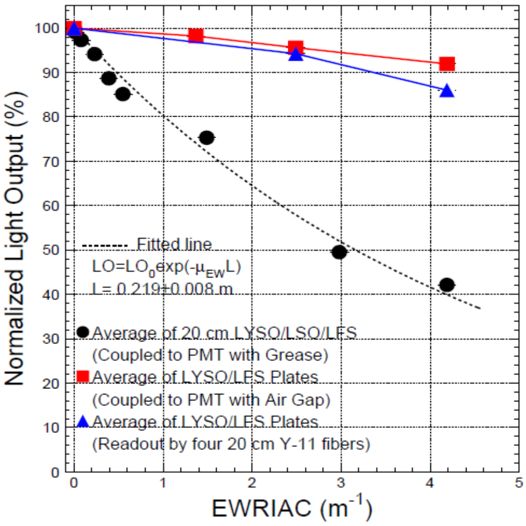

Figure 6. Light output is shown as a function of the induced absorption in LYSO crystals.

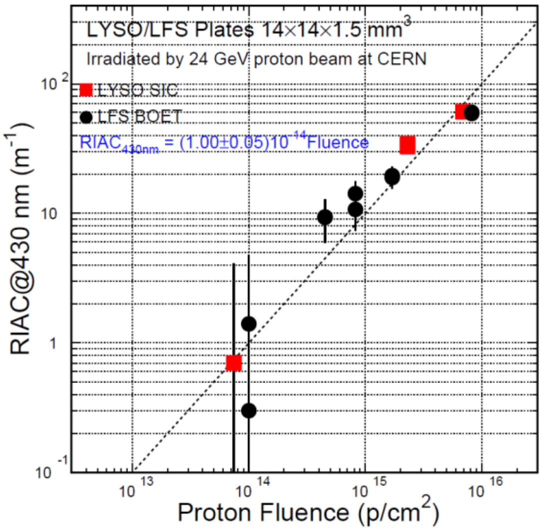

Figure 7. Induced absorption is shown as a function of 24 GeV proton fluence for LYSO crystals.

Figure 6 shows 5% and 50% losses observed for LYSO crystals of 14×14×1.5 mm and 2.5×2.5×20 cm respectively after 150 Mrad, showing clearly the advantage of reduced light path length. Figure 7 shows induced absorption as a function of 24 GeV proton fluence for 14×14×1.5 mm LYSO plates. About 3 m^{-1} is observed after 3×10^{14} cm^{-2} which is the maximum expected by the CMS FCAL at the HL-LHC.

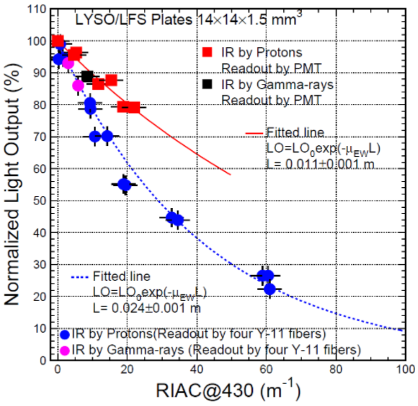

Figure 8. Light output is shown as a function of γ-ray induced absorption in 14 x 14 x 1.5 mm LYSO plates

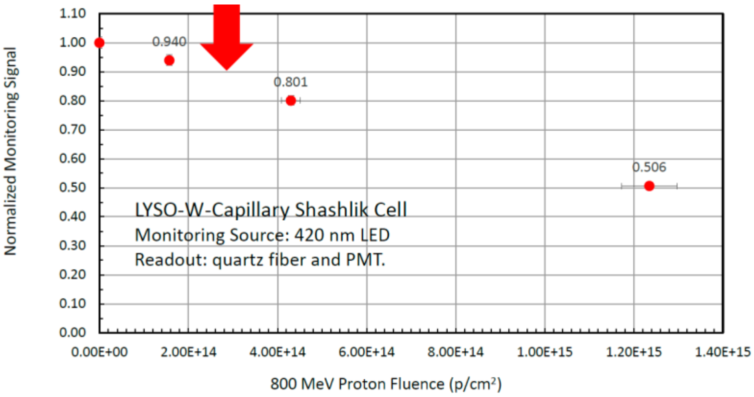

Figure 9. Monitoring response is shown as a function of 800 MeV proton fluence for an LYSO/W/Quartz capillary tower with a red arrow showing the maxim fluence expected by CMS FCAL

Figure 8 shows light output as a function of induced absorption for 14×14×1.5 mm LYSO plates after proton and γ-ray irradiation. Consistent losses at 6% are observed for crystals with 3 m^{-1} absorption by both protons and ɣ-rays. Figure 9 shows monitoring response as a function of 800 MeV proton fluence for an LYSO/W/Quartz capillary tower. About 10% loss is observed after 3×10^{14} cm^{-2} proton fluence, indicating that this detector concept provides a very stable calorimeter under severe radiation.

4. Optimization

Figure 10 and 11 show light output as a function of integration time for two 25×25×0.4 mm LuAG:Ce ceramic samples before and after 220 Mrad and 3×10^{14} cm^{-2} proton fluence and 220 Mrad respectively. No degradation was observed. Because of low material loss in processing, such a material is promising as a cost-effective active medium for calorimeter of this type.

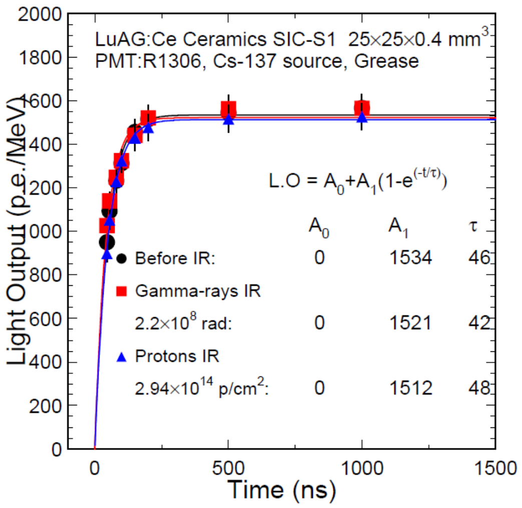

Figure 10. Light output is shown as a function of the integration time for a LuAG:Ce ceramic sample

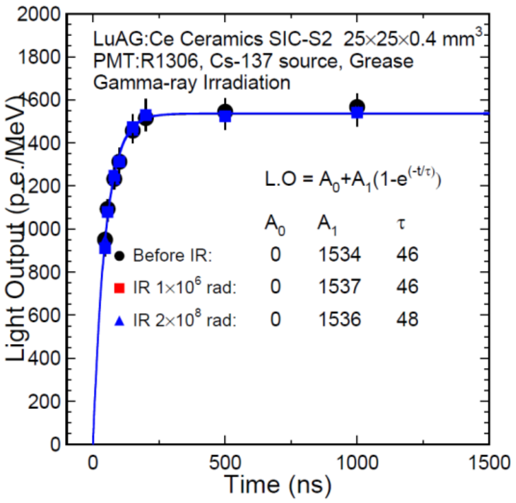

Figure 11 Light output is shown as a function of the integration time for a LuAG:Ce ceramic sample

5. Summary

To preserve precision e/γ measurement and face the challenge of the severe radiation environment expected by future HEP experiments at the energy frontier, a very compact crystal Shashlik ECAL was designed and tested in beam. Bright, fast and radiation hard LSO/LYSO crystals and quartz capillary based WLS provide a solid foundation for a stable and robust Shashlik calorimeter at the proposed HL-LHC. Scintillating ceramics, such as LuAG:Ce, may play an important role for a cost-effective Shashlik calorimeter.

Acknowledgments

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