Evolution Studies of the CMS ECAL Endcap Response and Upgrade Design Options for High-Luminosity LHC

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The operation of the CMS electromagnetic calorimeter (ECAL) during the High-Luminosity running of the LHC will be characterized by radiation levels and hadron fluences significantly beyond the design values. Moreover, a large increase in the number of proton-proton interactions per bunch crossing is expected with respect to the current conditions. Studies of the ECAL performance evolution based on LHC collision data, as well as irradiation and beam tests, indicate that its endcaps will need to be upgraded. An overview of the different replacement options under consideration is presented.

Introduction

The CMS electromagnetic calorimeter (ECAL) is a homogeneous crystal calorimeter. It consists of 75,848 lead tungstate ($PbWO_4$) scintillating crystals. ECAL is separated into a barrel region, covering the pseudorapidity range up to $|\eta| = 1.479$, and two endcap regions that extend the coverage up to $|\eta| = 3$. The crystals are arranged in a hermetic and quasi-projective geometry. $PbWO_4$ features a small radiation length (0.89 cm), a small Molière radius (2.19 cm), and a fast scintillation response. These properties have made it possible to build a compact and granular homogeneous calorimeter providing excellent energy resolution, response linearity and particle identification capability at the LHC [1].

Very different operating conditions are expected for the High-Luminosity (HL) running of the LHC, that is scheduled to take place between about 2025 and 2035, up to a final delivered integrated luminosity of about 3000 fb^{-1}. The instantaneous luminosity is expected to reach a value of $5 \cdot 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$, with about 140 proton-proton interactions taking place on average in the same bunch crossing (pileup). The radiation levels in the endcap region are strongly position-dependent. At high values of the pseudorapidity ($|\eta| \sim 2.6$), the photon dose rate will be about 30 Gy/h and the fluence of energetic hadrons will be of the order of $1.8 \cdot 10^{14}\ \text{cm}^{-2}$. These values exceed by a factor of at least four those the ECAL was designed to withstand.

The ECAL has played a crucial role in many analyses performed with LHC collision data, including the discovery of the Higgs boson in CMS [2]. This will still be the case for a large class of physics analyses that will be performed with HL-LHC data. Therefore, the long-term physics reach of the CMS experiment will strongly depend on an enduring ECAL performance. It is crucial to understand in detail how the properties of $PbWO_4$ crystals evolve under irradiation

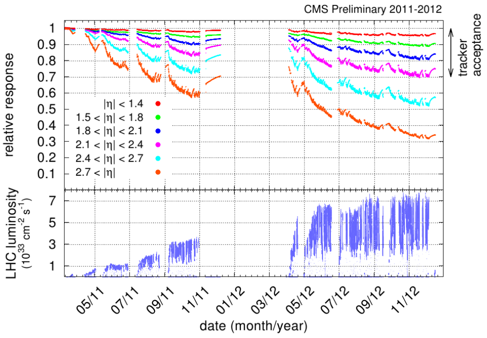

Figure 1: Relative response to laser light measured by the ECAL laser monitoring system, averaged over all crystals in bins of pseudorapidity, for the 2011 and 2012 data taking periods. [3]

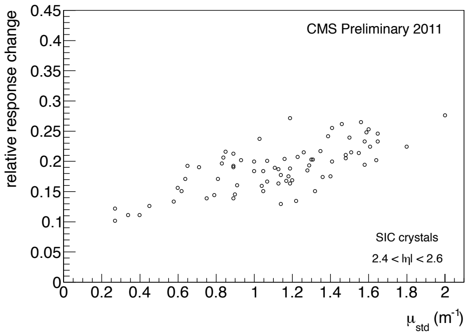

Figure 2: Correlation between relative change of response from ECAL monitoring data and the absorption coefficient, μ_{std}, induced by a standard γ irradiation in crystals produced by the Shanghai Institute of Ceramics. [4]

and to study the performance of the calorimeter in high pileup conditions.

Performance evolution

A loss of transparency of the $PbWO_4$ crystals under irradiation has been established with the LHC collision data collected so far [3]. A laser light injection system has been used to continuously monitor this effect during the data-taking. The loss of transparency has been observed to be strongly correlated with the LHC instantaneous luminosity and with the crystal position in the detector, being the largest at high values of $|\eta|$ (Fig. 1). These monitoring data have been used to correct the crystal response as a function of time and stabilize the energy scale of objects whose energy measurement is based on ECAL.

The main mechanism leading to the transparency loss observed in the detector so far is the formation of colour centres due to ionizing radiation. This type of damage is not cumulative and recovers with time when the irradiation stops (as can be seen in Fig. 1). The loss of transparency measured in the detector with collision data correlates with the results obtained from photon irradiation during the crystal quality control tests before installation (Fig. 2). However, another component of transparency loss is observed to arise after hadron irradiation [4]. It consists of an induced absorption length due to interactions of energetic hadrons with the crystal lattice. It does not recover at room temperature when irradiation stops and therefore builds up during the data-taking. At the large values of integrated luminosity expected at the HL-LHC, this ageing component will become the dominant one. The transparency loss extends throughout the $PbWO_4$ transmission band and causes the lower band edge to shift towards higher wavelengths. The residual light output is expected to be about 10% of the nominal one at $|\eta| \sim 2$ after 3000 fb^{-1}, leading to a contribution to the Higgs diphoton invariant mass peak resolution of the order of several percent (Fig. 3) [5]. On the other hand, the transparency loss will remain acceptable in the barrel region, because of the much lower radiation levels there.

Another effect due to crystal transparency loss is the amplification of the effective noise in the ECAL readout electronics. The electric signal pulse from the ECAL photosensors is sampled by an ADC at 40 MHz. A conversion factor from ADC counts to energy is then applied. While the electronic noise stays constant in units of ADC counts, the loss of transparency will lead to larger conversion factors, effectively amplifying the energy equivalent of the noise. This effect will strongly degrade the trigger performance in the endcap region, increasing the energy thresholds required on electron and photon triggers. The ECAL resolution will also be worsened by non-uniformity of light collection and non-linearity. In conclusion, all terms (stochastic, noise, constant) of the endcap ECAL resolution are worsened by the crystal hadron radiation damage [6]. Moreover, the large number of pileup interactions expected at the HL-LHC will significantly increase the detector occupancy. In these conditions, energy deposits from adjacent bunch crossings will bias the crystal energy readout. The main handle available to fight this effect is increasing the detector granularity.

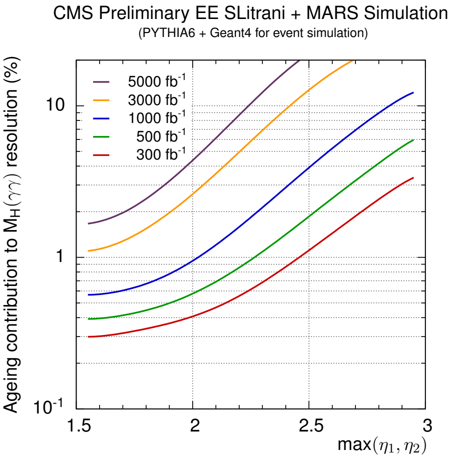

Figure 3: Contribution to the Higgs mass resolution due to the ECAL ageing, for the two photon decay of the Higgs boson in the endcap regions. [5]

Upgrade options

The loss of performance justifies an upgrade of the ECAL endcaps for operation in HL-LHC conditions. Several options have been studied for replacing the CMS electromagnetic and hadronic (HCAL) calorimeters in that region with sampling calorimeters based on new technologies, with finer granularity than the existing devices. The two main design schemes under consideration are described in the following sections.

Sampling design using inorganic scintillating crystals

A sampling calorimeter based on radiation-hard inorganic scintillating crystals interleaved with heavy absorber material plates has been proposed to replace the ECAL endcaps. The light produced in the crystals is wavelength-shifted and extracted towards the photosensors by capillaries or fibres running in the longitudinal direction of the channel (Fig. 4). Two scintillating materials under consideration are LYSO and CeF_3. Both have been studied in irradiation tests and have been shown to be able to withstand larger hadron fluences than $PbWO_4$ (Fig. 5) [7]. CeF_3 even shows a spontaneous recovery of the hadron damage when irradiation stops. The proposed absorber material is tungsten. This design aims at a stochastic term in the calorimeter resolution of about 10%. The low radiation length and Molière radius of this configuration lead to a very compact and granular design. Two prototypes have been realized and successfully tested in beams. One uses LYSO crystals with fibres running through the channel; the other uses CeF_3 crystals with fibres running along chamfers located at the channel corners [8].

High-granularity design

A replacement of both ECAL and HCAL endcaps with a highly segmented (longitudinally and transversally) system, based principally on silicon sensors, has also been proposed. The aim of this design is to obtain an excellent three-dimensional shower profile reconstruction and particle identification. The current proposal consists of a total of about 600 m^2 of silicon sensors of different thickness, segmented into about 9 million channels and interleaved with varying amounts of heavy absorber material. Current R&D studies aim at a highly integrated design of sensors, absorber material and cooling infrastructure.

Conclusions

The High-Luminosity running of the LHC poses a significant challenge in terms of radiation levels and number of pileup interactions. The mechanisms of radiation damage to the ECAL $PbWO_4$ crystals have been studied with LHC data and irradiation tests and have been found to lead to a strong loss of physics performance in the endcap regions in HL-LHC conditions, while the barrel region will continue to perform well. It is therefore necessary to replace the ECAL endcaps with a more radiation-hard and granular detector. Two options are currently being considered: one is based on a sampling design using heavy inorganic scintillators, while the other consists of a high-granularity silicon-based detector.

References

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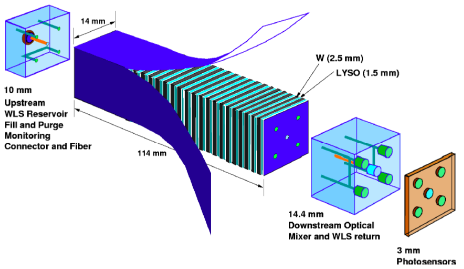

Figure 4: Sketch of a Shashlik configuration based upon interleaved W and LYSO scintillating crystal layers.

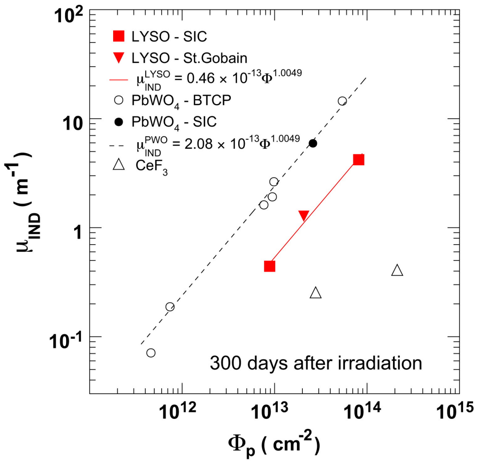

Figure 5: Induced absorption at the peak-of-emission wavelength for $PbWO_4$, LYSO and CeF_3, measured longitudinally through the crystals, as a function of integrated proton fluence, for various producers - SIC, BTCP, St. Gobain. [7]