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Evolution of the response of the CMS ECAL, and upgrade design options for electromagnetic calorimetry at the HL-LHC

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Abstract

The performance of the CMS electromagnetic calorimeter (ECAL) has been continuously monitored at the LHC. The evolution of this performance is a critical issue for the future. Work has started to assess the need for possible changes to the detector to ensure adequate performance for High-Luminosity LHC (HL-LHC) operation, planned for 2022 and beyond. Results from CMS running, beam tests and laboratory measurements on proton-irradiated crystals are combined to predict the performance of the current detector at the HL-LHC. This is achieved using MC simulations of the CMS detector, where the ECAL response has been tuned to account for the aging of the detector components. In addition, various R&D studies are presented in case modification or replacement of the ECAL Endcaps is needed for the HL-LHC period.

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Evolution of the response of the CMS ECAL and upgrade design options for electromagnetic calorimetry at the HL-LHC

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The performance of the CMS electromagnetic calorimeter (ECAL) has been continuously monitored at the LHC. The evolution of this performance is a critical issue for the future. Work has started to assess the need for possible changes to the detector to ensure adequate performance for High-Luminosity LHC (HL-LHC) operation, planned for 2022 and beyond. Results from CMS running, beam tests and laboratory measurements on proton-irradiated crystals are combined to predict the performance of the current detector at the HL-LHC. This is achieved using MC simulations of the CMS detector, where the ECAL response has been tuned to account for the aging of the detector components. In addition, various R&D studies are presented in case modification or replacement of the ECAL Endcaps is needed for the HL-LHC period.

Keywords: CMS; Upgrades; Calorimeters; Radiation-hardness; Electronics; Pile-up.

1. The CMS Electromagnetic Calorimeter

The CMS¹ electromagnetic calorimeter² (ECAL), as depicted in Fig. 1, is a compact, hermetic, fine-grained and homogeneous calorimeter made of 75848 Lead tungstate (PbWO_4) scintillating crystals, arranged in a quasi-projective geometry and made up of a barrel region (EB), with pseudorapidity coverage up to $|\eta| = 1.48$, closed by two endcaps (EE) that extend its coverage up to $|\eta| = 3$. The scintillation light is read out with avalanche photodiodes (APDs) in the EB and with vacuum phototriodes (VPTs) in the EE. To facilitate photon identification, the crystals have a transverse size comparable to the Molière radius ($R_M = 21$ mm) in PbWO_4 . The front-face cross section of the crystals is 22.0×22.0 mm² in the EB and 28.6×28.6 mm² in the EE, with crystal depths of 23 and 22 cm (26 and 25 radiation lengths) respectively. Preshower detectors (ES), comprising two

plans of silicon sensors interleaved with lead absorber for a total of three radiation lengths, are located in front of each endcap, at $1.65 < |\eta| < 2.6$, to help in π_0/γ separation.

Fig. 1. The CMS electromagnetic calorimeter.

2. ECAL at High Luminosity LHC

The ECAL was initially designed for 10 years of LHC running with pp collisions at 14 TeV, for a peak luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, and a total integrated luminosity of 500 fb^{-1} . Starting from 2022, during the High Luminosity LHC (HL-LHC) period, the instantaneous luminosity is expected to reach $5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, collecting 3000 fb^{-1} . The instantaneous and integrated radiation levels are expected to be a factor 6 higher than at the LHC.

The HL-LHC will allow us to expand the physics potential of the LHC, but it is crucial to understand how the upgrade will affect the performance of ECAL. In particular radiation damage will affect the crystal transparency, and consequently the energy resolution. Moreover higher luminosity will also impose further constraints on the trigger, and the number of multiple interactions in the same bunch crossing (pile-up) is expected to increase.

3. Radiation damage and transparency

Studies³ of PbWO₄ crystals have established that ionizing damage of the crystals is recovered at room temperature (18 °C), while high-energy protons and pions cause a cumulative loss of light transmission in PbWO₄, which is permanent at room temperature. The cumulative nature of the hadron-induced damage implies that the light output from the crystals is expected to decrease in proportion to their integrated exposure to energetic hadrons, beyond the level required for acceptable performance at HL-LHC.

The contributions from hadron-induced damage to signal losses is expected to become significant starting at the highest η values in the endcaps, towards the end of LHC running. Beam test results on irradiated crystals have been used to quantify the effects expected from cumulative hadron damage. With current information, it is possible to extrapolate the light output loss as a function of integrated luminosity expected for the present CMS ECAL. As can be seen in figure 2, after 500 fb⁻¹ (blue line) at $\eta = 2.5$ there is a 90% loss. For this reason, it is planned to replace the current EE with a new radiation-hard detector during the third long LHC shut down, in 2022, at which point the integrated luminosity should be around 500 fb⁻¹.

Fig. 2. Response change for the crystals as a function of η for 50 GeV electrons. Different colours correspond to different integrated luminosities.

4. Electronics

Possible future CMS triggering requirements of 10 μsec latency and a Level-1 hardware (L1) trigger rate of 1 MHz cannot be accommodated by the existing ECAL electronics and a complete replacement of the on-detector and off-detector electronics may be necessary. The EB/EE (ES) front-end electronics have a pipeline memory with 256 (192) cells, corresponding to a maximum latency of 6.4 (4.8) μsec . Reducing the number of samples being read out could result in a higher L1 trigger rate, up to ~ 200 Hz, where only the off-detector electronics would need to be replaced. Replacing all the electronics provides several benefits, such as mitigating concerns about the longevity of the existing components and allowing more efficient removal of spurious signals at the trigger level. We are exploring the possibility of upgrading the EB electronics and replacing the EE+ES with a new radiation-hard detector. The new detector must have adequate energy resolution, suitable fiducial acceptance and pile-up rejection capabilities for the HL-LHC conditions in the forward region.

5. Endcap calorimeter upgrade plans

The replacement of the existing EE+ES with a new radiation-hard calorimeter includes the possibility of coupling the EE+ES replacement with that of the Hadron Calorimeter Endcaps (HE). This possibility divides the upgrade into two scenarios: a new standalone EE if the HE absorber is left, and a complete redesign of both endcap calorimeters if not. The multiple interactions in each bunch crossing will increase to 128 at high luminosity, from 21 in 2012. at high luminosity. ECAL is expected to play a major role in pile-up mitigation. This could be done in two different ways: increasing the granularity and segmentation of the EE, to separate and recognize particles from different vertices, and having a time resolution of ~ 20 ps for a vertex position resolution of 5 cm.

5.1. Standalone EE

For a new standalone EE, a sampling calorimeter is a possibility, utilizing a radiation-hard, inorganic scintillator (LYSO or CeF_3) and Pb or W as absorber material. There are possibilities for light readout via wavelength shifting fibres (WLS) in a shashlik configuration (figure 3) or with photon sensors on the sides of the detector cells. It is important that the light path is short to assure radiation tolerance.

Fig. 3. Shashlik configuration.

5.2. An $HE+EE$ calorimeter

As a replacement for $EE+HE$, dual readout could provide simultaneous measurements of electromagnetic and hadronic energy deposits using separate Cherenkov and scintillation light readout. Under consideration are wavelength shifting capillaries or crystal fibres for scintillation detection and quartz fibres or crystal fibres for Cherenkov detection. Alternatively, a fine-grained and longitudinally segmented imaging calorimeter could resolve and measure electromagnetic and hadronic activity. Tracker information can be used to associate charged particles to particular calorimeter energy deposits, leaving the remaining energy to be associated with neutral particles. This 'particle flow' approach can lead to improved particle and jet energy measurements.

5.3. Conclusions

The HL-LHC will allow us to expand the physics potential of the LHC. Several studies to understand how the upgrade will affect the performance of ECAL have been done. The CMS plan is to upgrade the EB electronics and to substitute the EE during the third long LHC shut down in 2022. Depending on the future substitution of the Hadron Calorimeter Endcaps it could be possible to couple the $EE+ES$ replacement with that of the HE.

References

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