Evolution of the response of the CMS ECAL and possible 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 ageing 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: Performance of High Energy Physics Detectors; Radiation-hard detectors; Calorimeters; Calorimeter methods

*On behalf of the CMS collaboration.
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1 The ECAL calorimeter at the LHC

The electromagnetic calorimeter (ECAL) [1], of the Compact Muon Solenoid (CMS) [2], is an homogeneous calorimeter with 75848 PbWO$_4$ scintillating crystals, arranged in a quasi-projective geometry in the central barrel (EB) and in two endcaps (EE), covering the pseudo-rapidity range $|\eta| < 1.48$ and $1.48 < |\eta| < 3$, respectively. The scintillating light is readout by avalanche photodiodes (APDs) in the EB, and vacuum phototriodes (VPTs) in the EE. The Molière radius (22 mm) and radiation length (8.9 mm) are key elements for its compact structure and high granularity, while providing excellent energy containment.

During the first run of the Large Hadron Collider (LHC) [3] (in 2011-2012), with continuous improvements to the calibration and analysis, the ECAL provided an energy resolution for photons from $H \rightarrow \gamma\gamma$ events ranging from 1.1\% to 2.6\% (in EB) and from 2.2\% to 5\% (in EE), and a timing resolution of 190 ps (in EB) and 280 ps (in EE). Such excellent performance resulted in the fundamental Higgs boson discovery with the CMS detector [4].

The ECAL was initially designed to operate for 10 years of LHC running, at a peak luminosity of $L = 10^{34}$ cm$^{-2}$s$^{-1}$, up to a total integrated luminosity of $\int Ldt = 500$ fb$^{-1}$.

2 The LHC and HL-LHC

At the end of the LHC run 1 (end 2012), the LHC delivered an integrated luminosity of about 30 fb$^{-1}$, running at a centre-of-mass energy $\sqrt{s} = 8$ TeV with an instantaneous peak luminosity of $7.7 \times 10^{33}$ cm$^{-2}$s$^{-1}$. By 2022, the LHC is expected to reach the end of Phase I operation as originally planned, with collisions at $\sqrt{s} = 13$ TeV, $L = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and $\int Ldt = 300$–500 fb$^{-1}$.
Figure 1. Left: dark current evolution in the Avalanche Photodiodes installed in the ECAL Barrel (2 APDs are installed on each crystal). The plot shows the average dark current measured per channel as a function of time. The colours indicate different eta regions of the ECAL barrel. Right: single channel noise measured on the pre-samples of laser events taken during the standard monitoring sequences in 2011 and 2012.

In order to fully exploit the LHC potential, a major upgrade is foreseen in 2022. The High-Luminosity LHC is a new machine designed for high precision measurements and possible new discoveries. It is expected to operate for 10 years and to collect $\int L dt = 3000 \text{ fb}^{-1}$, by the end of 2033. During this Phase II (HL-LHC) operation, there will be a very challenging running environment with a peak luminosity five times larger than the initial design conditions and radiation levels typically a factor of six higher, with strong pseudo-rapidity dependence in the EE. Moreover at higher luminosities, the number of multiple interactions in the same bunch crossing (pile-up) as well as the delivered event rate are expected to strongly increase. The HL-LHC represents a great opportunity to explore a rich physics program. However, the detectors must be optimised in order to fulfill the requirements for the physics plans.

The ECAL will be operated beyond its design specifications by the end of Phase I. It is crucial that the current performance is maintained during Phase II, to fully exploit the HL-LHC potential.

3 The evolution of the ECAL performance

During current operation, the ECAL has experienced some radiation damage. By monitoring the evolution of the ECAL performance, it is possible to model such effects and provide long term projections for the future runs.

3.1 The increase of electronic noise in the ECAL barrel

Due to the neutron flux generated by the interaction of hadrons in the calorimeter, there has been an increase in the APD dark current. The dark current measured during LHC run 1 operation (2011-2012), is shown in figure 1 (left) as a function of time. The dark current varies by about a factor of two from $|\eta| = 0$ to $|\eta| \simeq 1.5$. The increase of the energy equivalent electronic noise is shown in figure 1 (right). The energy equivalent electronic noise was 45 MeV at the beginning of 2011. This reached 52 MeV in the central barrel and 60 MeV at $|\eta| = 1.48$, by the end of 2012.

By combining measurements and extrapolation models based on the MARS program [5], it is possible to simulate the evolution of the APD noise for the HL-LHC conditions. Long term
The ECAL aging

Channel response is constantly monitored with $\lambda = 447\text{ nm}$ laser monitoring system, averaged over all crystals in bins of pseudo-rapidity, for the 2011 and 2012 data taking periods. Results are expected soon. With this, and the ionization data, a detailed degradation model can be made, which will be used as input to simulations.

The evolution of the channel transparency projections indicate that the noise will increase at $|\eta| \simeq 1.5$, with a further factor of two expected by the end of Phase I (2024) and more than a factor of five by the end of Phase II. The evolution of the noise has an important impact on the quality of data, as was experienced during 2012. It is thus fundamental to understand it and take it into account in the physics analyses.

### 3.2 Response loss

Radiation damage is responsible for the loss of transparency of the ECAL crystals, through the creation of crystals defects. In particular, hadron damage to PbWO$_4$ crystals is known to be a major problem at room temperature. It is permanent and cumulative, while transmission losses from $\gamma$ irradiation spontaneously recover. Results from beam tests show that, at the hadronic fluence expected during Phase II at high eta, crystal transparency will be strongly reduced with nearly complete darkening [6].

VPT conditioning also contributes to response loss for channels in the endcap region, due to the cumulated charge on the photo-cathode. An asymptotic response loss on the order of 20%–30% is expected over future operation.

In figure 2 (left), the evolution of the ECAL channel response is shown for different eta ranges, as measured over 2011-2012, with the laser monitoring system. Losses are on the order of a few percent in the EB and reach $\simeq 30\%$ in the most forward EE regions used for electron and photon reconstruction ($|\eta| \simeq 2.5$). The cycles of loss and recovery, due to transmission losses and subsequent annealing from ionising radiation damage, are also visible in the figure. The effects observed are consistent with radiation hardness tests performed during construction [7].

The evolution of ECAL channel response has been simulated for HL-LHC conditions with an extrapolation model based on radiation damage and VPT response loss data. Results are shown in figure 2 (right) for a 50 GeV electron beam as a function of eta, for several conditions of instantaneous and integrated luminosity. At $|\eta| \simeq 2.5$ a response loss of about 90% at $\int L\,dt = 500\text{ fb}^{-1}$ is expected.
The response losses and the increased electronic noise will also lead to an additional broadening to the resolution of the Higgs invariant mass for the two photon decay channel ($M_{\gamma\gamma}$). Results are shown in figure 3, where the additional broadening at $|\eta| \simeq 2.5$, with $\int L dt = 500 \text{ fb}^{-1}$ amounts at 2% and this is a limiting factor for good ECAL performance. In order to maintain the same capabilities and performance for physics studies during the HL-LHC, the endcap calorimeter will have to be replaced with a new radiation hard detector.

4 Constraints for operation in Phase II

In addition to the replacement of the endcap calorimeter, due to the ageing constraints discussed in section 3, other upgrade actions are foreseen for HL-LHC Phase II. The current CMS trigger is handled by a Level-1 hardware (L1) reduction followed by an High Level software based Trigger (HLT). The former allows to select the most interesting events in less than 4 $\mu$s, based on information from the calorimeters and muon detectors, the latter to further decrease the event rate from around 100 kHz to around 300 Hz, before data storage. It is foreseen to upgrade the L1 trigger for the HL-LHC, so that information both from the tracker and other sub-detectors could be acquired and exploited. The replacement of the on-detector electronics will allow to account for the future CMS triggering requirements of 10 $\mu$s latency and a L1 trigger rate of 1 MHz, which cannot be accommodated by the existing ECAL electronics, characterised by a front-end buffer with a maximum latency of 6.4 $\mu$s and 120-150 kHz as maximum possible rate.

Furthermore, the detector should be optimised to mitigate the effect of pile-up, with an average of 140 vertices per bunch crossing expected during Phase II. This will be most critical in the forward region, where it will be very difficult to identify the original vertex of the final state particles reconstructed in the detector. A highly granular calorimeter with high precision pico-second timing (20-30 ps) would improve the capability to mitigate pile-up, by identifying objects from secondary vertices and discriminating particles from different vertices by measuring their time of flight.
5 Possible design options for electromagnetic calorimetry at the HL-LHC

All the options for the upgrade of the current calorimeter must be able to operate in the extremely hostile environment of the HL-LHC with good performance. All the components of the upgraded detector, such as scintillators, wavelength shifters (WLS), photo-detectors and electronics will have to be sufficiently radiation-tolerant to withstand the ionising doses. A large number of channels may be required for the Phase II calorimeters, which should be matched to compact and inexpensive electronics. Suitable trigger and cooling systems will also be required. Dedicated R&D studies are ongoing in each of the above mentioned areas.

The HCAL Endcap calorimeter also needs to be replaced for the HL-LHC operation. Two different upgrade scenarios are being considered.

5.1 Scenario 1

In this scenario the new ECAL endcap is designed in a standalone configuration. A sampling calorimeter is a possible option, using radiation-hard inorganic scintillators as active material, such as LYSO and CeF$_3$, alternating layers of absorber (lead or tungsten), in order to reduce the effects of radiation damage.

The Shashlik design [10] allows to collect the scintillation light produced in the active material by means of wavelength shifter (WLS) embedded into light guides made of quartz capillaries that guide the light to a radiation tolerant photodetector. Such a configuration would reduce the average path of scintillating light in the active material and hence would be less sensitive to the ageing of the scintillating crystal. Configurations with photon-sensors glued on the side of the sampling structure are also being studied.

5.2 Scenario 2

In the second scenario the replacement of both the forward ECAL and Hadron Calorimeter (HCAL) [11] with a common integrated calorimeter is being considered.

A dual readout calorimeter is a possible option [12]. It is a sampling calorimeter that measures components of the electromagnetic and hadronic energy deposits at the same time, by using the simultaneous readout of Cherenkov and scintillation light. Studies are ongoing to assess the possibility to remove the intrinsic fluctuations in the hadronic and electromagnetic component of the hadronic shower, thus providing an offline compensation, by combining the two light outputs. Several simulation studies are ongoing to optimise the calorimeter parameters and geometry. Considered technologies consist in absorbers with embedded fused silica and scintillating fibers. In both cases, the fibers could be either doped to obtain a scintillating material or un-doped to be used as a Cherenkov radiator. Preliminary results indicate a very good energy resolution less than 10%, for 50 GeV jets.

A particle flow calorimeter, based on studies made by the CALICE [13] collaboration is another option being considered for the scenario 2 hypothesis. It is thought as a fine-grained calorimeter, where individual sampling layers are highly segmented and readout independently with millions of channels, so that a three-dimensional image of the showers inside the calorimeter can be reconstructed. Preliminary designs present a classical sandwich calorimeter with layers of absorber alternating active media. It is being optimised for particle flow algorithms, to separate and track...
showers as they develop. Several solutions are under study to provide the multi-channel structure of such a detector, such as Gas Electron Multiplier chambers (GEMs) or silicon pads. Such a design could be particularly useful for pile-up mitigation and jet resolution improvement.

6 Conclusions

Although the LHC is at the beginning of its operation, with $\sim 30 \text{fb}^{-1}$ of integrated luminosity, evidence of some radiation damage is already visible in the ECAL. The observation is in general agreement with expectations and is taken into account in data analysis, to ensure the high quality of the ECAL detector performance and the corresponding physics results.

In ten years from now, the HL-LHC will operate at a factor of five higher instantaneous luminosity with respect to LHC, eventually delivering up to $3000 \text{fb}^{-1}$ in Phase II. Such challenging conditions impose stringent detector requirements in terms of performance and radiation-hardness. Simulation studies have been carried out, to predict the evolution of the ECAL response in the high-radiation environment and to understand the requirements for the detector upgrade in order to maintain a good level of performance.

Several R&D studies have started to investigate the best upgrade options for the forward region of the CMS calorimeter, in order to exploit the physics potential offered by the HL-LHC. The key points to be considered are the radiation-hardness of the elements, high granularity and segmentation and excellent timing resolution which may add important information for pile-up mitigation and object identification.

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