Simulation of the CMS electromagnetic calorimeter response at the energy and intensity frontier

Badder Marzocchi*, on behalf of the CMS Collaboration

* Sapienza, Università di Roma & INFN, sezione di Roma1
E-mail: badder.marzocchi@cern.ch

Abstract. The electromagnetic calorimeter (ECAL) of the CMS experiment at the LHC is a homogeneous calorimeter made of 75848 lead tungstate (PbWO$_4$) scintillating crystals, designed for high precision electron and photon energy measurements in hadron collisions at the TeV scale. The detailed simulation of the calorimeter response is crucial for physics analyses involving electrons, photons, jets or missing energy. The detector simulation has been tuned during the first LHC run, including a detailed description of the upstream material. The increase of centre-of-mass energy, bunch crossing rate and instantaneous luminosity in the second run has resulted in updated and improved data readout, settings and reconstruction techniques. Furthermore, aging effects due to radiation, in particular increases in noise in the photodetectors and crystal transparency losses, have caused a change of the calorimeter response. All of these effects have been taken into account in order to improve the simulation of the calorimeter response and to ensure that it describes the data well over time, notwithstanding the evolving conditions. In 2024 the ECAL will undergo an upgrade to cope with the high luminosity phase of the LHC (HL-LHC). The temperature of the calorimeter will be lowered to mitigate the aging effects, the front-end electronics will be replaced with a faster version and the data will be read out in streaming mode towards the off-detector electronics. The fast PbWO$_4$ response time will be exploited to measure the timing of high-energy showers with high precision. A detailed simulation description of the crystal response is fundamental for the design of the detector electronics and to predict the performance for the energy and timing measurements. The techniques employed in tuning the simulation of the detector response for the present running conditions and for the upgrade will be presented.

1. Introduction
The electromagnetic calorimeter (ECAL) of the CMS detector was designed in order to reach excellent energy resolution for photons with energy from a few MeV to 1.5
TeV \[2\] and excellent electron and photon identification \[3, 4\], which were crucial for the discovery and the characterization of the 125 GeV Higgs Boson \[5, 6\]. In order to achieve this performance, ECAL was designed as a compact, homogeneous, hermetic and fine grain calorimeter embedded in 4T magnetic field, made of 75848 lead-tungstate (PbWO\(_4\)) scintillating crystals. Lead-tungstate is suitable for operation at LHC \[7\] due to its fast emission (80% of the scintillation light is emitted within 25 ns) and its resilience to irradiation. In addition, because of crystals’ short radiation length (\(X_0 = 0.89\) cm) and small Molière radius (\(r_M = 21.9\) mm), most of an electron or photon’s energy can be collected within a small matrix of crystals. As shown in Figure 1, ECAL crystals are divided into two main parts of the calorimeter: barrel (61200 crystals, shaped as a cylinder with an inner radius of 1.290 m, \(0 < |\eta| < 1.479\)), and endcaps (two forward caps, holding 7324 crystals each, \(1.479 < |\eta| < 3.0\)). The relatively low light yield of \(\approx 30\) γ/MeV makes it necessary to use intrinsic high-gain photodetectors, capable of operating in high magnetic fields and high dose of radiation. Avalanche photo-diodes (APDs) \[8\] are used for barrel crystals and vacuum photo-triodes (VPTs) \[9\] are used for endcaps crystals.

Moreover, a preshower (ES) is placed in front of the EE crystals with the aim of identifying neutral pions in the endcaps, and improving the position determination of electrons and photons. The preshower consists of two layers made of passive lead radiators (2\(X_0\) and 1\(X_0\)), which initiate electromagnetic showers, and active silicon strip sensors placed after each radiator (4288 strips, thickness of 310 \(\mu\)m and area of 1.9 mm\(\times\)61 mm), which measure the deposited energy and the transverse shower profiles.

**Figure 1.** CMS ECAL geometry schema. The ECAL barrel (green) is made of 36 Super-Modules: 18 in EB+ (\(z > 0\)) and 18 in EB- (\(z < 0\)) (left). The ECAL endcaps (blue) are divided in 4 Dees: 2 Dees in EE+ (\(z > 0\)) and 2 Dees in EE+ (\(z > 0\)) (right). Two preshowers (red) are put in front of the endcaps.

A key ingredient in the discovery of new particles and precision measurements of the Standard Model is the simulation of ECAL detector. In particular, crystal response
simulation is based on a simple strategy: simulate energy depositions in crystal volume with GEANT4 [10], assuming the response is proportional to energy depositions.

2. Full simulation of ECAL response
Regarding the simulation of ECAL response, at first, the full simulation is performed in three steps:

- Step-1: simulation of energy depositions with GEANT4
- Step-2: propagation of scintillation/Cherenkov photons
- Step-3: simulation of pulse shape at front-end stage and digitization

Then, the time evolution of photo-detector noise and crystal response is applied.

2.1. Step-1: Energy depositions with GEANT4
The standard simulation of electromagnetic shower in crystal material is performed, generating energy depositions to be converted into scintillation light. In addition, the Cherenkov radiation is also simulated. The time of individual depositions is recorded to simulate the time evolution of the electromagnetic shower, as shown in Fig. 2

![Figure 2. Energy deposition of an electromagnetic shower (z-axis, relative fraction) as a function of time (x-axis) and crystal depth (y-axis).](image)

2.2. Step-2: Propagation of scintillation/Cherenkov photons
In full simulation, the transport of optical photons from emission point to photo-detector is simulated using GEANT4. On the other hand, for more detailed studies, such as ray tracing inside the crystal, LITRANI Monte-Carlo [11] is used, but it is too slow to be used extensively in the CMS full simulation. The GEANT4 simulation input information is based on many geometrical properties (geometry of ECAL crystals and photo-detectors, quality of surface polishing, and properties of wrappings), decay times of PbWO$_4$ scintillation, and wavelength dependent parameters: spectrum of emitted photons, absorption of PbWO$_4$, refractive index of crystal (2.2) and glue, entrance window, and photon-detection efficiency of APDs and VPTs). Figure 3 shows the final photo-current pulse shape (90% of light yield collected within 25 ns), separating the scintillation and Cherenkov light components. The discrete peak structure is due to the photon propagation in forward and backward directions, while the peak widths are due to the dispersion and finite size of the photo-detector.
Figure 3. Total photo-current pulse shape (black), separating the scintillation (blue) and Cherenkov (red) light components, using GEANT4 simulation. The discrete peak distribution is due to the different light path after bouncing.

2.3. Step-3: Simulation of pulse shape at front-end stage and digitization
The photo-current pulse is convoluted with single pulse response (SPR) function of the front-end, measured with short laser pulses and nucleon interaction with APDs, which takes into account the internal capacitance of APDs, inductance and capacitance of cables. Two different front-end electronics are simulated: legacy [12] and upgrade prototype for HL-LHC [13]

- **Legacy**: CR-RC shaping with 43 ns shaping time and sampling ADC at 40 MHz.
- **Upgrade prototype for HL-LHC**: Trans-Impedance Amplifier (TIA) architecture with minimal shaping time and sampling ADC at 160 MHz.

The in-time and out-of-time pileup is simulated from -12 to +3 bunch-crossing (every 25 ns) and the energy is reconstructed using the “multifit algorithm” [14], in order to estimate the in-time signal amplitude and up to nine out of time amplitudes. Figure 4 shows an excellent data (test beam) and simulation comparison of the pulse shapes for both the legacy and HL-LHC upgrade prototype electronics.

3. Evolution of photo-detector noise and crystal response
The evolution of the detector response as a function of integrated luminosity is predicted using as input measurements taken from data, extrapolated to the foreseen HL-LHC Phase-2 integrated luminosities.

3.1. APD noise evolution
The VPT noise is not affected by radiation, therefore the noise is constant in time ($\approx$2 ADC counts), while the APD noise increases due to the radiation-induced increase of the APD leakage current. As shown in Fig. 5, the evolution of the APD dark current is measured as a function of time or integrated luminosity, fitted with 3 exponentials.
and one permanent damage term. The dark current-noise dependence is measured for different fluences. The noise measurements as a function of dark current (top-right) were performed at different temperatures in order to better understand its dependence, as in the upgrade a lowering of the cooling temperature is foreseen. With these ingredients, the evolution of the APD noise is predicted for the foreseen integrated luminosities of LHC-Run II and III.

3.2. Crystal response evolution

The radiation damage results from the development of absorption and scattering centres in the crystals. The crystals lose transparency and the response to particles evolves as a function of integrated luminosity. In addition, the radiation damage changes the pulse shapes, resulting in a loss of amplitude and a non-linearity of the response. The net impact is a degradation of energy resolution: a deterioration of the stochastic term, an increase of the noise and a deterioration of light collection uniformity. As shown in Fig. 6, the short term aging prediction of crystal response evolution is extrapolated fitting the data. The long term predictions to the end of HL-LHC Phase-2 are extracted using a complex model. In particular, the loss of light yield can be parametrized as:

\[
\frac{LY}{LY_0} = e^{-\mu_{ind}(x,\lambda)L}
\]

where \(\mu_{ind}(x,\lambda)\) is the induced absorption, affecting propagation of optical photons from emission point towards photo-detector of length \(L\). Therefore, the full model to predict the response of crystals during LHC and HL-LHC can be constructed in different steps, with the following inputs:

- Simulation of dose and fluence from FLUKA [15]
Figure 5. Top left: APD dark current as a function of integrated luminosity for one HV channel (50 crystals). Top right: noise as a function of the dark current with the legacy ECAL electronics. Bottom: APD noise evolution as a function of the integrated luminosity for different \( \eta \) values.

- Full simulation of the GEANT shower development
- Ray tracing inside the crystals using LITRANI
- Ageing of crystals and photo-detectors as a function of wavelength

where the test beam measurements of the light yield evolution as a function of induced absorption and the resolution degradation for different induced absorption coefficients \([16]\) are used to verify and refine the model. Figure 7 shows the final light yield loss and the degradation of energy resolution as a function of \( \eta \) for different integrated luminosity scenarios, using the full model and the input parameters taken from the test beam measurements. Almost a factor 2 of light yield loss and of energy degradation is expected at the end of Phase-2.
Figure 6. Top: fit of the dynamic model of colour centres creation/recovery under irradiation to explain the changes in crystal transparency. Each colour centres has 3 free parameters: creation rate, saturation level and recovery rate. Bottom: instantaneous luminosity as a function of time.

Figure 7. Left: expectation of the relative light output with respect to legacy of the ECAL crystals as a function of the pseudorapidity $\eta$ for various ageing conditions. Right: expectation of energy resolution constant term of the ECAL crystals as a function of the pseudorapidity $\eta$ for various ageing conditions.

4. Conclusions
ECAL crystal response simulation is based on a full simulation of energy depositions, propagation of scintillation and Cherenkov photons, pulse shape, and front-end digitization with GEANT4. In addition, APD noise evolution, predicted using CMS collected data, and crystal response evolution, predicted using test beam data and simulations from GEANT and FLUKA, are applied in order to cope with the increase
luminosity expected at the HL-LHC.

References

[1] CMS Collaboration, “The CMS experiment at the CERN LHC”, CERN-LHC-CMS, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004

[2] P. Adzic et al., “Energy Resolution of the barrel of the CMS Electromagnetic Calorimeter”, 2007 JINST 2 P04004, doi:10.1088/1748-0221/2/04/P04004

[3] CMS Collaboration, “Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, JINST, 10(08):P08010, 2015, doi:10.1088/1748-0221/10/08/P08010

[4] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, JINST, 10(06):P06005, 2015, doi:10.1088/1748-0221/10/06/P06005

[5] CMS Collaboration, “Measurements of Higgs boson properties in the diphoton decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV”, CERN-EP-2018-060, cds:2312121

[6] CMS Collaboration, “Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at $\sqrt{s} = 13$ TeV”, JHEP 11 (2017) 047, doi:10.1007/JHEP11(2017)047

[7] Lyndon Evans, Philip Bryant, “LHC Machine”, JINST 3 (2008) S08001, doi:10.1088/1748-0221/3/08/S08001

[8] Z. Antunovic et al., “Radiation hard avalanche photodiodes for the CMS detector”, 2005 NIM A537 379, doi:10.1016/j.nima.2004.08.047

[9] K. W. Bell et al., “Vacuum phototriodes for the CMS electromagnetic calorimeter endcap”, IEEE Trans. Nucl. Sci. 51 (2004) 2284-2287, doi:10.1109/TNS.2004.836053

[10] S. Agostinelli et al., “GEANT4 - a simulation toolkit”, Nucl. Instr. Meth. A, vol. 506, no. 3, pp. 250-303, 2003, doi:10.1016/S0168-9002(03)01368-8

[11] F. X. Gentit, “Litrani: a general purpose Monte-Carlo program simulating light propagation in isotropic or anisotropic media”, NIM A 486 (2002) 35-39, doi:10.1016/S0168-9002(02)00671-X

[12] CMS Collaboration, “The CMS electromagnetic calorimeter project : Technical Design Report”, CERN-LHCC-97-033, cds:349377

[13] CMS Collaboration, “Technical Proposal for the Phase-II Upgrade of the CMS Detector”, cds:2020886

[14] Emanuele di Marco, on behalf of the CMS Collaboration, “CMS electromagnetic calorimeter calibration and timing performance during LHC Run I and future prospects”, cds:1975982

[15] C. Battistoni, et al., “The FLUKA code: description and benchmarking”, AIP Conf.Proc. 896 (2007) 31-49, doi:10.1063/1.2720455

[16] T. Adams, et al., “Beam test evaluation of electromagnetic calorimeter modules made from proton-damaged PbWO₄ crystals”, JINST 11 (2016) P04012, doi:10.1088/1748-0221/11/04/P04012