The CMS electromagnetic calorimeter barrel upgrade for High-Luminosity LHC

Philippe Gras
on behalf of the CMS collaboration
CEA/IRFU Saclay, France
E-mail: philippe.gras@cern.ch

Abstract. The High Luminosity LHC (HL-LHC) will provide unprecedented instantaneous and integrated luminosity. The lead tungstate crystals forming the barrel part of the CMS Electromagnetic Calorimeter (ECAL) will still perform well, even after the expected 3000 fb$^{-1}$ at the end of HL-LHC. The scintillation light from the crystals is measured with avalanche photodiodes (APDs). Although the APDs will continue to be operational, there will be some increase in noise due to radiation-induced dark-currents. Triggering on electromagnetic objects with $\sim140$ pileup events necessitates a change of the front-end electronics. New developments in high-speed optical links will allow single-crystal readout at 40 MHz to upgraded off-detector processors, allowing maximum flexibility and enhanced triggering possibilities. The very-front-end system will also be upgraded, to provide improved rejection of anomalous signals in the APDs as well as to mitigate the increase in APD noise. We are also considering lowering the ECAL barrel operating temperature from 18$^\circ$C to about 8$\sim$10$^\circ$C, in order to increase the scintillation light output and reduce the APD dark current.

1. Introduction
The CMS experiment [1] is located at CERN at the Large Hadron Collider (LHC). At the end of year 2022 the LHC will have accumulated 300 fb$^{-1}$. After this first operation phase, the LHC will be upgraded to raise its peak luminosity to $5 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$. At that luminosity, 300 fb$^{-1}$ will be integrated each year to reach a total amount of data of 3000 fb$^{-1}$ at the end of year 2035 [2]. The LHC experiments, including CMS, will be also upgraded to meet the challenges brought by this unprecedented luminosity level and optimise the detectors for the rich physics program foreseen for HL-LHC.

2. The central electromagnetic calorimeter of the CMS experiment
The current central electromagnetic calorimeter of CMS [3] (barrel part of the calorimeter, or ECAL barrel) is a homogeneous calorimeter made of 61,200 lead tungstate, PbWO$_4$, crystals. It is highly granular, $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$, $\Delta \ln(\tan \theta/2) = 0.087$ in the longitudinal plan with $\theta$ the angle with respect to the the beam axis and 0.087 radian in the transverse plan. The crystals are 26 radiation lengths long and their square front size is $\sim 10$ Molière radii $\times 10$ Molière radii. The ECAL barrel is made of 36 supermodules, which were assembled on the surface, before being shipped down into the cavern where the CMS experiment is located and inserted into the CMS detector. The scintillation light is measured with avalanche photodiodes (APDs). To maximize the collection surface two APDs are glued on each crystal, the sum of
the two signals being read out. A picture of the APD pair assembly can be found in Fig. 1. The crystals are grouped for the readout electronics in entities of 25 crystals, $5 \times 5$ in $\eta \times \phi$. The data stream is split in two on the detector: one stream of events selected by the first trigger level with the full granularity offered by the calorimeter, an average of about 100,000 events per second and one stream to the trigger system read at 40 MHz with a reduced granularity. For the trigger system stream, each readout unit, which covers 25 crystals, delivers one signal which is the sum of signals over these crystals. A picture of the electronics of one readout unit is shown in Fig. 1.

The irradiation sustained by the crystal induces a reduction of their transparency. The crystals have the capacity to recover the transparency loss in absence of collisions, e.g. during the LHC machine fill, the transparency increases. Fig. 2 shows channel response changes during 2011 and 2012 operations of the electromagnetic calorimeter. The response is measured with a laser, at the rate of one measurement point every 40 min. The channel response includes the electronics chain. For the barrel this response changes is dominated by the crystal transparency variations. The barrel parts corresponds to the two red and green curves at the top of the figure, while the other curves correspond to the forward part of the ECAL constituted by the endcaps. The loss is limited to 10% in the most forward barrel pseudorapidity ranges represented in this plot. Loss will be larger for HL-LHC, reaching values currently reached in the endcaps. The laser monitoring system will be used as it is currently done for the barrel and endcaps to correct for the response variations.

The irradiation also effects the APDs, it induces damage in the silicon bulk, creating a leakage current called dark current. The net effect is an electronic noise proportional to the square root of this dark current, hence to the square root of the integrated luminosity. Measurement of the dark current during 2011 and 2012 is shown in Fig. 3. A particle can also deposit energy directly into the silicon bulk generating a signal. There are two handles to discriminate this anomalous signal from the signal from an electromagnetic shower: the signal shape, the anomalous signal is faster, narrower and arrives earlier, and correlation between channels, since an electromagnetic shower will systematically induce a signal on a group of neighbouring crystals, as opposed to anomalous signal which appears in one crystal. Fig. 4 illustrates this discrimination. The two-
Figure 2. Relative response to laser light (440 nm) measured by the ECAL laser monitoring system, averaged over all crystals in bins of pseudorapidity, for the 2011 and 2012 data taking periods. The two red and green top curves correspond to the barrel part, the curves below correspond to the endcap part of the calorimeter.

Figure 3. APD dark current measured during the 2011 and 2012 years of operation. The dark current increase is proportional to the integrated luminosity, apart from the limited recovery during the period without beam.

Figure 4. Anomalous signal discrimination. The plot represents the correlation between two discriminating variables of anomalous and scintillation signals, the timing of the signal maximum and a ratio of signal measured in adjacent crystal to the considered crystal. Anomalous signals can be rejected highly efficiently with the use of these two variables.
dimensional histogram shows the correlation of the signal timing with a variable sensitive to the localisation of the signal, defined for a crystal hit as one minus the ratio of the total transverse energy measured in the four closest crystals to the transverse energy measured in this crystal. In this histogram, a minimum transverse energy of 3 GeV is required on the crystal hits. The rate of anomalous signals is proportional to the instantaneous luminosity, so a factor 20 increase is expected for HL-LHC for the same transverse energy threshold, but the rate sharply decreases when the transverse energy threshold is increased.

3. Upgrade of the central electromagnetic calorimeter of the CMS experiment
Extrapolation of dark current evolution from 2011-2012 data to HL-LHC provides an estimation of 400 MeV noise at the end of HL-LHC. Complementary irradiation tests are being performed in order to verify this extrapolation. This noise level is considered adequate to reach required precision. Operation at a lower temperature, 8°C to 10°C, which would mitigate the increase of dark current is under study. The upgrade for the HL-LHC will concern the readout electronics from the output of the APDs up to the data acquisition (DAQ) and the trigger systems. Part of the laser monitoring system will also be upgraded.

The CMS trigger system for HL-LHC will keep the current concept of two levels of triggers: a Level-1 trigger implemented in dedicated electronics and a High Level Trigger implement in software and run in a cluster of computers. The Level-1 trigger rate will be increased by a factor 10 to reach 1 MHz and the tracker information will be added for the Level-1 trigger decision. While current ECAL electronics support a trigger latency up to 6.3 µs, 20 µs will be needed with the new trigger system. Fig. 5 illustrates the current architecture of the ECAL barrel readout. A preprocessing is performed for the trigger in the electronics located on the detector and two data streams go from the on-detector to the off-detector electronics, one to feed the Level-1 trigger system and one for the data of the selected events. The functionality of the off-detector electronics is split in four types of boards: detector control cards (DCC) to collect triggered event data and send them to the CMS DAQ system, trigger control cards (TCC) to collect the data for the trigger decision and send them to the CMS calorimeter trigger system, the clock and control system cards (CCS) to control, configure the on-detector electronics, provide it the clock
Figure 6. Level of the electronics noise induced by the dark current in function of the signal preamplifier parameters and type. Two options are considered a CR-RC shaping and a charge integration in a fixed time window.

Figure 7. Laser monitoring system (Left) before and (Right) after the upgrade. The crystals are illuminated by groups of 800 or 900. The laser is located outside the detector in the service cavern. A remotely controlled optical switch is used to direct the light in the different groups of crystals. Fibres are split inside the detector supermodules to feed each crystal. In the upgraded system, the diodes used to measure the light injected into the crystals will be moved to outside the detector.

Figure 8. Picture of the prototype of laser light intensity measurement setup. Shield is removed on a small part of the fibre, the fibre is unpolished and a photodiode is placed in front of the unpolished part.

and transmit it the Level-1 trigger accept signal received from the CMS trigger system. The upgrade of the electronics will exploit the developments in data-link and reduction of cost-to-bandwidth ratio, and the improvement of FPGA integration to use a single data stream. After the upgrade, the channels will be read at 40 MHz without on-detector trigger pre-processing, and the full off-detector functionality will be implemented in a single card type. In the current architecture the on-detector electronics includes a data pipeline to retain the event data the time the Level-1 trigger decision is taken. With the new architecture, this pipeline is moved to the off-detector electronics. The data link from on-detector to off-detector electronics will be done using the versatile link technology and companion GBT chips which were developed at CERN [4]. For each readout unit (25 crystals) three upstream links will be used for the detector data and one downstream for the controls of the electronics and the transmission of the clock.
We will take the advantage of the electronics change that is mandatory for the trigger system to optimise the shaping and the encoding of the signal. Figure 6 shows the electronics noise with an CR-RC amplifier, which is used in current electronics, for different APD dark current levels. This plot shows that for an increased dark current level it is useful to shorten the shaping time in order to minimise the effective induced noise. Reduction of shaping time constant will also help in mitigating the pile-up of events from nearby bunch crossings (since there will be an average of 140 hard interactions in a bunch crossing with the HL-LHC beam luminosity). As shown on this figure further improvements can be obtained by using a different approach for the signal readout. The curve with box markers shows the noise level if the signal is integrated in a fixed-time window. Use of the concept of the QIE (Charge Integrator and Encoder) developed for the CMS hadronic calorimeter [5] is very promising and extension of the design to the needs of the electronic calorimeter is under study. Finally, including a precise time encoding in the on-detector electronics to ship the signal time together with its amplitude is under studies. It will provide a powerful handle to mitigate the effects of the pile-up and to reject anomalous signals. The encoding of the signal amplitude is also being revised. The current system provides a quantisation step of about 35 MeV, while a $\sim 100$ MeV quantification should be sufficient to keep the quantisation noise small with respect to the noise induced by the APD dark current.

Finally, the laser monitoring system measures the light injected into the crystals with PN diodes located on the detector inside the supermodules, as represented in the sketch of Fig. 7. The readout of these PN diodes uses the same link technology than the readout of the APDs and is similar to the other readout units from the point of view of the DCCs. A first option will be to upgrade the electronics to support the new links. An alternative option under study is to measure the injected light outside of the detector on the main fibre, upstream the fibre splitting, as represented in Fig. 7. The measurement will be performed with a photodiode measuring light diffused from the fibre surface locally unpolished for this purpose, like in the picture of Fig. 8. This option has the advantage to limit interventions on the supermodules and to be cost effective. A prototype is being put in place for the LHC run 2, starting in 2015, and will be operated in parallel of the current system. That will allow an evaluation of this option and especially of the measurement precision which can be reached.

4. Summary
The HL-LHC will enable the acquisition of 10 times more data that will have been acquired with the LHC. The extremely large luminosity, resulting in a very large number of events per bunch crossing which get piled-up and in stringent irradiation conditions, brings new requirements for the experiment detectors. The plan for the upgrade of the barrel part of the electromagnetic calorimeter of CMS has been presented. The detector itself, a homogeneous lead tungstate calorimeter read out by avalanche photodiodes will be kept as such. The full electronic chain from the output of the APDs down to the CMS data acquisition system and the CMS trigger system will be changed. Part of the laser monitoring system which measures the detector response variation, mainly due to the irradiation effect on the lead tungstate crystal transparencies, will also be upgraded.

References
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