Study of radiation damage and possible upgrade of the CMS ECAL Laser Monitoring system

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Abstract. The Electromagnetic Calorimeter (ECAL), one of the main subsystems of the CMS detector, measures the energies of electrons and photons. The ECAL consists of 75848 lead tungstate (PbWO$_4$) crystals. The transparency of crystals is affected by irradiation, and the laser monitoring system is designed to measure the transparency changes for each ECAL crystal over time. In the future, the High-Luminosity LHC upgrade will increase the integrated luminosity of the LHC and lead to higher radiation damage in all components of the CMS detector. In this work we report the proposed upgrade for the laser monitoring system and the results of computing crystal transparencies based on Run 2 data.

1. Introduction
The CMS electromagnetic calorimeter is made of about 75000 scintillating crystals. It was built to measure with high precision the energies of electrons and photons and it has played a crucial role in the observation of the Higgs boson from its two-photon decay.

In the radiation environment of the LHC collisions the crystal transparency changes. A dedicated monitoring system is installed in the ECAL to monitor the crystal transparency evolution using laser light.

The High-Luminosity LHC (HL-LHC) is an upgrade to the LHC that will boost the potential for new discoveries in physics. The beginning of operation is scheduled to 2026, and the upgraded accelerator will provide a peak luminosity of $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$. The HL-LHC will deliver an integrated luminosity of 3000 fb$^{-1}$ over approximately 12 years of operation.

The HL-LHC upgrade will lead to higher radiation damage in all components of the CMS detector. To meet the requirements of the HL-LHC, many of the subsystems of the CMS detector should be upgraded [1]. In this work we report the proposed upgrade of the laser monitoring (LM) system, which is designed to measure the transparency of the ECAL crystals over time.

2. Experimental setup
2.1. Electromagnetic Calorimeter
The Electromagnetic Calorimeter (ECAL), one of the main subsystems of the CMS detector, measures the energies of electrons and photons [1, 2, 3]. The ECAL is made of lead tungstate (PbWO$_4$) crystals. Geometrically, the ECAL consists of a cylindrical barrel (61200 crystals, pseudorapidity range $0 < |\eta| < 1.48$) closed at each end with an end-cap (7324 crystals per end-cap, $1.48 < |\eta| < 3$). The barrel consists of 36 supermodules (SMs), each with 1700 crystals.
read out with avalanche photodiodes (APDs). Each SM is made up of four modules. An end-cap consists of two dees, each with 3662 crystals read out with vacuum phototriodes (VPTs).

The choice of lead tungstate was based upon the high density of the crystals and its radiation hardness so that the scintillation mechanism is not affected by irradiation. However, electromagnetic radiation induces temporary defects that reduce the transparency of the crystals. These defects anneal at room temperature. The laser monitoring (LM) system was designed to monitor the transparency of each ECAL system over time [1-3].

2.2. Laser Monitoring system

The laser monitoring (LM) system (Fig. 1) uses two lasers: blue and green. In order not to affect ECAL measurements during LHC data taking, laser light is injected at intervals of 3.17 μs provided every 88,924 μs in the LHC beam structure.

Laser light pulses are directed to individual crystals via a multi-level optical fiber system. The first switch near the light source directs the light to one of 88 calorimeter regions: each half of a SM (72 regions) or each quarter of a dee (16 regions). A primary optical fiber distribution system transports the laser pulses to each selected calorimeter region as shown in Fig. 1. A two-level distribution system directs fibers to individual crystals. The laser pulses are measured with APDs (for barrel) and VPTs (for end-caps). Stable PN diodes are used as a reference system. The ratios of APD or VPT response to PN signal are used to compute crystals transparencies. Thus, the aging of the light distribution system itself under irradiation does not affect the measurement. Fig. 2 shows the evolution of the crystal transparency in different regions of the detector in LHC Run 1 and Run 2.

The current precision of the transparency measurements is 0.2%. The required precision of the LM system may be relaxed to 1% at the HL-LHC due to a significant difference in luminosity and the possibility of calibration on physics events.

Figure 1. Scheme of the LM system [1] with the details of the light distribution apparatus.
Figure 2. Evolution of crystal transparency in different regions of the detector during LHC Run 1 and Run 2.

3. Proposed upgrade of the Laser Monitoring system

The proposed upgrade of the LM system is shown in Fig. 3. It involves measuring the injected light at the source rather than with PN diodes located in the supermodules [1].

Two monitoring spy boxes with 44 fibers each were installed on the light path after the optical switch. Fig. 4 shows the picture of the spy boxes. Each fiber will be equipped with a PiN diode that measures a small fraction of the light signal. Only 11 of them, which correspond to 11 monitoring regions (5 & half SMs), are equipped with PiN diodes at the moment. The new system has been running in parallel to the legacy system since Run 2.

Figure 3. The schematic view of the proposed LM system for the HL-LHC [1].

4. Prototype monitoring test results

To check the performance of the prototype system, we used Run 2 data [1]. It is known that the legacy system uses the ratio of APD and PN signals to compute crystal transparency, while the prototype system uses APD and PiN signals. For consistency between the two systems,
the PN/PiN ratio should be stable. Taking these points into account, we obtained two spy box stability maps using ten days of data from May 2016 and the whole 2016. Fig. 5 and 6 show the stability during beam-off and beam-on periods, respectively. The stability during the beam-off period is approximately 0.1-0.2%, similar to the performance of the legacy system. The spread of RMS during the beam-on period is larger, around 1-2%.

Figure 4. The spy boxes [1].

Figure 5. Intrinsic stability of the measurements computed using RMS of the APD/PN and APD/PiN signal for each channel during the LHC beam-off period [1].

Figure 6. The RMS of the APD/PN and APD/PiN signal during the LHC beam-on period [1].

There is a drift of the (APD/PiN)/(APD/PN) ratio versus time correlated with the instantaneous luminosity of the LHC (Fig. 7). Because of this drift, the PiN signal cannot simply be replaced by the PN signal. The slope characterizing the decrease in the transparency of the crystals depends on module number because fibers going to different modules have different lengths (Table 1). Thus, the ratio of PN/PiN is sensitive to differential aging of fibers. This effect is absent in the legacy system since both APD and PN photodetectors are located in the same place in the SMs.

To account for the drift of PN/PiN versus time, various actions can be performed [1]. First, the LM system can be used to provide corrections over short periods of time. According to 2017 data, PN/PiN signal is reduced by 1% in approximately 2 days at the beginning of the
Figure 7. History plot of (APD/PiN)/(APD/PiN) signal for the different modules of a selected supermodule [1].

LHC luminosity after technical stop and in approximately two weeks of work with luminosity $L \approx 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$. The laser signal is fairly stable: for most of the intervals the difference between PN and PN/PiN signal is less than 1%. Thus, the PiN signal can be replaced by the PN signal over short periods of 1-2 weeks. Residual drifts over this time will be corrected using calibration with physics events (Z, W).

Second, it is possible to simulate the differential loss between fibers going to different modules. To do that, one should get parameters for a simulation reducing the discrepancy between PN and PiN signals. Then it is necessary to check the performance of the simulation on a different data set.

Third, the crystal transparency can be normalized to a stable reference crystal within one monitoring region. Different monitoring regions (72 for barrel) will be intercalibrated using calibration with isolated electrons.

5. Conclusion

The CMS ECAL has efficiently operated during LHC Run 2. The excellent ECAL performance was crucial for the Higgs boson discovery made by the CMS Collaboration and remains very important for precision measurement and for searches of new physics. Further study to meet the designed precision of the laser monitoring system with spy boxes is ongoing. There are three possible ways to use spy box data: First, provide corrections over short time periods and correct for residual drifts. Second, simulate the differential loss between fibers. And third, normalize the crystal transparency to a reference crystal. In conclusion, the spy boxes have provided so far an excellent tool to measure the stability of the laser monitoring system. Further studies on the whole Run 2 data are needed to understand if the radiation hardness of the light distribution system is good enough for HL-LHC operation.

References

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Table 1: Length of L2 fibers [3]

| Module | L2 fiber length, mm |
|--------|---------------------|
| 1      | 2573$^{+12}_{-0}$  |
| 2      | 2723$^{+12}_{-0}$  |
| 3      | 2723$^{+12}_{-0}$  |
| 4      | 3123$^{+12}_{-0}$  |