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Predicting the performance of the CMS precision PbWO_4 electromagnetic calorimeter in the HL-LHC era from test beam results on irradiated crystals

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Predicting the Performance of the CMS precision PbWO_4 electromagnetic calorimeter in the HL-LHC era from test beam results on irradiated crystals

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Abstract—The harsh radiation environment in which detectors will have to operate during the High Luminosity phase of the LHC (HL-LHC) represents a crucial challenge for many calorimeter technologies. In the CMS forward calorimeters, ionizing doses and hadron fluences will reach up to 300 kGy (at a dose rate of 30 Gy/h) and $2 \times 10^{14} \text{ cm}^{-2}$, respectively, at the pseudorapidity region of $|\eta| = 2.6$. To evaluate the evolution of the CMS ECAL performance in such conditions, a set of PbWO_4 crystals, which had previously been exposed to 24 GeV protons up to integrated fluences between $2.1 \times 10^{13} \text{ cm}^{-2}$ and $1.3 \times 10^{14} \text{ cm}^{-2}$, has been studied in beam tests. A degradation of the energy resolution and a non-linear response to electron showers are observed in damaged crystals. Direct measurements of the light output from the crystals show the amplitude decreasing and pulse becoming faster as the fluence increases. The evolution of the performance of the PbWO_4 crystals has been well understood and parameterized in terms of increasing light absorption inside the crystal volume. A double-sided readout configuration, in which two identical photodetectors are coupled to the opposite ends of each crystal, has also been tested. The separate and simultaneous readout of the light from the two sides of the crystal allows us to correct for longitudinal shower fluctuations and to mitigate the degradation of energy resolution in highly damaged crystals. The non-linear response to electromagnetic showers, arising from high non-uniformity of light collection efficiency along the longitudinal axis of irradiated crystals, can also be corrected by means of the double-sided readout technique.

I. INTRODUCTION

The CMS electromagnetic calorimeter (ECAL) [1] is designed to provide hermetic coverage within the pseudorapidity region $|\eta| < 3.0$. The ECAL is crucial for the identification and reconstruction of photons and electrons, important for the planned HL-LHC (High Luminosity Large Hadron Collider) physics program. For Higgs physics, excellent resolution and efficient identification of photons is required to study the $H \rightarrow \gamma\gamma$ decay channel, for Higgs parameters and self-coupling measurements. Electrons are important for Higgs physics and for many physics topics beyond the Standard Model (BSM).

The CMS electromagnetic calorimeter is a homogeneous calorimeter made of 75 848 lead tungstate (PbWO_4) scintillating crystals, located inside the CMS superconducting solenoid magnet [1–3]. It is made of a barrel part covering the region of pseudorapidity $|\eta| < 1.48$ and two endcaps, which extend the coverage up to $|\eta| = 3.0$. The photodetectors are Avalanche

Fig. 1. Relative response to laser light injected in the ECAL crystals, measured by the ECAL laser monitoring system, averaged over all crystals in regions of pseudorapidity, $|\eta|$. The bottom plot shows the instantaneous LHC luminosity delivered during this time period.

Photo-Diodes (APD) in the barrel and Vacuum Phototriodes (VPT) in the endcaps. The barrel region is made of 36 identical supermodules, and the endcaps are constructed from four half-disk ‘Dees’. A preshower detector (ES), based on lead absorbers equipped with silicon strip sensors, is placed in front of the endcap crystals. Electrons and photons are typically reconstructed up to $|\eta| < 2.5$, the region covered by the silicon tracker, while jets are reconstructed up to $|\eta| < 3.0$. The ECAL energy resolution achieved during 2010–2011 is described in Ref. [4] and ranges from 1.1 to 2.6% in the barrel and 2.2 to 5% in the endcaps, for photons from the Higgs boson decay.

The CMS detector is expected to accumulate data corresponding to an integrated luminosity of 300 fb^{-1} by end of the LHC Phase-1 running period (2023). The collider will then be upgraded during the years 2024–6, to allow much larger instantaneous luminosities. The subsequent running period, termed HL-LHC, will deliver a factor of ten more integrated luminosity (up to 3 ab^{-1}) during the following decade. The operating parameters of the HL-LHC, require a re-examination of the ability of the detector active material and electronics to meet these more challenging requirements. Upgrades to the ECAL on-detector and off-detector readout will be required [5]. The longevity of the ECAL PbWO_4 crystals has been examined by means of beam tests results conducted on irradiated crystals, and these will be presented below.

Fig. 2. (a): linear fit (red line) of the correlation between the hadron fluence to which the crystals were exposed and the corresponding induced absorption coefficient, μ_{ind} . (b): loss of light output in proton-irradiated PbWO_4 crystals as a function of induced absorption, compared with predictions from simulation (red line).

II. EFFECT OF LHC IRRADIATION ON PbWO_4 CRYSTAL LIGHT OUTPUT

Radiation damage affects the light output of the PbWO_4 crystals. Crystal transparency losses are caused by two types of damage. Ionization by charged particles leads to the formation of colour centers that reduce the transparency of the crystals, leading to a light transmission loss which depends on the ionizing dose rate [7]. The transparency partially recovers during periods without irradiation through spontaneous annealing at the ECAL operating temperature of 18°C . High energy hadrons, above a few tens of MeV, create permanent crystal defects and shift the transparency band edge towards longer wavelengths, inducing a cumulative loss of light transmission [6–13]. These losses are not recoverable at room temperature, and they will be an important component of the response losses observed at HL-LHC.

Radiation damage effects are monitored and corrected for using a dedicated light monitoring system, which injects laser light into the crystals. The evolution of crystal response during the current Phase-1 of the LHC run is shown in Fig.1. The response losses currently observed in the endcap regions ($|\eta| > 1.48$) are indicative of those that will be observed in the barrel region during HL-LHC.

Several irradiation campaigns have been conducted in recent years to study the correlation between the hadron fluence and the loss of transparency which is usually quantified using the induced absorption coefficient:

$$\mu_{\text{ind}}(\lambda) = \frac{1}{L} \times \ln \left(\frac{T_{\text{before}}}{T_{\text{after}}} \right) ,$$

where T_{before} (T_{after}) is the longitudinal light transmission value at $\lambda = 420 \text{ nm}$ measured before (after) irradiation and L is the length of the crystal. Test results from irradiated ECAL crystals, from dedicated irradiation campaigns with 24 GeV protons in 2011 and 2012, as well as test crystals irradiated

inside the CMS detector at high $|\eta|$, are shown in Fig. 2 [14]. The increase of induced absorption coefficient with radiation results in larger crystal light output losses. The measured loss of light output as a function of induced absorption is in good agreement with Geant4 simulation predictions. At the end of HL-LHC, the CMS ECAL barrel and endcap PbWO_4 crystals will have been exposed to fluences corresponding to $\mu_{\text{ind}} \sim 2 - 3 \text{ m}^{-1}$ and $\mu_{\text{ind}} \sim 10 - 20 \text{ m}^{-1}$, respectively. The impact of the radiation damage on the CMS ECAL PbWO_4 crystals after being exposed to hadron fluences predicted at the end of HL-LHC can thus be inferred from such test beam results.

III. DOUBLE-READOUT BEAM TEST RESULTS ON IRRADIATED PbWO_4 CRYSTALS

A special test configuration has been used, where irradiated PbWO_4 crystals have been read out at both ends. This permits a detailed examination of the mechanisms responsible for the degradation of signal linearity and energy resolution to electrons as well as the detailed validation of the simulation predictions, which are based on the modelling of light propagation inside the crystal volume [15].

The energy resolution of the CMS ECAL can be parameterized as:

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C ,$$

where A represents the stochastic term, B the electronic noise, and C the constant term [2].

The ageing of crystals and photodetectors will influence all three terms in the energy resolution. The stochastic term A will increase due to the reduction of light output caused by LHC irradiation. The noise term B will increase due to radiation-induced increases in the APD dark current. The loss of light transmission also results in a loss of crystal uniformity. Light produced further from the photodetector

Fig. 3. (a): Schematic representation of a double-ended read-out configuration, involving a pair of VPTs, used to measure the response losses of irradiated CMS ECAL PbWO₄ crystals. The red dots and lines represent optical scintillation photons produced by the electromagnetic shower and their propagation throughout the crystal volume. (b): Geant4 simulation of average shower profiles for 50 and 200 GeV electrons in PbWO₄ superimposed onto the light collection efficiency curves for the front (blue) and rear (green) photodetectors, for an irradiated crystal with $\mu_{ind} = 10 \text{ m}^{-1}$.

will be attenuated more than light produced close to the photodetector. The longitudinal position of the electromagnetic shower maximum fluctuates event-by-event, and so the total light signal measured by the APD will be affected by these fluctuations. As a result, this non-uniformity in light collection affects the constant term C . This mechanism is also responsible for the non-linearity of the response since more energetic showers will develop closer to the rear of the crystal making the signals less attenuated than those from low energy electrons.

To evaluate the impact of the radiation damage on the CMS ECAL performance, CMS-like PbWO₄ crystals, have been tested with electron beams provided by the CERN SPS, with energies ranging from 10 to 250 GeV, after being exposed to hadron fluences similar to those predicted at the end of HL-LHC. The results of these tests will be presented for crystals read out with the double readout scheme.

Each crystal of a set of nine was read out from both ends using VPTs, identical to those used in the CMS ECAL detector [2], as shown in Fig. 3a. The response of each crystal has been measured with electron beams at several energies between 10 and 250 GeV. The signals from the two VPTs were combined to estimate the position of the shower maximum and thus compensate for longitudinal fluctuations, as illustrated in Fig. 3b using a Geant4 simulation. Benefiting from the double-ended readout, the energy estimator used was: $S_{corr} = \sqrt{F \times R}$, where F and R are the signals measured by the front and rear VPTs respectively.

The non-linearity of the crystal response due to radiation damage can be defined, by comparison with a non-irradiated crystal, as the change of response between 50 and 200 GeV:

$$\Delta NL = \frac{S_i(200)}{S_i(50)} \times \frac{S_{ni}(50)}{S_{ni}(200)} \quad ,$$

where $S_i(200)$ ($S_{ni}(200)$) is the signal measured by the VPT for an irradiated (non-irradiated) crystal at a given beam energy. Similarly, the increase of the constant term due to radiation damage can be obtained by subtracting the constant term of a non-irradiated crystal:

$$\Delta C = \sqrt{C_i^2 - C_{ni}^2} \quad ,$$

where C_i (C_{ni}) is the constant term measured for an irradiated (non-irradiated) crystal. The performance of irradiated crystals in terms of non-linearity and the degradation of the constant term are shown in Fig. 4 for the single readout configuration (front or rear VPT only), and for the combined signal obtained with a double readout configuration. Once the optimal energy estimator, S_{corr} , is used, the signal linearity is largely restored and the constant term degradation is mitigated with respect to the single readout configuration from 10% to 3%, at the largest μ_{ind} values tested. The Geant4 [16] simulation developed to model these effects shows good agreement with the observed results.

Fig. 4. Test beam results showing the performance of hadron irradiated crystals in terms of response linearity (a), and constant term degradation (b). The results are shown for single-ended (blue and green) and double-ended readout (red) configurations and are compared with the predictions from the Geant4 model (dotted lines).

IV. PERFORMANCE PREDICTION OF THE CMS PRECISION PbWO₄ ELECTROMAGNETIC CALORIMETER IN THE HL-LHC

The results presented in Fig. 4 show the significant increase in non-linearity and degradation of resolution due to crystal irradiation for the single photodetector readout case, relevant for CMS. The crystals in the barrel region, with expected $\mu_{ind} \sim 2 - 3 \text{ m}^{-1}$, will retain good performance during HL-LHC and will be kept. However those in the endcap regions, with expected $\mu_{ind} \sim 10 - 20 \text{ m}^{-1}$, will exhibit significantly degraded performance. The endcaps will therefore be entirely replaced with a high-granularity silicon based calorimeter (HGCAL) for HL-LHC operation. The double-readout configuration, while not practical to be implemented in the current CMS detector, shows promise as a possible solution to mitigate the effects of crystal transparency losses in future detectors.

For HL-LHC, new front-end readout electronics will be installed in the ECAL barrel, to yield optimal noise performance and to help discriminate anomalous APD signals using enhanced signal information. In addition, the supermodules will be cooled down from 18°C to 9°C, in order to reduce the noise induced by increases in APD dark current. Finally both the on-detector and off-detector electronics must be completely replaced to satisfy increased Level-1 trigger requirements on trigger rate and latency.

These upgrades are necessary to maintain the Phase-1 performance of ECAL for HL-LHC luminosities. The effect of the upgrade is shown in Fig. 5, which shows the energy resolution of photons from $H \rightarrow \gamma\gamma$ decays predicted by the

Geant4 simulation, plotted as a function of $|\eta|$ for various integrated luminosities. The plot shows that, for an integrated luminosity corresponding to 1000 fb⁻¹, the upgrade restores the Phase-1 performance.

V. CONCLUSION

The HL-LHC upgrade to the LHC accelerator places new demands on the LHC experiments, which must retain good performance in order to harness the large datasets for physics that the HL-LHC operating period will provide. For the CMS ECAL, the evolution of the light output of the PbWO₄ crystals must be established, to predict their performance at HL-LHC. This has been achieved by means of beam tests and Monte Carlo simulations of irradiated crystals. A Geant4 simulation model which predicts the degradation of PbWO₄ crystal performance due to radiation damage in term of light output loss, response non-linearity and energy resolution has been developed. Electron beams with energies up to 250 GeV were used to measure irradiated PbWO₄ crystals, equipped with a special double-readout scheme, and the results of these tests were used to validate the simulations and understand the mechanisms responsible for the loss of performance. The results indicate that the ECAL barrel crystals will retain good performance during HL-LHC and will be retained. The CMS ECAL endcap crystals will suffer larger performance degradation and will thus be entirely replaced. The results are also used to predict the performance of the ECAL barrel during the harsh radiation environment foreseen for the High Luminosity phase of LHC. They show that resolutions for photons from the $H \rightarrow \gamma\gamma$

Fig. 5. Simulated resolution for photons from $H \rightarrow \gamma\gamma$ decays, plotted as a function of $|\eta|$ for increasing HL-LHC luminosities. The arrows show the improved photon resolution for 1000fb^{-1} after the upgrade of the ECAL readout and lowering of the operating temperature.

decay that are comparable with LHC Phase-I can be achieved at HL-LHC following the planned upgrade of the detector readout.

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