Beam tests of proton-irradiated PbWO$_4$ crystals and evaluation of double-ended read-out technique for mitigation of radiation damage effects

Marco Lucchini on behalf of the CMS Collaboration
European Organization for Nuclear Research, CERN, CH-1211 Gèveva 23, Switzerland
E-mail: marco.toliman.lucchini@cern.ch

Abstract. The harsh radiation environment in which detectors will have to operate during the High Luminosity phase of 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 $2 \times 10^{14}$ cm$^{-2}$, respectively, at the pseudo-rapidity region of $|\eta| = 2.6$. To evaluate the evolution of the CMS ECAL performance in such conditions, a set of PbWO$_4$ crystals, exposed to 24 GeV protons up to integrated fluences between $2.1 \times 10^{13}$ cm$^{-2}$ and $1.3 \times 10^{14}$ 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 PbWO$_4$ crystals calorimetric performance has been well understood and parameterized in terms of increasing light absorption inside the crystal volume. A double-ended read-out configuration, in which two identical photodetectors are coupled to the opposite ends of each crystal, has also been tested. The separate and simultaneous read out of the light from the two ends of the crystal allows 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-ended read-out technique.

1. Introduction
To exploit the full potential of the LHC at CERN a major upgrade will be carried out around 2023 to increase the instantaneous luminosity of the collider. During this High Luminosity LHC phase (HL-LHC), all the detectors will have to face a challenging radiation environment and the understanding of the performance of the current detectors under these conditions is of fundamental importance. The radiation levels are expected to be a factor 5 larger than during the standard LHC running, and the integrated luminosities - thus integrated radiation levels - will become a factor 6 greater than the design values [1]. To understand whether the CMS electromagnetic calorimeter (ECAL) will be able to maintain good performance during HL-LHC, several studies on Lead Tungstate (PbWO$_4$) crystals have been performed, establishing that high-energy hadrons cause a cumulative loss of light transmission in PbWO$_4$ [2, 3, 4, 5]. To evaluate the impact of such degradation on the calorimetric performance of the CMS ECAL, a set of PbWO$_4$ crystals, following exposures to hadron fluences similar to those predicted at the end of HL-LHC, has been tested with electron beam in the energy range from 10 to 250 GeV.
double-ended read-out of the crystals has also been tested to better understand the mechanisms of light propagation inside the crystal volume and the degradation of the signal linearity and resolution to electrons. These experimental data have been used to construct and validate a simulation model in order to predict the detector performance in situ.

2. The CMS ECAL during High Luminosity LHC

The CMS ECAL detector [7] was designed to withstand the radiation levels expected by the end of the nominal LHC running [8], before LS3, when 500 fb⁻¹ of data are planned to be collected. The expected ionizing radiation levels correspond to 0.2 Gy/h in EB and 6 Gy/h in EE (at |η| = 2.6). The hadron fluence after 500 fb⁻¹ is expected to be 1.2×10¹¹ cm⁻² for EB and 3 × 10¹³ cm⁻² for EE (at |η| = 2.6) [1]. To further exploit the full potential of LHC, a major upgrade of the interaction region will be required around 2023 (LS3 shutdown) in order to achieve a peak luminosity of $\mathcal{L} = 10^{35}$ cm⁻² s⁻¹ and a leveled value of $\mathcal{L} = 5 \times 10^{34}$ cm⁻² s⁻¹ during the High Luminosity LHC Phase (HL-LHC) which is expected to deliver an integrated luminosity of 3000 fb⁻¹ by 2035. According to dedicated simulations, during HL-LHC the ionizing dose rate inside CMS are predicted to be ∼5 times higher (1 Gy/h in EB and 30 Gy/h in EE) and the integrated particle fluences to be ∼6 times higher (7.6×10¹² cm⁻² in EB and 2×10¹⁴ cm⁻² in EE) [1]. Such hadron fluences will degrade the crystal performance especially in the forward region of the detector where radiation levels are higher.

3. Radiation damage in PbWO₄ crystals

The main consequence of a high radiation environment in the PbWO₄ crystals will be the loss of transparency. This is due to two types of damage: the first is induced by ionizing radiation and the second by hadrons. The ionizing damage causes the formation of colour centres that reduce the transparency of the lead tungstate, leading to a light transmission loss which depends on dose rate [3]. The crystal transparency recovers in the periods without irradiation through spontaneous annealing at the ECAL operating temperature of 18°C. Hadrons induce a significantly different type of damage which involves the creation of clusters of colour centres characterized by the following features [9, 10, 11, 12]. First, there is almost no recovery at room temperature, hence the damage effect is cumulative. Second, the band edge of the transmission curve is shifted by several tens of nanometers to higher values leading to an overlap with the PbWO₄ emission peak.

Several irradiation campaigns have been performed 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:

$$\mu_{ind}(\lambda) = \frac{1}{L} \cdot \ln \frac{T_{before}}{T_{after}}$$

where $T_{before}$ ($T_{after}$) is the longitudinal light transmission value at $\lambda = 420$ nm measured before (after) irradiation and $L$ is the length of the crystal. The increase of induced absorption coefficient with radiation is responsible for a crystal light output loss. Results combining irradiations of ECAL Endcap like crystals performed with 24 GeV protons in 2011 and 2012, as well as irradiation inside the CMS detector, are shown in Fig.1 [14].

4. Test beam results using double-ended read-out

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 a stochastic term, B the electronic noise and C a constant term [7].
As discussed in [14], damaged crystals show a non-linear response to electrons and a degradation of energy resolution. Due to loss of transparency and thus decrease of light output, both the stochastic and the noise terms degrade due to larger photostatistic fluctuations and smaller signal over noise ratio, respectively. These terms dominate at low energies (below 50 GeV) whereas at high energies the energy resolution is dominated by the constant term which also increases in irradiated crystals due to highly non-uniform efficiency of light collection along the longitudinal axis of the crystal. As the longitudinal position of electromagnetic shower maximum fluctuates event-by-event, the total light signal measured by the photodetector attached to the rear end of irradiated crystals will be affected by these fluctuations. This mechanism is also responsible for the non-linearity of response since more energetic showers will develop closer to the rear photodetector and thus the light signal will be less attenuated with respect to low energy electrons.

A double-ended read-out configuration allows to study in detail these effects as it provides the simultaneous read-out of light from both ends. For this reason, following a first set of test beam measurements performed on hadron-damaged PbWO$_4$ crystals [14], a further investigation of the mechanism underlying the performance degradation of irradiated crystals has been carried out by instrumenting a set of lead tungstate crystals with a double-ended read-out configuration. Each crystal was thus read-out from both ends using Vacuum Photo-Triodes (VPTs), identical to those used in the CMS ECAL detector [7], as shown in Fig. 2. The response of each crystal has been measured with electron beam of energy ranging from 10 to 250 GeV. The signal from the two VPTs was combined to estimate the position of shower maximum and thus compensate for its longitudinal fluctuations as illustrated in Fig. 3 according to $S_{\text{corr}} = \sqrt{F \cdot R}$, where $F$ and $R$ are respectively the signals measured by the front and rear VPT.

The non-linearity of 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 normalized to beam energy:

$$\Delta NL = \frac{S_{i}(200)}{S_{i}(50)} \cdot \frac{S_{ni}(50)}{S_{ni}(200)}$$

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

$$\Delta C = \sqrt{C^2_i - C^2_{ni}}$$

where $C^2_i$ ($C^2_{ni}$) is the constant term measured for an irradiated (non-irradiated) crystal. The performance of crystals in terms of non-linearity and degradation of constant term are shown in Fig. 4 for a single read-out configuration (front or rear VPT only) and for the combined signal obtained with a double-ended read-out configuration. Once the double read-out correction is applied, $S_{corr}$, the signal linearity is restored and the constant term degradation is mitigated with respect to a single read-out configuration from 10% to 3%. A Geant4 [15] simulation tool has been developed to model these effects and its predictions are compared with experimental data in the figures, showing a reasonable agreement with observed results.

5. Conclusions

A campaign of test beam measurement has been carried out to evaluate the performance of hadron-irradiated PbWO$_4$ crystals to electrons in the 10-250 GeV range. The crystals were instrumented with double-ended read-out using VPTs, identical to those used in the CMS ECAL detectors. Test beam results allow to understand the mechanism underlying the degradation of crystal performance due to radiation damage in term of light output loss, response non-linearity and constant term degradation and to build a Geant4 simulation model which describes such effects. Although for practical reasons, a double-ended read-out configuration cannot be implemented in situ in the CMS ECAL detector, the present results can be used to predict the performance of the standard single read-out configuration as used in the CMS ECAL during the harsh radiation environment foreseen for the High Luminosity phase of LHC.
Figure 4. Test beam results showing the performance of hadron irradiated crystals in terms of response linearity (left) and constant term degradation (right). The performance is shown for single-ended (blue and green) and double-ended read-out (red) configurations and compared with prediction from a Geant4 model (dotted lines).

References

[1] The CMS Collaboration, Technical Proposal for the Phase-II Upgrade of the CMS Detector, CERN-LHCC-2015-010, CMS-TDR-15-02, LHCC-P-008 (CERN, Geneva, Switzerland, 2015).
[2] E. Auffray and A. Singovski, Experimental Study of Lead Tungstate Scintillator Proton-Induced Damage and Recovery, IEEE Transactions on Nuclear Science, Vol. 59, No. 5, 2012.
[3] M. Huhtinen, P. Lecomte, D. Luckey, F. Nessi-Tedaldi, F. Pauss, Nucl. Instr. and Meth. A 545 (2005) 63-87 and CMS Note 2005-010.
[4] P. Lecomte, D. Luckey, F. Nessi-Tedaldi, F. Pauss, D. Renker, Nucl. Instr. and Meth. A 587 (2008) 266 - 271 and CMS Note 2006-131.
[5] P. Lecomte, D. Luckey, F. Nessi-Tedaldi, F. Pauss, Nucl. Instr. and Meth. A 564 (2006) 164-168.
[6] The CMS Electromagnetic Calorimeter Group, P. Adzic et al., 2010 JINST 5 P03010.
[7] The CMS Collaboration. The CMS Electromagnetic Calorimeter Technical Design Report, CERN/LHCC 97-33, CMS TDR 4 (CERN, Geneva, Switzerland 1997).
[8] The CMS Collaboration, CMS: The Compact Muon Solenoid – Technical Proposal, CERN/LHCC/94-38 (CERN, Geneva, Switzerland, 1994).
[9] F. E. Maas, et al., Physical Review Letters 94 (2005) 082001.
[10] A. Annenkov, M. Korzhik, P. Lecoq., Nucl. Instr. and Meth. A 490 (2002) 30.
[11] P. Kozma, R. Baigal, P. Kozma Jr., Nucl. Instr. and Meth. A 484 (2002) 149.
[12] M. Kobayashi, K. Harada, Y. Hirose, M. Ishii, I. Yamaga., Nucl. Instr. and Meth. A 400 (1997) 392.
[13] G. Dissertori, P. Lecomte, D. Luckey, F. Nessi-Tedaldi, F. Pauss, Th. Otto, S. Roesler, Ch. Urscheler, Nucl. Instr. and Meth. A 622 (2010) 41-48.
[14] T. Adams et al., Beam test evaluation of electromagnetic calorimeter modules made from proton-damaged PbWO4 crystals, 2016 JINST 11 P04012.
[15] GEANT4 collaboration, S. Agostinelli et al., GEANT4: A Simulation toolkit, NIM A 506 (2003) 250..