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Measurements of Lead Tungstate crystals behaviour under irradiation for the CMS electromagnetic calorimeter at the LHC

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Abstract

Lead Tungstate crystals will be used as calorimetric medium in high energy physics at CERN, in a particularly hostile radiation environment. Methods of testing their behaviour under irradiation are discussed here and are illustrated by some R&D results.

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For the CMS Collaboration

1 Introduction

At CERN, the Large Hadron Collider (LHC) is being constructed. There, two detectors are foreseen to study hard proton-proton collisions at a centre-of-mass energy of 14 TeV. One of them, the Compact Muon Solenoid [1], is shown in Fig. 1.

Figure 1: Longitudinal section of the CMS detector (one quadrant). The parameter η (Eta) corresponds to $-\ln \tan(\theta/2)$, with θ the angle with respect to the beam axis, with the origin in the interaction point.

Surrounding the proton-proton collision region, this large, nearly cylindrical instrument with a length of 21.6 m, a diameter of 14.6 m and a total weight of 14500 tons, is being developed and constructed to be ready in 2005. Within this detector, the electromagnetic calorimeter ECAL (Barrel, EB, and Endcap, EE in Fig. 1 and, in more detail, Fig. 2) will consist of Lead Tungstate crystals, a homogeneous medium which is the absorber and the scintillating medium at the same time [2]. Its conception is based on the need to optimise the discovery potential of a light Higgs particle, with a mass $m_H < 150$ GeV, decaying into two photons. The detector resolution is the crucial factor in its performance, and for this reason the detector calibration has to be kept constant at the few $\times 0.1\%$ level.

2 PbWO_4 Calorimeter Design

Beyond the benefit of a homogeneous calorimeter, Lead Tungstate has been chosen for several reasons. It has a fast scintillation emission, with a light decay time which matches the LHC bunch crossing time of 25 ns. It has small radiation length ($X_0 = 0.89$ cm) and Molière radius ($R_M = 2.2$ cm), so that a very compact and highly granular calorimeter can be built [2]. However, its light output has a temperature dependence of $2\%/^\circ\text{C}$, which puts some constraints on the detector construction.

Figure 2: Longitudinal section of the CMS electromagnetic calorimeter (one quadrant).

The ECAL barrel electromagnetic calorimeter is designed to have an inner radius of 1.24 m and a granularity $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$ using 23 cm ($26 X_0$) long crystals with a front face of $\sim 22 \times 22 \text{ mm}^2$ for a total crystal volume of 8.14 m^3 . Avalanche Photodiodes shall be used as photodetectors. The barrel ECAL covers the pseudorapidity region $|\eta| < 1.48$.

The ECAL end-cap calorimeter is designed along a similar scheme, however using 22 cm long crystals (owing to the presence of a $3 X_0$ thick preshower detector in front) and with $24.7 \times 24.7 \text{ mm}^2$ front face dimensions. The endcap ECAL covers the pseudorapidity region $1.48 < |\eta| < 3.0$.

Given all these parameters, the ECAL will consist of approximately 80000 crystals.

3 Crystal Development

The development of Lead Tungstate crystals of a quality suitable for use in the CMS ECAL has been pursued with manufacturers at the Bogoroditsk Techno-Chemical Plant (BCTP) in Russia, and in China (Shanghai Institute of Ceramics, SIC, and Beijing Glass Research Institute, BGRI). A detailed discussion on the progress made in this development can be found in Refs. [3] and [4]. The intrinsic properties of Lead Tungstate crystals have been thoroughly tested in the laboratory and in beam tests, and many results can be found in Ref. [2] and in several publications (for example [5] and [6]).

Figure 3: Dose rates (Gy/h) of electromagnetic radiation in the CMS electromagnetic calorimeter at the maximum design performance of the LHC.

The most critical issue in crystal development is their radiation hardness. The environment for the CMS ECAL is particularly hostile in this respect. At the highest design performance of LHC, which corresponds to a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ one expects, at the electromagnetic shower maximum, dose rates between 0.2 Gy/h at $\eta = 0$ and 0.3 Gy/h at $\eta = 1.5$, and values up to 15 Gy/h at $\eta = 3$ in the ECAL end caps (Fig. 3). Integrated over ten years of detector operations, these numbers would correspond to doses ranging between 2.5 kGy in the ECAL barrel to 200 kGy in the end caps. At the back of the crystals the dose rate is in the best case (at $\eta = 0$) a factor 10 smaller than at the maximum of the electromagnetic shower, due to the contribution of the electromagnetic part in hadronic showers cascades (see Fig.4).

Figure 4: Radiation dose profiles in the ECAL at various $|\eta|$ values when LHC is running as designed, from Ref. [7].

The hadron flux in the calorimeter is almost entirely due to neutrons, and it is expected to reach $2 \times 10^{13} \text{ n/cm}^2$

in the ECAL barrel for an integrated luminosity of $5 \times 10^5 \text{ pb}^{-1}$ (equivalent to 10 years of running at LHC). However, no damage by neutron irradiation has been seen [8], while a sample-dependent effect is observed with photon irradiation. It has been shown that the scintillation mechanisms is not damaged, nor is the scintillation emission spectrum changed [9, 10]. The degradation of light output is namely due to radiation-induced absorption, i.e. the formation of colour centres, which reduce the crystal transparency. In the CMS detector it will be thus possible to monitor transmission losses due to irradiation using a light injection system in the calorimeter, and to apply corrections for them.

Extensive R&D work has been and still is carried out to improve the crystal radiation hardness through the optimisation of raw materials purity, of stoichiometry, through doping and post-growth treatments in gaseous atmospheres (so-called annealing).

In this paper, we review several techniques to test the behaviour of crystals under irradiation. In Sec. 4 a direct technique is presented, in detail, which reproduces as close as possible the environment expected during LHC running. Along with the method, some achievements are illustrated which were obtained on R&D Lead Tungstate crystals produced in China and which were made possible through such kind of tests. The correlation is then illustrated between changes in the extracted light yield of crystals and changes in their transmission, which corroborate what is mentioned above and in Ref. [10].

However, direct irradiation tests are cumbersome, in that the access to an irradiation facility is needed. It is thus natural to seek for measurement techniques which allow to establish the radiation hardness properties of crystals from tests which can be performed in the laboratory either by predicting it from optical parameters (Section 5) or through some easier way to irradiate them (see Section 6).

4 Direct crystal irradiation tests

Figure 5: Setup for direct crystals irradiation tests at PSI.

The most direct way to establish the radiation resistance of a crystal is to irradiate it at a dose rate and, if needed, a total dose corresponding to what is expected during its operation in the detector. The ECAL group is performing such tests at various facilities and with different setups, one of which is described herein in detail.

In radiation hardness tests performed at the PSI Eichlabor in Villigen, a Swiss facility for the calibration of radioactivity detectors, the crystals are irradiated using γ from ^{60}Co decay. Irradiations are performed with a 40 TBq ^{60}Co source, with the crystal placed on a remotely controlled table whose position is accurately controlled to set the dose rate. The whole system is installed in an air conditioned bunker, with the readout electronics located outside the irradiation room. The irradiation is performed along the side of the crystal (Fig. 5) rather than from the tip, to take into account the radiation levels expected along the crystals length in the CMS ECAL. Thus, full size crystals are irradiated over 2/3 of their length to crudely simulate the actual radiation dose distribution expected in the ECAL, while short crystals are irradiated along their full length. A weak monitoring source, usually 3 MBq of ^{60}Co , at the tip of the crystal excites scintillation through the 1.17 and 1.33 MeV γ it emits, to serve for light yield measurements. The crystal is mounted on a photomultiplier and it is coupled to it with optical grease, the whole assembly being appropriately shielded and collimators being adjusted to minimise irradiation of the phototube. In particular, the whole assembly is mounted into a 5 cm thick cylindrical lead shield to protect the photomultiplier. The photomultiplier is operated at a gain of around 10^8 ; the high voltage stability is monitored to $\pm 0.05\%$. The anode signal is split, one half of the signal goes via a 100 ns delay to a CAMAC charge integrating LeCroy ADC

Figure 6: Characteristic ^{60}Co spectrum in PbWO_4 seen by a photomultiplier

type 2249, whereas the other half goes to a threshold discriminator, whose outputs are fed into a scaler and into a CAMAC-controlled precision gate generator which defines the charge integrating time, usually 200 ns. The temperature in the vicinity of the crystal is continuously monitored via two Pt_{100} platinum resistors, giving a relative temperature monitoring accuracy of a few $10^{-3} \text{ }^\circ\text{C}$. The typical energy spectrum seen by the photomultiplier is shown in Fig. 6, and light yield changes are determined from the displacement of the photoelectric “peak” (very much widened by photostatistics) produced by the γ s emitted from the monitoring source.

More details about the measurement setup can be found in Ref. [11].

Usually, one crystal at a time is irradiated and its light yield is monitored in situ during several hours before irradiation to allow the thermalisation of the crystal, thus to ensure good thermal and optical stability of the system. In fact, since PbWO_4 crystals respond to a temperature change with a $-2\%/^\circ\text{C}$ change in light yield, it is important for them to be in thermal equilibrium, so that they will follow adiabatically the slow changes in room temperature, and the measured light yield can then be corrected for them. An absolute accuracy on the relative light yield loss of better than 3% is obtained for crystals yielding at least 7 photoelectrons/MeV and around 1% for 10 photoelectrons/MeV. After the stabilisation period, without any access to the room nor modifications of the setup, the irradiation procedure begins. Every 30 mn (or later into the irradiation, every 1 h or 2 h) the irradiation is interrupted and the light yield is measured. After several hours of irradiation, the crystal damage typically saturates, and thus the irradiation is stopped. From there on, data taking is continued, in the same mode as for the thermal stabilisation, if an eventual short- or medium-term recovery of the crystal shall be observed.

Figure 7: Summary of results on the optimisation of undoped PbWO_4 crystals from SIC: Relative light yield loss versus integrated dose for various 5 cm long SIC crystals under side irradiation.

The test procedure described above was applied to several batches of undoped PbWO_4 crystals produced by the Shanghai Institute of Ceramics. Those crystals, typically cut in pairs from the same “father” ingot, underwent a

post-growth treatment were they were annealed in a gaseous atmosphere at temperatures close to their melting point. Such a treatment is believed to allow compensation of oxygen deficiencies, an important cause for the formation of colour centres.

In a first round of optimisations, air and oxygen were used. Fig. 7 shows such a pair (115-1 and 115-2) where one crystal was annealed in air and the other one in an oxygen atmosphere; clearly, annealing in oxygen gives better results in terms of crystal radiation hardness. Following this first experimental confirmation, other pairs of crystals were annealed in an oxygen atmosphere using different annealing cycles, whose details are confidential to the crystal producers. From the results, an example of which (147-1) can be seen in Fig. 7, the best annealing cycle in oxygen was selected. In a third round, the reproducibility in the production of radiation resistant, 5 cm long crystal samples was proven, as is demonstrated in the same Figure as well. All three crystals represented withstand dose rates of 0.25 Gy/h without losing more than 2% in light yield.

After this positive result, R&D was continued towards production of full-size, radiation-hard crystals, taking also into account mass-production issues (use of multi-pulling furnaces, economic aspects of raw material preparation and crystal treatment, e.g.). At this purpose, crystal growers explore the compensation of defects in the crystal

Figure 8: Relative light yield loss versus integrated dose for the side-irradiation of the Sb-La doped, 23 cm long crystal J122 from SIC for a dose rate of 0.4 Gy/h.

lattice through the addition of dopants[4, 12]. The latest achievements are represented in Figs.8 and 9. The studied

Figure 9: Relative light yield loss versus integrated dose for the side-irradiation of the Sb-La doped, 23 cm long crystal J122 from SIC for a dose rate of 4 Gy/h.

crystal J122 was doped with Antimony and Lanthanum combined for compensation of individual dopant segregation. It shows no observable light yield change if irradiated at a dose rate as expected in the ECAL barrel, while a very tolerable loss of $5 \pm 3\%$ is observed at 4 Gy/h (ECAL end-cap dose rate), saturating at a total dose of 10 Gy. As it has been shown elsewhere already (See Sec. 3 and references therein), the observed decrease in light yield is the direct consequence of a radiation damage to the crystal transmission. The transmission change at a given light

Figure 10: Induced absorption coefficient as a function of wavelength, for the irradiation of SIC crystal J122 at a dose rate of 4 Gy/h.

wavelength λ is usually expressed as an induced absorption coefficient $\mu_{ind}(\lambda)$ given by $\mu_{ind}(\lambda) = \frac{1}{L} \ln \frac{T_0(\lambda)}{T(\lambda)}$ with L the crystal length. In fact, for crystal J122, the measured induced absorption coefficient (Fig. 10) is very small throughout the spectrum.

5 Optical tests of radiation hardness properties

Figure 11: Induced absorption coefficient versus logarithm of the relative light yield loss at various times during recovery after front irradiation of several BCTP crystals (one type of symbol per crystal).

While the qualitative correlation between loss of observed light yield, which is the relevant quantity for the intended use of the detector, and transmission loss is easily established, the quantitative correspondence can greatly vary from crystal to crystal and depends on a number of optical parameters (transparency itself, surface quality, coating, wrapping). In fact, it has been experimentally shown in Ref. [9] that

$$\mu_{ind} = \frac{1}{L_{mean}} \ln \frac{N_0}{N}, \quad (1)$$

where $N_0(N)$ is the extracted light yield before (after) irradiation and L_{mean} is the mean path of photons, a quantity which can vary from crystal to crystal, depending on all the mentioned parameters. The validity of equation 1 is well illustrated by Fig. 11 from Ref. [9], where one sees the linear correlation between μ_{ind} at 500 nm and $\ln \frac{N_0}{N}$ measured at various times during recovery after irradiation. The straight lines all go through the origin, a confirmation that scintillation is not altered by irradiation. However, the slopes of these lines are different between crystals.

In order to define the preproduction specifications of BCTP crystals for the CMS ECAL, the possibility to predict the behaviour under irradiation from optical parameters was investigated [13]. At this purpose, 63 crystals were studied, which already passed the requirements which ensure a sufficient light collection uniformity, namely:

1. longitudinal transmission > 10% at 350 nm

2. longitudinal transmission $> 55\%$ at 420 nm
3. longitudinal transmission $> 65\%$ at 600 nm
4. a wavelength dispersion for a transversal transmission of 50% below < 6 nm for 6 measurements along the length of the crystal.

For these crystals, the slope of the transmission band edge measured on the longitudinal transmission between 340 nm and 370 nm was plotted against the observed relative light yield loss after front irradiation with a ^{60}Co source at a dose rate of 0.15 Gy/h up to 1.5 Gy (Figure 12). From the scatter-plot it is evident that crystals with a slope of the band edge larger than 1.5%/nm also suffered a relative light yield loss inferior to 6%. Indications are thus present that, for crystals of similar optical characteristics, the slope of the band edge is correlated with the radiation hardness of the crystals and can be used as a predictive requirement to maximise crystals radiation hardness. Further evidence on a large sample of crystals shall corroborate these first results.

Figure 12: Scatter plot of relative light yield loss versus slope of the transmission-band edge for 63 BCTP crystals, after irradiation up to 1.5 Gy

6 Tests with UV-light of crystals radiation hardness

Figure 13: Correlation between absorption coefficient induced by UV irradiation ($\mu_{420\text{UV}}$) and the one induced by γ irradiation ($\mu_{\text{sat}420}$) at 420 nm for 7 BCTP crystals after three different UV exposure times.

Measurements from direct γ irradiation has remained so far the most conservative evidence of crystal radiation hardness. It would be however interesting to find other, "lighter" methods to cause a similar damage in the crystals similar without the need for the heavy infrastructure of γ irradiation. This possibility is being investigated [14] and first results are available. The method is based on the observation that UV-light exposure causes the same kind of optical damage, through production of colour centres, as γ radiation. [15, 16].

At this purpose, UV light from a Xe-lamp extended in the 300 - 420 nm spectral region was used for lateral crystal illumination, so that not only the surface, but also the bulk of the crystal is expected to receive this light. The chosen geometry gave a mean flux of $0.75 W/cm^2$ on the crystals. On a series of 7 crystals, the induced absorption coefficient at 420 nm, $\mu_{\text{sat}420}$ was measured, after irradiation at 100 Gy/h up to 500 Gy, as well as, after recovery before each new exposure, the absorption coefficient induced at 420 nm by UV light, $\mu_{420\text{UV}}$. The γ -irradiation there corresponds to the specifications of Ref. [13], where $\mu_{\text{sat}420} < 1.5 m^{-1}$ is required after such an irradiation. The correlation is plotted in Fig. 13 for UV exposure times of 3s, 10 s and 20 s respectively. The linear correlation between the two measured parameters indicates that, at least for crystals as the present ones, grown in the same conditions (little technological and dimensional differences among them), UV-light exposure could be a simple, non-destructive direct test of radiation hardness. Again, the results will have to be consolidated on a larger sample of crystals, but are already very promising.

7 Conclusions

Several methods have been reviewed, which are used to establish Lead Tungstate crystals radiation hardness for the radiation dose regime expected in the CMS ECAL. Gamma-irradiation of crystals remains the most direct and thus robust method. It is used to give feed-back to the crystal growers and has allowed them to produce extremely radiation-hard crystals of the size required for CMS. For crystals with similar, good optical characteristics, first results show that the slope of the longitudinal transmission band-edge can be an indicator of radiation hardness. Illumination of crystals with UV light tuned to suitable wavelengths and intensity has also given indications to be a very interesting, non-destructive, light-infrastructure method to establish radiation hardness.

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