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Experimental Study of the Lead Tungstate Scintillator Proton-Induced Damage and Recovery

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Experimental Study of Lead Tungstate Scintillator Proton-Induced Damage and Recovery

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on behalf of CMS-ECAL group

Abstract— Lead tungstate (PbWO_4 , or PWO) scintillating crystals are used by two of the four experiments at the Large Hadron Collider (LHC): 75848 in CMS and 17920 in ALICE. For the CMS electromagnetic calorimeter, one of the most important crystal properties is its radiation hardness. With the increase of luminosity, the radiation level will increase drastically, particularly in the high pseudorapidity regions of the calorimeter. Beside the effects of color-centre formation caused by γ -radiation, additional measurable effect originated by hadron irradiation could appear, which will further deteriorate the optical transmission of the crystals and therefore their efficiency. In this paper, we will present results of the proton-induced damage in PWO and a study of optical transmission recovery at different temperatures and under different light-induced “bleaching” conditions for proton-irradiated crystals.

Index Terms— PWO, radiation damage, optical bleaching

I. INTRODUCTION

The CMS Electromagnetic Calorimeter ECAL made of 75848 lead tungstate crystals (PbWO_4 , PWO) was designed in 1994 for an integrated luminosity of 500fb^{-1} to be achieved in 2020 [1]. In such an irradiation environment, radiation damage is mainly caused by the electromagnetic component of ionising radiation at the ECAL location in the detector. As a consequence the radiation damage characteristics of PWO crystals under gamma irradiation were extensively studied during the R&D phase from 1994-2001 [2]. A careful monitoring of the crystal properties and in particular of the radiation hardness was performed during production from 2001-2008 in order to ensure that crystals fulfil the specifications [3].

The operation of the LHC during the first 2 years has shown a great potential for an increase of the luminosity up to 300fb^{-1} per year from 2020 with an integrated luminosity of 3000fb^{-1} by 2020 to 2030. This will lead to a significant increase of the radiation dose rate level in the electromagnetic

calorimeter and in particular in the high pseudo-rapidity region of the calorimeter (end cap region of CMS-ECAL). Beside the effects of colour-centre formation caused by γ -radiation, additional measurable effects produced by hadronic interactions with nuclei of the PWO crystals have to be accounted for.

A study of high energy hadron induced PWO barrel crystal damage has been performed by CMS since 2004 [4-6]. In order to study the effect of hadron originated radiation damage on a larger number of samples of PWO crystals and its impact on the performance of CMS ECAL, a dedicated program of proton irradiation in the CERN proton synchrotron (PS) facility was launched the end of 2009. A specialized set-up has been designed to irradiate 12 endcap crystals instead of one during an irradiation campaign.

In this paper, results of high energy proton irradiation of 10 PWO crystals from BTCP (Bogoroditsk Technical Plant in Russia) from the endcap production, as well as a systematic study of proton-induced damage recovery, stimulated with heating and light, are reported. The aim of the recovery process study was first, to understand if hadron induced damage can recover like gamma-induced damage and second, to find a suitable combination of recovery stimulating processes which can be implemented in the endcap parts of the detector to recover damages in situ. A model of the proton induced damage mechanism of PWO crystal is proposed.

II. IRRADIATION CONDITIONS AND CHARACTERISATION

Ten BTCP crystals from the endcap production have been irradiated with protons in June 2010. Before irradiation the crystals were irradiated with γ -rays with an absorbed dose of 500Gy using a Co^{60} source, and characterized by the CERN Accos machine [7] developed for the optical and geometrical characterization of the PWO crystals from CMS.

Irradiations with protons have been performed at the CERN PS facility line T7. The proton energy was 24GeV. The size of the proton beam was $3\text{x}3\text{cm}^2$ with a proton flux of $10^9\text{s}^{-1}\text{cm}^{-2}$. The integrated fluence delivered to the crystals was chosen to be $3\text{-}4\text{x}10^{13}\text{p/cm}^2$.

To irradiate simultaneously 12 crystals, a special remote controlled rotating system handling 12 alveola holders containing one crystal each has been constructed. It allows irradiation of several crystals without entering the proton

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irradiation zone. To be able to measure the optical transmission of a crystal as soon as possible after irradiation a dedicated measurement set-up was built (see figure 1).

Fig. 1: Spectrophotometer combined with the dedicated rotating system developed for the proton irradiation of 12 Endcap crystals and to measure the transmission before and after irradiation

During the first 4 months, the transmission measurements were performed with this dedicated set-up in the irradiation zone. Once handling the crystals manually was possible, transmission and light yield measurements for some crystals were performed on the ACCOS machine. Induced absorption was determined by a comparison of the initial transmission and transmission after irradiation and different thermal or optical treatments, as well as the light yield.

III. GAMMA IRRADIATION AND PROTON IRRADIATION

Figure 2 presents the induced absorption spectra obtained after γ -radiation and proton irradiation.

Figure 2: Induced absorption for gamma and proton irradiated crystals

The γ -radiation induced absorption spectra have been studied in detail during the development of the PWO crystal production technology for CMS ECAL. It is well established that the induced absorption spectrum of γ -irradiated lead tungstate crystals contains several bands with peaks at 350 nm (3.5 eV), 400 nm (3.13 eV), 470 nm (2.66 eV), 520 nm (2.4 eV), 600 nm (2.08 eV) and 720 nm (1.73 eV). Peak position and intensity of the induced absorption bands are dependent on the crystal growth conditions and may show minor variations at the level of a few % from crystal to crystal. The origin of these absorption bands is described in [2,8].

The same induced absorption bands are present in proton-induced absorption spectra with 24GeV/c protons with an integrated fluence of $3\text{--}4 \times 10^{13} \text{ p/cm}^2$, with different relative intensities, particularly for two bands in the UV region (bands at 3.5eV, 3.13eV) [9]. These absorption bands have been attributed to Frenkel type defects (FTD) [2], which can be created during the crystal growth and converted into color centers under irradiation. In case of proton irradiation, these bands dominate due to the high density and clusterization of these defects and are stable at room temperature.

This cluster model can explain the light scattering, which appears in PWO crystals after proton irradiation, but not after gamma irradiation (see figure3).

Fig. 3: Green laser scattering in a proton irradiated crystal

The clusters have a slightly smaller energy band gap than the normal crystal structure and therefore have also a different refraction index. The difference of refraction index at boundaries between cluster and regular crystal structure leads to light scattering.

IV. RECOVERY STUDIES

In contrast to γ -induced damage [10,11,12,13], the spontaneous recovery of proton-induced damage is very slow at room temperature. Consequently an accumulation of the damage may occur with increasing LHC luminosity. This in turn leads to a deterioration of the detector properties. Thus, we studied the recovery of hadron damage with thermal or optical treatment and a combination of both treatments with the aim of identifying a possibility to avoid the accumulation of defects generated by hadrons in ECAL and particularly in the Endcap region.

A. Recovery with temperature

Several crystals were annealed at different temperatures. The improvement of transmission starts to be visible after annealing at 50°C. Figure 4 shows the evolution of induced absorption spectra after annealing at different temperatures. A clear improvement is visible in the band edge region, and the recovery rate is similar to the recovery of the other bands. Destruction of the centers at 350nm is very sensitive to temperature because of the electron escape probability $\approx e^{-E_{TA}/kT}$, where E_{TA} is the thermo-activation energy.

An increase of annealing temperature allows a faster and more efficient recovery as shown in figure 5.

Fig. 4: Induced absorption of proton irradiated crystal after different annealing temperature

Fig. 5: Normalized induced coefficient at 420nm of proton irradiated and annealed at 30°C, 50°C, 75°C, 300°C

About 45 % of the induced absorption at 420nm can be removed by annealing at 75°C for 10 days and only 3% of the damage is still present after annealing at 300°C for 82hours. The small residual damage at 300°C means probably a low concentration of the macro defects in the crystal caused by protons at a given fluence.

As expected the improvement of the transmission by thermal annealing brings an improvement of the light yield. A clear correlation between the induced absorption recovery at 420nm and the light yield recovery is observed. (figure 6)

The study of the change of the light scattering generated in PWO crystals after proton irradiation with temperature annealing validates the model of clusterisation of the Frenkel type defects. Annealing of the crystal leads to a decrease of the light scattering in the crystal, and complete disappearance after annealing at 100°C, which indicates that a significant fraction of the clusters are destroyed at that temperature (see figure 7).

Fig. 6: Correlation between normalised light yield loss and normalised induced absorption at 422nm after annealing at different temperature

Fig. 7: Light scattering in a crystal after proton irradiation (a), and after annealing at 100°C

This study of recovery of proton damage with temperature showed that the proton damage is not stable, and recovers even at low temperature. However, the temperature necessary to recover a significant part of the proton damage is too high to be applied in situ in the ECAL detector. The maximal acceptable temperature to avoid any damages to components of ECAL (electronics, glue, etc.) is below 60°C. Therefore studies of recovery by light stimulation have been performed.

B. Light stimulation recovery

It has been shown that γ -radiation induced damage in PWO crystals can be recovered faster than spontaneous recovery at room temperature if the crystal is illuminated with optical photons from blue to infrared. The light stimulation of the crystal initiates intracenter electronic transitions of color centers allowing their radiating recombination and by consequence the recovery of the damage [14,15].

The room temperature light stimulation recovery of proton damage in the Endcaps crystal has been studied in detail. Crystals were illuminated with LEDs of wavelengths of 740nm and 475nm. Figure 8 shows the evolution of induced

absorption spectra after light stimulation annealing at two wavelengths.

Fig. 8: Induced absorption spectra of a proton irradiated crystal after light illumination at room temperature

As shown in figure 9, an improvement of the optical transmission by light stimulation has been observed in a wavelength region from 400-800nm. About 20% of the transmission damage in the wavelength region of scintillation emission (420nm) recovers after 550 hours of illumination with 740nm and 20% more after complementary illumination with 475nm. However no recovery is observed in the band gap region. As in the case of the recuperation of γ -induced damage, stimulation works better for the oxygen vacancy based FTD (FTD_O), which create an induced absorption in the wavelength region of scintillation emission (420nm).

Fig. 9: Evolution of the normalized induced absorption coefficient at 378nm, 422nm, and 493nm under illumination with IR LED (740nm, 11.7×10^{17} ph/s*cm²) and blue-green LED (475nm, 8.1×10^{17} ph/s*cm²) at room temperature.

As in the case of thermal annealing, the improvement of the transmission with light stimulation leads to an improvement of the light yield. A clear correlation between the induced absorption recovery at 422 nm and the light yield improvement is observed as seen in figure 10.

Fig. 10: Correlation between induced normalized light yield loss versus normalized induced absorption at 422nm after illumination with IR LED (740nm, 11.7×10^{17} ph/s*cm²) and blue-green LED (475nm, 8.1×10^{17} ph/s*cm²) at room temperature.

The influence of the light stimulation treatment at room temperature on the light scattering in the crystal has been studied. No change of the light scattering is observed after crystal illumination with different wavelengths (see figure 11). This indicates that light stimulation treatment alone does not allow destroying the FTD clusters; it can just change their charge state stimulating captured electrons for radiating recombination.

Fig. 11: Light scattering in PWO crystal after proton irradiation (a) and after illumination under LED at 475nm

C. Combined treatment

A study of combining the advantage of annealing at moderate temperature with illumination with light of different wavelengths has been performed. The combination of thermal annealing and light stimulation shows a global improvement of the crystal transmission including a shift of the spectrum cut off.

Figure 12 shows the evolution of a normalised induced absorption of proton-irradiated crystals, which underwent several combined optical and thermal treatments.

Fig. 12: Evolution of normalized induced absorption of proton irradiated crystals under light stimulation with different wavelengths and temperatures

The light stimulation complements the annealing effect. At 50°C where the thermal annealing has small effects on the damage recovery, the light stimulation increases the recovery of the absorption at wavelengths above 400nm corresponding to oxygen vacancy based FTD (FTD_O). Increasing the temperature to 60°C allows the start of cluster destruction, and the kinetics of the defect annealing becomes faster. Results of the combining action of annealing at 75°C and illumination with light of 840, 530nm show an even better improvement of transmission. Contrary to γ -radiation induced damage [9], proton induced damage stimulation process by IR (840nm) photons does not accelerate significantly the recovery process at 75°C. At that temperature the rate of thermal ionization of colour centers FTD_O becomes comparable with the rate of recombination due to the absorption of IR. On the other hand changing the stimulating light color from IR to 530nm shows an acceleration of the induced absorption recovery (70% of the damage recovers). It should be noted that a similar factor of improvement can be achieved in 200-250h if green light is applied for stimulation from the beginning.

V. CONCLUSION

Crystal damage induced by protons recovers under both thermal and optical stimulation. Light and thermal treatment act differently on the defects created by protons. With thermal treatment the absorption band at 360nm starts to be removed even at low temperature (>50°C), the efficiency of recovery increases with temperature. Destruction of clusters of Frenkel defects by low temperature thermal treatment is confirmed by the disappearance of light scattering in the volume of crystals. Illumination with light does not affect clusters; we do not observe the disappearance of light scattering in the crystal after light stimulation. The combination of both treatments allows a faster recovery at lower temperature, 40% of the damage recovering after 3 weeks of illumination at 530nm at 50°C. This treatment could be potentially used in situ in ECAL detector during long technical stops, if technically feasible.

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