Studies of the effect of charged hadrons on lead tungstate crystals

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Abstract. Scintillating crystals are used for calorimetry in several high-energy physics experiments. For some of them, performance has to be ensured in difficult operating conditions, like a high radiation environment, very large particle fluxes and high collision rates. Results are presented here from a thorough series of measurements concerning mainly the effect of charged hadrons on lead tungstate. It is also shown how these results can be used to predict the effect on crystals due to a given flux of particles.

1. Introduction
The effect of large hadron fluxes on PbWO₄ crystals has become an important subject of investigation with the construction of the Large Hadron Collider (LHC) at CERN and of experiments using such crystals. The question had to be studied, whether large hadron fluences cause a specific, possibly cumulative damage, and if so, what its quantitative importance is and whether it only affects light transmission or also the scintillation properties of lead tungstate. It should be noticed that all damage observed in earlier tests [1, 2] could always be ascribed to the ionising dose associated with the hadron flux, apart from some indication of a hadron-specific damage in BGO, which can be extracted [3] from existing data, as discussed later herein. However, none of the previous tests on lead tungstate had been extended to the full integrated fluences expected at the LHC. Therefore, a thorough series of irradiation tests on lead tungstate crystals [4, 5, 6] has been performed over several years, with exposures reaching up to the highest integrated fluence expected at the LHC after 10 years of running. In this presentation, an overview is given on the main results obtained through these tests, and the understanding reached is summarised.

2. Proton and γ irradiation studies
In a first study to explore the dependence on the integrated fluence of a possible hadron-specific damage [4], eight CMS [7] production crystals of consistent quality [7] were irradiated in a 20 to 24 GeV/c proton flux of either \( \phi_p = 10^{12} \) p cm\(^{-2}\)h\(^{-1} \) or \( \phi_p = 10^{13} \) p cm\(^{-2}\)h\(^{-1} \) at the CERN PS accelerator [8]. The maximum fluence reached was \( \Phi_p = 5.4 \times 10^{13} \) p cm\(^{-2} \). The crystals were nearly parallelepipedic, with dimensions 2.4 × 2.4 × 23 cm\(^3\). To disentangle the contribution to damage from the associated ionising dose, complementary \(^{60}\)Co γ-irradiations were performed at a dose rate of 1 kGy/h on further seven crystals, since a flux \( \phi_p = 10^{12} \) p cm\(^{-2}\)h\(^{-1} \) has an associated ionising dose rate in PbWO₄ of 1 kGy/h. The maximum dose reached, of 50.3 kGy, is just \( \sim \) 50% below the one reached in proton irradiations. The measurements of transmission
damage revealed [4] that proton irradiation decreases the light transmission for all wavelengths and moves the ultra-violet transmission band-edge to longer wavelengths, as can be seen in figure 1. In γ-irradiated crystals, the transmission band-edge does not shift at all, even after the highest integrated dose; one only observes the well-known absorption band [10] around 420 nm that can be appreciated in figure 2. These results demonstrate the qualitatively different nature of proton-induced and γ-induced damage.

The damage is usually quantified through the induced absorption coefficient for a given wavelength $\lambda$, which for the Longitudinal Transmission, measured through the length $\ell$ of a crystal, is defined as

$$\mu_{LT}^{IND}(\lambda) = \frac{1}{\ell} \times \ln \frac{LT_0}{LT}$$

where $LT_0$ ($LT$) is the Longitudinal Transmission value measured before (after) irradiation through the length of the crystal, and analogously for Transverse Transmission (TT). The data for $\mu_{LT}^{IND}$ versus light wavelength for proton-irradiated crystals in figure 3 show a $\lambda^{-4}$ dependence, which is absent in γ-irradiated crystals. This is an indication of Rayleigh scattering from small centres of severe damage, as they might be caused by the high energy deposition of heavily ionising fragments along their path, locally changing the crystal structure. Since the crystals contain heavy elements, Pb and W, it was argued in [4] that a hadron-specific damage can in fact arise from the production, above a ~20 MeV threshold, of heavy fragments with up to 10 μm range and energies up to ~100 MeV, causing a displacement of lattice atoms and energy losses, along their path, up to 50000 times the one of minimum-ionising particles. The observed behaviour confirms this qualitative understanding. A further evidence evidence of Rayleigh scattering is the complete polarisation of scattered light, as observed using Polaroid films.

As it can be seen in figure 4, where the evolution over time of damage values measured at the peak of scintillation emission wavelength, $\mu_{LT}^{IND}(420 \text{ nm})$, is plotted, only a small fraction of the hadron damage recovers on a time scale comparable to the expected duration of LHC running.

The correlation between the induced absorption coefficient at 420 nm and fluence [4] shown in figure 5, is consistent with a linear behaviour over two orders of magnitude, showing that proton-induced damage in PbWO$_4$ is predominantly cumulative, unlike γ-induced damage,
Figure 3. Plot of $\mu_{IND}(\lambda)$ versus $\lambda$ for proton-irradiated crystals ($a''$, $c$, $h$) and for $\gamma$-irradiated ones ($u$, $v$, $w$, $x$, $y$, $z$) [4]. The dot-dashed line shows $\lambda^{-4}$, fitted to the proton-damage data.

which reaches equilibrium [4, 10]. No flux dependence was observed.

Damage values from protons and $\gamma$’s were also compared in a study performed on BGO[11].

Figure 4. Evolution of longitudinal induced absorption $\mu_{IND}(420 \text{ nm})$ over time for proton irradiated crystals [4].

Figure 5. Induced absorption $\mu_{IND}(420 \text{ nm})$ as a function of cumulative proton fluence [4].
The changes in band-edge are similar to what is seen in PbWO$_4$, and long enough after irradiation, when the ionising-radiation damage contribution has recovered (figure 6), a remaining proton-induced damage can be extracted, that behaves linearly with fluence, as visible in figure 7.

The relevant quantity for detector operation being the scintillation light output, any effect of hadrons on this quantity is of great importance. Detector calibration through a light injection system, as foreseen e.g. by CMS [7], is based on the assumption that changes in light output are all due to changes in light transmission. The study published in [5] compares the correlations between Light Output loss and induced absorption in proton- and $\gamma$-irradiations for the same set of crystals above. Those correlations (figures 8 and 9) show that, in the explored range of proton fluences, no additional, hadron-specific damage to the scintillation mechanism could be observed in lead tungstate within the measurement’s precision.

Figure 6. Evolution over time of the Longitudinal induced absorption, $\mu_{IND}(440 \text{ nm})$, for proton- (full symbols) and for $\gamma$-irradiated (white symbols) BGO crystals, extracted from data in [11].

Figure 7. Correlation between the absorption $\mu_{IND}(440 \text{ nm})$ induced by proton irradiation and proton fluence in BGO, extracted from data in [11].

Figure 8. Correlation between induced absorption, $\mu_{IND}(420 \text{ nm})$, and Light Output loss for proton induced damage in PbWO$_4$ [5].

Figure 9. Correlation between induced absorption, $\mu_{IND}(420 \text{ nm})$, and Light Output loss for $\gamma$-induced damage in PbWO$_4$ [5].
3. Comparative proton and positive pion irradiation studies

Crystals used in high-energy physics detectors will typically be exposed to hadrons – mostly charged pions – with different energies. In the CMS experiment at the LHC for example [7], the large hadron fluxes are due to particles - mostly pions - whose energies rarely exceed 1 GeV.

To understand how to scale proton-damage values to the ones caused by such pion fluences, a previously γ irradiated crystal (w in [4] and in figure 3) was cut into three, 7.5 cm long, sections (w1, w2 and w3) after thermal annealing of its γ-induced damage.

The middle section, w2, was irradiated with 290 MeV/c positive pions at the Paul Scherrer Institute in Villigen, Switzerland. Details about the irradiation are found in [6]. The crystal was irradiated up to a total fluence $\Phi_\pi = (5.67 \pm 0.46) \times 10^{13} \text{ cm}^{-2}$, while the average flux on the crystal was $\phi_\pi = 4.13 \times 10^{11} \text{ cm}^{-2} \text{ h}^{-1}$.

The first, w1, and last, w3, sections were irradiated with 24 GeV/c protons. They were placed at the same time, w1 in front of w3, into the proton-irradiation facility [8] of the CERN PS accelerator, with the beam entering through the small w1 face, so that the hadronic cascade could develop through both crystals, as illustrated in figure 10. The procedure was totally analogous to the one described in [4]. The proton fluence on the w1 crystal front face was $\Phi_p = (1.17 \pm 0.11) \times 10^{13} \text{ cm}^{-2}$.

After it was demonstrated, in [5], that hadron damage only affects light transmission in PbWO$_4$, the study of pion damage was focussed on this observable.

At first sight (figure 11) the light transmission measured through the length of the crystal as a function of wavelength shows, after irradiation, the same behaviour for positive pions and protons. The band-edge shift is observed, which is characteristic for hadron-irradiated lead tungstate and BGO. It should be pointed out that similar damage amplitudes for the three crystals were obtained on purpose through a suitable choice of fluences.

The evolution of damage with time for all three crystals is shown in figure 12, where it is evident that pion damage follows the same pattern as observed for proton-irradiated crystals [4].
Figure 12. Evolution of the longitudinal induced absorption $\mu_{LT,IND}^{(420 \text{ nm})}$ over time, showing recovery, for the three sections of crystal $w$ [6].

The data, as indicated by the lines, are well fitted by the same function used in [4], namely a sum of a constant plus two exponentials with time constants $\tau_1 = 17.2$ days and $\tau_2 = 650$ days. A similarly good fit is obtained through the form

$$
\mu_{LT,IND}^{(420 \text{ nm}, t_{\text{rec}})} = B_0^j \left( e^{-t_{\text{rec}}/\tau_2} + B_2^j \right) + B_1^j e^{-t_{\text{rec}}/\tau_1}
$$

(2)

where $t_{\text{rec}}$ is the time elapsed since the irradiation and $j$, \(j = 1, 2, 3\) is the crystal index. This parametrisation yields, for $t >> \tau_1$, a damage amplitudes ratio between crystals which is independent from the elapsed time. The fits being almost indistinguishable, the comparison between crystals remains independent of the selected fit function.

A deeper insight into the damage amplitude ratio between positive pions and protons was gained in [6] by looking at the induced absorption profile along the depth of the crystals. The transverse induced absorption coefficients $\mu_{TT,IND}^{(420 \text{ nm})}$ were obtained from measurements of the Transverse Light Transmission (TT) performed sideways at various positions along the crystals length, as indicated in figure 10. The profiles for this quantity are plotted in figure 13.

It was advocated in [4] that damage could be proportional to the density of stars, i.e. of inelastic hadronic interactions caused by a projectile above a given threshold energy. To verify

Figure 13. Transverse induced absorption, $\mu_{TT,IND}^{(420 \text{ nm})}$ as a function of position along the crystal [6]. Data for $w1$ and $w3$ are shown according to the crystals’ position during irradiation.
this hypothesis, the damage profiles from figure 13 have been rescaled first of all to an identical fluence value, of $10^{13}$ cm$^{-2}$, as it is justified due to the cumulative nature of the damage. The so-obtained profiles are shown in figure 14. In figure 15, the star densities from FLUKA Monte Carlo simulations are shown as a function of depth in the crystal, where arrows indicate the lengths covered by the crystals during irradiation. One notices the fast drop, due to absorption, for 200 MeV $\pi^+$, while the density rises and stays high for 24 GeV/c protons throughout the depth corresponding to $w_1$ and $w_3$. The comparison of the damage profile from protons in $w_1$ and $w_3$ and pions in $w_2$ from figure 14 with the simulated star densities profiles in figure 15 shows an agreement that confirms in a striking way the hypothesised mechanism. A direct comparison is then performed in figure 16. The ratios of rescaled transverse absorption coefficients measured for positive pions in $w_2$ and for protons in crystal $w_1$ are plotted as a function of depth. The corresponding ratio of star densities obtained from the FLUKA simulations described in [4] and [12] is also plotted. The measured ratios and the star densities ratios are in agreement throughout, within the experimental uncertainties.

This comparison establishes that the damage amplitudes caused by 24 GeV/c protons and
290 MeV/c positive pions in lead tungstate scale according to the star densities caused by those particles in the crystal as calculated by Monte Carlo simulations.

4. Conclusions and outlook

Irradiation studies with 20 to 24 GeV/c protons and $^{60}$Co photons in a fluence regime as expected at the LHC demonstrate that hadrons cause a specific, cumulative damage in lead tungstate, which solely affects the crystal light transmission while its scintillation properties remain unaffected. Therefore, it is possible to monitor the damage through light injection. All characteristics of the damage are consistent with it being due to an intense local energy deposition from heavy fragments. Since this damage mechanism should be absent in crystals with elements below Z=71 [13], a hadron damage test in such crystals should confirm the present understanding. A positive pion irradiation shows that the damage amplitudes caused by 24 GeV/c protons and 290 MeV/c pions in lead tungstate scale like the star densities those particles cause in the crystals according to simulations. The results can thus be used to estimate the expected damage for different experimental conditions.

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