First results on radiation damage in PbWO$_4$ crystals exposed to a 20 GeV/c proton beam

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Abstract

We have exposed seven full length production quality crystals of the electromagnetic calorimeter (ECAL) of the CMS detector to a 20 GeV/c proton beam at the CERN PS accelerator. The exposure was done at fluxes of $10^{12}$ p/cm$^2$/h and $10^{13}$ p/cm$^2$/h and integral fluences of $10^{12}$ p/cm$^2$ and $10^{13}$ p/cm$^2$ were reached at both rates. The light transmission of the crystals was measured after irradiation and suitable cooling time for induced radioactivity to decrease to a safe level. First results of these measurements are shown. The possible damage mechanisms are discussed and simulations based on one possible model are presented. The implications for long-term operation of CMS are discussed and it is shown that in the whole barrel and at least most of the ECAL endcap hadron damage alone – even if cumulative – should not cause the crystals to fail the CMS specification of $\mu_{\text{IND}} < 1.5$ m$^{-1}$ during the first 10 years of LHC operation.

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showed that the measured LT has an accuracy of 300–800 nm in 1 nm steps. The light beam was about 7 mm wide and 10 mm high. A check of reproducibility capital letters. Two of the crystals, labeled a(a’) and F(F’), were irradiated twice, so for a’ and F’ the last column

We have measured LT for each crystal with a Perkin Elmer Lambda 900 spectrophotometer using depolarized light

Table 1: Fluences determined from $^{22}$Na activity in the Al foils and total fluences used for our analysis.

| ID | $\Phi$($^{22}$Na) | $\Phi$-total |
|----|-----------------|--------------|
| a  | $9.64 \times 10^{12}$ | $9.64 \times 10^{12}$ |
| F  | $1.54 \times 10^{12}$ | $1.54 \times 10^{12}$ |
| a' | $1.37 \times 10^{13}$ | $1.47 \times 10^{13}$ |
| b  | $5.21 \times 10^{11}$ | $5.21 \times 10^{11}$ |
| c  | $8.36 \times 10^{11}$ | $8.36 \times 10^{11}$ |
| d  | $1.35 \times 10^{13}$ | $1.35 \times 10^{13}$ |
| E  | $8.34 \times 10^{12}$ | $8.34 \times 10^{12}$ |
| F' | $9.10 \times 10^{12}$ | $1.67 \times 10^{13}$ |
| G  | $1.93 \times 10^{12}$ | $1.93 \times 10^{12}$ |

The fundamental difference between $\gamma$-irradiation and energetic hadrons is that the latter produce inelastic nuclear interactions (stars) in the crystal. These interactions break up the target nucleus and thus create impurities and distortions in the crystal lattice. The slow nuclear fragments produced in each hadronic interaction can have a range of up to 10 $\mu$m. Along their path they displace a large number of lattice atoms, but also ionize much more densely than a minimum ionizing particle. Neither the displacements, nor the dense ionization, although in a very small volume, can be produced in $\gamma$-irradiations. Since the threshold for star production is $\sim$20 MeV, reactor neutron irradiations do not cover this regime either.

2 The crystals, irradiations and measurements

We have studied CMS production quality crystals from Bogoroditsk. The crystals have a nearly parallelepipedic shape with dimensions of $2.6 \times 2.6 \times 23$ cm$^3$. Except for slightly non-compliant mechanical dimensions all crystals satisfied the technical specifications for their use in the CMS ECAL. All crystals were pre-tested for radiation hardness at the Geneva Hospital $\gamma$-irradiation facility for 2 h at 250 Gy/h and showed a radiation induced absorption coefficient $\mu_{\text{IND}} < 1.5$ m$^{-1}$ at 440 nm as required by the CMS technical specifications [1]. The crystals were subsequently annealed.

An irradiation test of PbWO$_4$ with hadrons is complicated mainly by the fact that the crystals become highly radioactive. Therefore our aim was to make the simplest possible test by irradiating bare crystals and measuring the longitudinal light transmission (LT) after irradiation. The irradiations were performed at the IRRAD1 facility in the T7 beam-line of the CERN PS accelerator. The proton momentum was 20 GeV/c and the exposure was uniform to within a factor of two over the crystal front face at fluxes of $\sim 10^{12}$ p/cm$^2$/h and $\sim 10^{13}$ p/cm$^2$/h. The beam was parallel to the long axis of the crystal. The fluence was determined by $^{22}$Na activity in aluminum foils in front of the crystals and correlated with the induced radioactivity in the crystals themselves measured at 4.5 cm distance, as shown in Fig.1. The $^{22}$Na activity for the irradiation of crystal F’ is inconsistent for some unknown reason. For this crystal we deduce the fluence by using the induced radioactivity and the correlation determined from the other irradiations. Table 1 shows the fluence from $^{22}$Na and the total fluence used in our analysis. Crystals which were irradiated at a rate of $10^{12}$ p/cm$^2$/h are indicated by small letters, those exposed to $10^{13}$ p/cm$^2$/h by capital letters. Two of the crystals, labeled a(a’) and F(F’), were irradiated twice, so for a’ and F’ the last column of table 1 shows the added fluence of two irradiations.

We have measured LT for each crystal with a Perkin Elmer Lambda 900 spectrophotometer using depolarized light of 300–800 nm in 1 nm steps. The light beam was about 7 mm wide and 10 mm high. A check of reproducibility showed that the measured LT has an accuracy of $\pm 1\%$ [2].
(a) Longitudinal Transmissions after one low and one high
fluence irradiation for crystals “a” (10^{12} \text{ p/cm}^2/\text{h}) and
“F” (10^{13} \text{ p/cm}^2/\text{h}).

(b) Induced absorption coefficients at 440 nm for all crys-
tals, measured 20 and 50 days after irradiation, as a func-
tion of total fluence.

Figure 2: Longitudinal Transmission changes dependence on hadron fluence.

Figure 3: Crystal recovery. Because crystals irradiated to \sim 10^{13} \text{ p/cm}^2 could be measured only 10 days after
irradiation, short time constants are not visible.

3 Results

Fig. 2(a) shows the full LT curves over the whole measured range of wavelengths, for crystals a(a’) and F(F’). Crystal “a” was irradiated at a 10 times smaller rate than crystal “F”. As can be seen, the LT for the lower fluence irradiation is different between “a” and “F”. This can be due to the fact that \mu_{\text{IND}}(440 \text{ nm}) might be dominated
by the damage induced by the total ionization, i.e. conditions similar to \gamma-irradiations. Such a damage is known to
saturate at a level which depends on the dose rate. At the higher fluences, however, the LT curves are quite similar,
which might indicate that between integral fluences of 10^{12} \text{ p/cm}^2 and 10^{13} \text{ p/cm}^2 specific hadronic damage starts
to dominate. An important observation is also that after hadron exposure the LT band-edge has shifted to longer
wavelengths.

Fig. 2(b) shows, as a function of fluence, \mu_{\text{IND}}(440 \text{ nm}) measured 20 and 50 days after the end of each irradiation.
At low fluences our data do not allow to make a distinction between a pure dose rate and a possibly cumulative
effect. At high fluences the dependence on rate is very small, while our data indicate a clear – possibly linear –
dependence on integral fluence. With the fluences reached and for the rates used, we observe no sign of saturation.
Causes of the effects observed could be:
- High-energy hadrons producing a specific cumulative damage, with essentially no recovery, combined with a
damage which anneals at room temperature with a time constant of at least several months.
- The \gamma dose rate caused by the charge of the protons B.

Room temperature recovery, recorded up to now, is shown in Fig. 3. The data do not yet allow to extrapolate to
LHC-like time-scales.
4 Monte-Carlo simulations

Simulations were performed to understand the hadron fluences, star density and dose as a function of depth in the crystal. They show that after an initial increase all distributions are fairly flat with a slow decrease after a maximum at $\sim 7.5$ cm.

The average values for one proton per cm$^2$ are 1.63 cm$^{-2}$ for the charged hadron fluence, 0.126 cm$^{-3}$ for the star density and 1.37 nGy for ionizing dose. A detailed simulation of the full atomic cascade initiated by the fragments shows that for an incident proton fluence of $10^{13}$ p/cm$^2$ the concentration of displacements and interstitials might reach $10^{-8}$ which is far below the pre-irradiation imperfections. Thus if specific hadronic damage is produced, it is more likely to be due to the dense ionization of the ion tracks. Fig. 4 shows that for the fragment spectra produced by inelastic interactions, the energy loss can be more than 4 orders of magnitude above the $dE/dx$ of a minimum ionizing particle. Making the hypothesis that tracks exceeding a value $(dE/dx)_{\text{crit}}$ are responsible for hadronic damage, we can compare the 20 GeV/c irradiation with the expected CMS ECAL endcap (EE) conditions. Fig. 5 shows that, depending on $(dE/dx)_{\text{crit}}$, the simulated track length per star produced by the 20 GeV/c beam is a factor between 2.7 and 8.7 higher than in the EE. The star density for $10^{13}$ cm$^{-2}$ protons corresponds to more than $\eta = 2$ in the EE. With the possible factor of 2.7–8.7, our irradiations cover the high-precision area of the EE for 10 years operation and possibly even the whole EE up to $\eta = 2.9$.

Figure 4: Ionizing $dE/dx$ (and total for Pb) of ions in PbWO$_4$ and simulated fragment spectra from hadronic interactions.

Figure 5: Track length above a given $(dE/dx)_{\text{crit}}$ per star (inelastic hadronic interaction) and star densities for 10 years in the ECAL endcap and for our irradiation test.
5 Conclusions

Our LT measurements of PbWO$_4$ crystals after exposure to 20 GeV/c protons are consistent with a hypothesis of cumulative hadronic damage, although the small number of crystals and limited fluence range does not allow a definitive statement yet. Room temperature recovery is very slow and possibly partial. Even under the most pessimistic assumption of permanent cumulative damage, our results verify that the CMS barrel ECAL will meet its design specifications over 10 years. Simulations, used to compare the conditions in our test beam and the EE under the hypothesis of hadronic damage, indicate that in most of the EE $\mu_{\text{IND}}$ due to hadronic damage alone is likely to stay below $1.5 \text{ m}^{-1}$ for 10 years of LHC operation. To gain a better understanding we will extend our irradiations to higher fluences ($5 \times 10^{13} \text{ p/cm}^2$) and to possibly lower hadron energies, and we will follow the damage recovery. Finally, comparative $\gamma$-irradiations at dose rates corresponding to those of the proton beam are expected to provide the most stringent test of specific hadronic damage.

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References

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