PF
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN LIBRARIES, GENEVA

CERN-PPE/96-172

4 Sept. 1996

CERN-PPE-96-172

su 9709

LOW DOSE-RATE IRRADIATION SET-UP FOR SCINTILLATING CRYSTALS

C. D'Ambrosio, C. Ercoli, S. Jaaskelainen, E. Rosso, P. Wicht

CERN, Geneva, Switzerland

Abstract

With a 1 Ci ^{60}Co -source we measured the radiation damage and its recovery in PbWO_4 crystals. The method consists in measuring the anode current produced in the silicon diode of a Hybrid PhotoMultiplier Tube (HPMT) during the irradiation of the crystal. At regular time intervals, we took photon counting spectra with the same HPMT. By checking the resulting channel positions of the photoelectron peaks, we controlled the stability of our experimental set-up. Temperature control and monitoring were achieved by forced thermostated water circulation inside the irradiation box and by using a PT100 and two AD590 temperature probes. First results on irradiations of a few PbWO_4 crystals are presented and future plans are communicated.

Submitted to Nuclear Instruments and Methods in Physics Research

INTRODUCTION

The Large Hadron Collider (LHC) at CERN will be equipped with two multipurpose detectors, CMS [1] and ATLAS [2]. For CMS, the electromagnetic calorimeter (ECAL) will be composed of PbWO₄ (Lead Tungstate) scintillating crystals [3] readout via Avalanche Photo Diodes (APD). The system has to be controlled and monitored in temperature, as the crystal light yield and the APD gain depend on it. The ECAL will contain some 110,000 crystals, with dimensions of $\sim 23.8 \times 23.8 \text{ mm}^2$ (base), $20.5 \times 20.5 \text{ mm}^2$ (top) and 230 mm height (crystal dimensions will slightly vary with their position in the calorimeter). In the barrel each crystal will receive on the average a dose of $\sim 1 \text{ kGy}$ per year (110 days of operation) at a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, i.e. on the average 9 Gy per day, 0.37 Gy per hour.

Since a few years, an R&D effort is going on to characterize PbWO₄ crystals and to aim at a crystal growing procedure able to furnish uniform quality crystals. Apart from other properties (light output, temperature dependence, scintillation decay time), it is important to study in a systematic way the damage caused by radiation to PbWO₄. In particular, radiation damage at dose rates close to those present in LHC and associated recovery processes should affect the crystal light yields in a known way, to avoid frequent recalibrations during data taking.

It is also worth noting that, at these low dose rates, scintillation yield of PbWO₄ is not affected locally. However, the collected light on the photodetector is affected by crystal coloration due to the radiation and consequent loss of crystal transmission [4, 5].

Based on these considerations, we have developed an experimental set-up, capable of monitoring light yields during irradiation and simulating at best LHC conditions. Its basic principle is:

- to measure the photocurrent detected during an irradiation from a ⁶⁰Co source by a Hybrid Photo Multiplier Tube (HPMT)^{#1} [6, 7] coupled to the PbWO₄ crystal;
- to monitor the system stability via pulse-height spectra measured at regular time

^{#1} Mod. PPO275C produced by DEP, NL-9300 AB Roden, The Netherlands

intervals during irradiation by using the excellent single photoelectron response of the HPMT [8];

– to monitor and control crystal temperature during irradiation.

EXPERIMENTAL ARRANGEMENT

The set-up (Fig. 1a) consists of a brass box, in which a PbWO_4 – crystal can be placed. Its rear face is in dry optical contact with an HPMT (Hybrid PhotoMultiplier Tube), while the front face looks at a ^{60}Co source which emits a gamma cascade of 1.17 MeV and 1.33 MeV energy (strength: 37×10^9 Bq)^{#2}. The crystal is gently pressed on the photocathode window by a suitable spring to ensure a reproducible optical contact. All the gaps between crystal and brass can be filled with Lead sheets, in order to minimize the gamma flux reaching the HPMT. The light-tight box contains three accesses which are used for light transmission-, pulse-height spectrum- and temperature- measurements (Fig. 1b). The HPMT is a cross-focussed model and its working principle has already been detailed in [6, 7] and papers cited therein. Here, it is operated at - 10 kV potential across photocathode and anode with 30 volts on the inversely biased diode. Its photocathode is a UV-enhanced S-20 on a Quartz window.

During the ^{60}Co -irradiation at a typical rate of 0.150 Gy/h ($\sim 22 \times 10^6$ Bq)^{#3} the crystal emits continuously scintillation light. This is detected by the HPMT photocathode and produces a current at the HPMT silicon anode. This anode photocurrent is recorded via the bias voltage connection with a picoammeter^{#4} and processed on a remote PC^{#5} using a GPIB link and the Labview - programme (Fig. 2): every two seconds the current is

^{#2} the source with all its installation was kindly put at our disposal by the section CD of the RP group at CERN-TIS division

^{#3} The average linear absorption coefficient of ^{60}Co -gammas in PbWO_4 is $\mu = 0.6 \text{ cm}^{-1}$. 80 % of the gammas interact via the Compton process. Part of the Compton scattered gammas escape and suffer partly Compton scattering again in the material surrounding the crystal with fractional re-emission into the PbWO_4 . The net effect results in a total dose absorbed by the crystal proportional to the number of photons entering the crystal front face. The dose can be estimated via the formula $\approx (\mu/\rho)_{\text{PbWO}_4} / (\mu/\rho)_{\text{water}} \times \text{Dose in water}$ [Gy], where the dose in water was known via the TIS-RP group.

^{#4} Mod. Keithley 485.

^{#5} Olivetti 486-100 Mhz.

measured and after every 30 measurements the average is calculated, displayed and stored. Any photocurrent variation indicates therefore a change of the induced radiation damage of the PbWO₄ – crystal. The HPMT anode current i is roughly connected with the number n_γ hitting the crystal per second:

$$i[nA] \approx \frac{H.V.}{3.6} \times n_{phel} \times n_\gamma \times 1.6 \times 10^{-19} \quad (1)$$

where H.V. is the potential difference across the HPMT in volts, n_{phel} the number of photoelectrons produced with one absorbed gamma and 3.6 the voltage required to generate an electron-hole pair.

The system probes the scintillation yield of PbWO₄, which is reported to be unaffected during irradiation [5], convoluted with the transmission spectrum of PbWO₄, which is affected by radiation. This can be roughly written as:

$$i(D) \approx \int QE(v) E(v) T(v,D) dv$$

where $i(D)$ is the photocurrent, D is the dose, QE is the quantum efficiency of the photocathode, E and T respectively the normalized emission and transmission spectra of PbWO₄, and v is the wavenumber. The integration limits span the whole PbWO₄ emission spectrum range.

As an irradiation exposure can last for days or even for weeks, it is essential to monitor the stability of the HPMT and its supplies. To achieve this without touching the arrangement or changing any of the operating parameters, we made use of the unique feature of an HPMT to perform a pulse-height spectrum, while being operated as a continuous photocurrent device. The signal collected from the bias-contact of the diode is sent to a preamplifier (included into the HPMT case) and then to a spectroscopy amplifier^{#6}. Its output is then processed in a MultiChannel Buffer^{#7} and the spectrum stored in the PC (Fig. 2). A weak calibration source of ⁶⁰Co is permanently placed at one side of the crystal within the box (see Fig. 1). To perform the pulse height spectrum (Fig. 3) we lower for

^{#6} mod.: EG&G Ortec 672

^{#7} mod.: EG&G Ortec 926

about five minutes the irradiation source in a sink. The irradiation source can then be pulled up again and the irradiation continues. Each taken pulse-height spectrum can be compared to the previous ones: the channel position of the photoelectron peaks (see Fig. 3) indicate the gain of the detection system. We have not noticed a significant shift in the channel number of the photoelectron peaks, therefore no correction had to be applied to any of the photocurrent charts.

In order to monitor and stabilize the temperature inside the box, three temperature probes have been installed: two (a PT100 and an AD590) at the rear of the box (Fig. 1a, practically no radiation flux is present in this position) and one (AD590) near its front, facing the crystal side and the calibration source (see fig. 1b). For the latter probe, the radiation flux is roughly the same than that hitting the crystal, therefore allowing for a study of its radiation damage by comparison with the rear AD590. Temperature stabilization is achieved by a closed water circuit of constant temperature^{#8}, channelling through the walls of the box, which is in turn insulated from the ambient. The signals of the temperature-probes (and the temperature settings for the Lauda) pass via an acquisition card^{#9} to the PC and are processed by the Labview programme.

In Fig. 4, part of the photocurrent chart of crystal nr 1003 versus time and its equivalent dose are presented. It shows three curves: curve a) is the raw photocurrent versus dose as recorded by the system. Temperature variations induce crystal light yield variations and these are visible on curve a) as distortions to the monotonic behaviour of the photocurrent. Curve b) (right hand scale) are the temperatures measured during the irradiation with temperature control switched off. Curve c) represents curve a) corrected by curve b) for temperature variations. Fig. 5 shows the results of temperature control: the seven temperature settings between 18 °C and 24 °C are inversely mirrored by the registered photocurrent showing a clear dependence of the PbWO₄ - light yield on temperature: ~2.1% decrease of scintillation yield per °C between 15 to 30 °C, as measured with our set-up.

^{#8} mod.: Lauda R6

^{#9} mod.: Nat. Instr. LAB PC+ card

In order to study the crystal recovery, we have installed in the box a quartz fibre which carries the light of a lamp and shines it unfocussed on the crystal side, facing the calibration source (Fig. 1). Some of this light is transmitted to the HPMT via the crystal, probing consequently the crystal light transmission variations due to recovery. Finally, the pulse-height spectrum of a well characterized crystal (calibration crystal) is measured with the box and the calibration source before and after irradiation, to have another check on the system stability.

To estimate the minimum photocurrent detectable over the noise level (essentially the Keithley noise), we have measured the photocurrent produced in the HPMT by the crystal irradiated with the weak ^{60}Co calibration source: the variation of current is shown in Fig. 6. A signal to noise ratio of at least two is obtained by averaging the baseline and the signal points, with a standard deviation of ~ 7 pA. Therefore, the set-up is capable of detecting corresponding gamma fluxes as low as ~ 10 kBq (for ^{60}Co), which means an equivalent dose rate of ~ 20 nGy/s (72 $\mu\text{Gy/h}$)

RESULTS

With the 1 Ci – ^{60}Co source and our geometrical arrangement (the front side of the box was at 27 cm distance from the source) the irradiation rate was ~ 150 mGy/hour (41.7 $\mu\text{Gy/sec}$)^{#4}, which should provide (see equation (1)) between 15 to 30 nA current at the HPMT anode, depending on crystal quality (rates are ~ 370 mGy/h for LHC environment and ~ 150 mGy/h in current beam tests performed at CERN).

Crystal nr.1003 (a two years old crystal) shows in Fig. 7 a marked decrease of scintillation light due to radiation damage. The decrease rate is ~ 9 % per Gy at the beginning of the irradiation, slowing down to 0.6 % per Gy towards the end (total dose of 18 Gy). Small recoveries between irradiations are visible; the time left for the recoveries at ~ 2.7 Gy and ~ 5.7 Gy between irradiations was some eight hours, during day-time, and about ten days at

^{#4} The error estimated for the dose is $\sim 10+15$ %.

~ 17 Gy. It is worthwhile mentioning that, while recovering, the crystal nr.:1003 was left in the box and did not see any light (except a small quantity used to probe the recovery after 2.7 Gy).

The photocurrent chart is extremely clean, the measurement error on the current being $\leq 5 \text{ pA}/30000 \text{ pA} = 1.67 \cdot 10^{-4}$, where 5 pA is the minimum sensitivity of the amperemeter. The recovery of light transmission during eight hours of no irradiation was measured by the HPMT, by injecting light into the crystal via the fibre. It amounts to about 2% of the value reached at the stop of the irradiation. The corresponding photocurrent chart shows only ~1% recovery (see Fig. 7), the difference between the two measurements being related to the different emission spectra of the lamp (a simple filament bulb) and of the crystal.

In Table I, the values of the photocurrents and their derivatives are shown after 1 Gy and 10 Gy irradiation dose respectively, for the four crystals tested. Note that the temperature for the first two of them was not stabilized. It is worth noting, that all crystals presented, except crystal nr 1003, have already received around ~500 Gy dose in previous irradiations and have been then annealed.

The ability of the system to study the dynamics of the irradiation process (rate of radiation damage, rate of recovery, dependence of these on temperature, etc.) is shown in Fig. 8. It shows the photocurrent versus time for the same crystal (nr. 1318) at two different operation temperatures. Fig. 8a shows an irradiation performed at 30 °C up to about 9 Gy and then at 25 °C. The slopes, just before and after the temperature jumps, are - 0.03% Gy⁻¹ and - 0.25% Gy⁻¹ respectively. They show clearly that the recovery rate depends on temperature and that reaching a steady state means essentially equalling damage rate to recovery rate. This is confirmed in Fig. 8b, where, after annealing, crystal nr. 1318 was irradiated at 18 °C until ~8 Gy. At this moment, temperature was changed to 16 °C and then to 20 °C. The consequent slopes show an acceleration of the damage process at 16 °C and a small recovery at 20 °C (the sign of the slope became positive).

CONCLUSIONS

We have developed and operated a new set-up, which measures the photocurrent produced by PbWO₄ scintillating crystals during low dose-rate irradiation by a ⁶⁰Co source. It is based on an HPMT photodetector, of which the anode current is measured to monitor variations in light yield and light transmission. Photons are counted to obtain an absolute calibration and to monitor the system stability to better than 10⁻³. The PbWO₄ – temperature is stabilized to ~ 0.1 °C and all relevant parameters and measurements were computer controlled.

First results on a few crystals irradiations are presented: decreases in light reaching the detector range from more than 30 % (nr 1003, old crystal) to ~ 2 % (nr 1318, year 1996 crystal) for ~15 Gy dose. As a result of a low dose-rate irradiation, the crystal seems to reach a steady state, where the radiation damage rate and the recovery rate equal each other. Studies to characterize this behaviour will be carried out, together with continuing irradiations of relatively large samples of crystals in the framework of a “regional centre” being set-up at CERN.

ACKNOWLEDGEMENTS

We wish to thank H. Leutz and D. Puertolas for the frequent and useful discussions and suggestions; T. Gys, G. Lecoœur and R. Loos together with D. Piedigrossi for help and technical support; P. Baillon, E. Auffray and P. Lecoq for their support and interest; Frédéric Lejal and Stefan Haider for help with the Labview programme; and finally J. Bourges and T. Otto, who kindly put at our disposal the ⁶⁰Co irradiation facility and instructed us in the difficult world of dosimetry. PbWO₄ –crystals were kindly handed to us by E. Auffray and P. Lecoq and were grown at the Bogoroditsk Technological Plant in Russia.

REFERENCES

- [1] CMS, "The compact muon solenoid", *Technical proposal*, CERN/LHCC 94-38
- [2] ATLAS, "Technical proposal for a general-purpose pp experiment at the Large Hadron Collider at CERN", *Technical proposal*, CERN/LHCC 94-43
- [3] P. Lecoq et al., "Lead Tungstate (PbWO_4) Scintillators for LHC EM-Calorimetry", CERN/PPE, CMS Technical note 94-308 (1994)
- [4] C.L. Woody et al., "A Study of the Optical and Radiation Damage Properties of Lead Tungstate Crystals", *IEEE Transactions on Nuclear Science*, vol. 43, NO. 3, (1996), p. 1585
- [5] E. Auffray, P. Lecoq, "Report to CMS referees", October 29, 1996
- [6] C. D'Ambrosio, T. Gys, H. Leutz, D. Piedigrossi, D. Puertolas, and S. Tailhardat, "Photon counting with a hybrid photomultiplier tube (HPMT)", *Nucl. Instr. and Meth. in Physics Research*, vol. A338, (1994), p. 389
- [7] C. D'Ambrosio, T. Gys, H. Leutz, D. Piedigrossi, D. Puertolas, S. Tailhardat, T. Shimizu, and O. Shinji, "Further results on photon counting with small diameter scintillating fibres", *Nucl. Instr. and Meth. in Physics Research*, vol. A345, (1994), p. 279
- [8] C. D'Ambrosio, "First results on crystal light yield measurements with a Hybrid Photo Multiplier Tube", ECAL Light Yield Meeting, CERN, Min ECAL/PWO/LY-01, MS, 21 June 1995

Table I Light yields and their variations for four crystals irradiated at the indicated temperatures (dose rate 150 mGy/h). All slopes are negative.

Crystal number	i [nA] at 1 Gy	Δi [Gy ⁻¹] at 1 Gy	i [nA] at 10 Gy	Δi [Gy ⁻¹] at 10 Gy	Temperature [°C]
1003	31.3	9.6 %	23.3	0.6 %	23±2.5**
1016	29.8	3 %	28	<0.1%	23±2.5**
1318	26.55	1.3 %	25.55	0.1%	18±0.1
1318	20.55	0.8 %	20.18	0.03 % *	30±0.1
1266	25.1	1.6 %	24	<0.01 %	22±0.1

All crystals have been previously irradiated and then annealed, except crystal nr 1003.

All crystal are of “type 3”, except crystal nr 1003, which is of “type 1” [3].

* Slope at 8 Gy

** Not temperature-stabilized

FIGURE CAPTIONS

Fig. 1 Experimental set-up: the irradiation box together with the main services, the crystal and the HPMT detector (photocathode diameter 18 mm).

Fig. 2 Electric and electronic connections. Note the special use of the HPMT bias connection to drain the photocurrent.

Fig. 3 a) Photoelectron spectra of crystal nr 1003, before and after 18 Gy dose. Peak positions are unchanged, while the effect of radiation damage on light yield is visible by a modified spectral distribution, namely a decrease in the average photoelectron distribution.

b) Photoelectron spectra of crystal nr 1119, i) was taken during three hours just after the irradiation; ii) was taken after spectrum i). The difference in the tails of the two spectra shows a phosphorescence emission. The spectrum taken before irradiation (not shown) perfectly overlapped the one taken after five hours irradiation.

Fig. 4 Photocurrent chart of crystal nr 1003, without temperature control: curve a) is the raw photocurrent versus dose as recorded by the system; curve b) is the temperature chart while irradiating. Temperature variations induce crystal light yield variations ($\sim 2.1\%$ decrease light yield per $^{\circ}\text{C}$), which are visible on curve a) as distortions to the monotonic behaviour of the photocurrent. Curve c) is curve a) corrected for temperature variations using curve b).

Fig. 5 Crystal nr 1266 irradiation chart: Left hand scale represents the photocurrent and right hand scale the temperature. Temperature was set at 18°C and then increased in steps of one degree up to 24°C after ~ 3 Gy irradiation. The crystal induced photocurrent decreased proportionally with 2.07% per $^{\circ}\text{C}$.

Fig. 6 Sensitivity estimation for the irradiation set-up: variations in photocurrent induced by exciting scintillations in crystal nr 1003 with the ^{60}Co calibration source. The minimum detectable dose rate was estimated to ~ 20 nGy/s or ~ 70 $\mu\text{Gy/h}$.

Fig. 7 Photocurrent versus dose for crystal nr 1003. At the beginning of the irradiation the photocurrent decreases with a rate of 9 % per Gy. This decrease levels off to 0.6 % per Gy after about 18 Gy dose. At 2.7 Gy and 5.7 Gy, a recovery time of some eight hours was provided. After about 18 Gy the crystal has recovered during 10 days.

Fig. 8 a) Irradiation of crystal nr 1318 performed at 30 °C up to about 9 Gy and then at 25 °C. The slopes, just before and after the temperature jumps, are $-0.03\% \text{ Gy}^{-1}$ and $-0.25\% \text{ Gy}^{-1}$ respectively.

b) After annealing, crystal nr 1318 was irradiated at 18 °C until ~8 Gy. At this value, the temperature was lowered to 16 °C for two hours, then raised to 20 °C and finally brought back to 18 °C. The corresponding slopes show an acceleration of the damage process at 16 °C and a small recovery at 20 °C (the sign of the slope becomes positive). The dose rate was 150 mGy/h.

Top view of the test box

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3a

Fig. 3b

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8a

Fig. 8b