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Assessing the performance under ionising radiation of lead tungstate scintillators for EM calorimetry in the CLAS12 Forward Tagger

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ABSTRACT

The well-established technology of electromagnetic calorimetry using Lead Tungstate crystals has recently seen an upheaval, with the closure of one of the most experienced large-scale suppliers of such crystals, the Bogoroditsk Technical Chemical Plant (BTCP), which was instrumental in the development of mass production procedures for PWO-II, the current benchmark for this scintillator. Obtaining alternative supplies of Lead Tungstate crystals matching the demanding specifications of contemporary calorimeter devices now presents a significant challenge to detector research and development programmes.

In this paper we describe a programme of assessment carried out for the selection, based upon the performance under irradiation, of Lead Tungstate crystals for use in the Forward Tagger device, part of the CLAS12 detector in Hall B at Jefferson Lab. The crystals tested were acquired from SICCAS, the Shanghai Institute of Ceramics, Chinese Academy of Sciences. The tests performed are intended to maximise the performance of the detector within the practicalities of the crystal manufacturing process.

Results of light transmission, before and after gamma ray irradiation, are presented and used to calculate *dk*, the induced radiation absorption coefficient, at 420 nm, the peak of the Lead Tungstate emission spectrum. Results for the SICCAS crystals are compared with identical measurements carried out on Bogoroditsk samples, which were acquired for the Forward Tagger development program before the closure of the facility.

Also presented are a series of tests performed to determine the feasibility of recovering radiation damage to the crystals using illumination from an LED, with such illumination available in the Forward Tagger from a light monitoring system integral to the detector.

1. Introduction

Following the closure of the Bogoroditsk Technical Chemical Plant (BTCP) in Russia, the Shanghai Institute of Ceramics, Chinese Academy of Sciences (SICCAS) is one of the most practical remaining facilities for the large-scale production of Lead Tungstate ($PbWO_4$) crystals. This type of scintillator has been used for EM calorimetry in a variety of experimental facilities [1–4], including the Forward Tagger Calorimeter (FT-Cal), a subsystem of the Forward Tagger device, part of the CLAS12 facility being constructed in Hall B at Jefferson Lab [5].

The Forward Tagger has been developed for meson spectroscopy experiments in CLAS12 using the technique of low Q^2 electron scattering. These electrons give rise to quasi-real photons, which are reconstructed by detecting the scattered electron in the Forward Tagger between polar angles of 2.5° and 4.5°. At such close proximity to the beamline, the FT-Cal scintillators will be subjected to significant radiation rates, averaging 0.05 Gy/h, but up to ten times this rate is expected for crystals closest to the beamline. Even higher rates may be seen during CLAS12

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experiments that will not utilise the Forward Tagger, but for which the device will remain installed. This requires a sufficiently radiation-hard material to be used. Lead Tungstate was chosen as it has been shown in many studies to be a material very resistant to radiation damage [6]. Combined with its fast decay time and small radiation length, $PbWO_4$ is considered to be a good match to the demanding specifications of the FT-Cal [5].

The FT-Cal comprises 332 $PbWO_4$ crystals, each measuring 200 × 15 × 15 mm, produced by SICCAS using the modified Bridgman method [7]. These crystals are read out with individual Avalanche Photo Diodes (APD), whose gains can be matched, and monitored during run periods, via a light monitoring system, which provides LED illumination tuned to the luminescence spectrum of the scintillator. The initial specifications demanded of the FT-Cal crystals are outlined in Table 1.

Radiation hardness of the crystals is quantified by the radiation induced absorption coefficient, dk, given in the following equation:

$$dk = \frac{1}{\text{length}} \ln\left(\frac{T_{bef}}{T_{irr}}\right) \tag{1}$$

where T_{bef} is the light transmission at 420 nm, the peak of the $PbWO_4$ emission spectrum, measured before irradiation, and T_{irr} the light transmission at 420 nm after irradiation. Crystals exhibiting greater levels of radiation damage to light transmission have higher values of dk.

As a consequence of the practicalities of the manufacturing process, and the need to produce crystals in a timely and cost-effective manner, production crystals are often found to possess properties outside the ranges specified in Table 1. For this reason, a further programme of quality control is required to assess whether their characteristics are within acceptable values.

This paper describes the programme of evaluation undertaken to assess the SICCAS crystals acquired for the FT-Cal in terms of the light transmission and radiation hardness requirements of operations within CLAS12. The program consists of three parts. The first is a study of the light transmission, verifying that, before irradiation, crystals possess light transmission values consistent with those specified in Table 1. The second part assesses the radiation hardness of the crystals by determining the induced radiation absorption coefficient, dk, measuring the light transmission before and after irradiation and calculating dk using Eq. (1). The third part is the assessment of the ability to recover radiation damage to the crystals by means of optical annealing using visible light illumination from an LED, exploiting the availability of such illumination from the light monitoring system of the FT-Cal.

A total of 370 crystals, including spares, were initially acquired from SICCAS, and for each crystal the induced absorption coefficient was measured. The results were used to identify 51 crystals that would not be accepted for deployment in the FT-Cal. These rejected crystals were replaced by SICCAS, and subjected to the same irradiation procedure to find their values of dk. The 332 most radiation-resistant crystals were then selected for installation, with the remainder to be held as spares. LED recovery measurements were performed for a smaller subset of the acquired crystals, verifying the suitability of the FT-Cal light monitoring system for use in crystal annealing.

The SICCAS crystals were also compared with sample BTCP crystals; a set of 8 crystals used for prototyping of the FT-Cal [5] and a single crystal of a slightly different geometry (160 mm long, tapering from 16 × 16 mm at one end to 13 × 13 mm at the other), deployed in several previous calorimeter devices at Jefferson Lab, including the ECal subsystem of the Heavy Photon Search (HPS) experiment [8]. The BTCP examples chosen represent a typical range of properties and response to irradiation of this type of crystal.

2. Crystal irradiation tests

The use of $PbWO_4$ crystals as scintillators in EM calorimeters has been extensively studied for a variety of experiments, including CMS and ALICE at CERN [1,2], PANDA at FAIR [3], and the CLAS Inner Calorimeter (CLAS-IC) at Jefferson Lab [4]. As a result of these studies, a good understanding exists of the mechanisms of radiation damage in $PbWO_4$ crystals, and how this damage manifests in terms of crystal light yield [9]. Under irradiation, impurities and defects in the crystal structure, and traps for electrons and holes lead to the formation of colour centres, the overall effect of which is a decrease in light transmission of the crystal at optical wavelengths. After exposure, these colour centres spontaneously relax, with a fast thermal component acting over a timescale of around 30 min [10]. This fast recovery is demonstrated in Fig. 1, in the form of dk measurements at 420 nm performed on a sample SICCAS crystal in the 30 min immediately following irradiation. Because of the damage recovery component in $PbWO_4$, both creation and elimination of colour centres will take place during crystal irradiation, and the total damage induced will depend on the equilibrium between these two effects, determined by the dose rate used for the irradiation procedure [11,12].

Following this fast recovery, crystals continue to recover on a slower timescale, and their light transmission approaches that of an undamaged crystal after a sufficiently lengthy period, of the order of several weeks. This recovery can take place at room temperature, with the possibility that the acquisition of some dose rate dependent damage may prevent full recovery. Complete recovery can be realised via thermal annealing [13].

Although the processes of radiation damage in $PbWO_4$ are well-known, the applications cited above used BTCP-type crystals, which are no-longer commercially available. The SICCAS-type crystals which will be used for the FT-Cal exhibit similar behaviour under irradiation to BTCP crystals, but there are appreciable differences with respect to the BTCP-type.

To understand these differences, and any potential effects on the deployment of these crystals in the FT-Cal, a preliminary programme of irradiation studies was performed at CERN, using the Automatic Crystal quality Control System (ACCOS) [14] on a

Table 1
Initial specifications requested from SICCAS for the $PbWO_4$ crystals of the FT-Cal.

Property	Value
Length (mm)	200.00 ± 0.15
Width (mm)	15.00 ± 0.15
Height (mm)	15.00 ± 0.15
Longitudinal transmission (360 nm)	$\geq 25\%$
Longitudinal transmission (420 nm)	$\geq 60\%$
Longitudinal transmission (620 nm)	$\geq 70\%$
Light yield ($T = 18$ °C)	≥ 13 phe/MeV
Radiation induced absorption at 420 nm, dk, measured 30 min after 30 Gy irradiation at 120 Gy/h	$\leq 1.0\ \text{m}^{-1}$

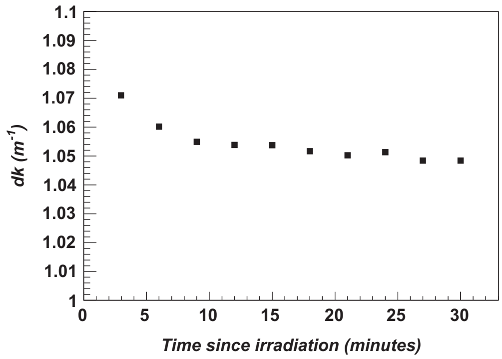

Fig. 1. Radiation induced absorption coefficient, *dk*, at 420 nm for a SICCAS $PbWO_4$ crystal, measured at 3-min intervals following irradiation with 30 Gy. After around 30 min, the fast recovery component is complete.

subset of the acquired SICCAS crystals. These studies showed significant variations of the crystal parameters, with several examples failing to meet the radiation hardness specifications shown in Table 1. For these reasons, a detailed assay of the performance under irradiation of all the crystals acquired for the FT-Cal was undertaken.

To observe the effects of normal operation in CLAS12 on the FT-Cal crystals, a 30 Gy dose was chosen, equivalent to the dose expected in the region of the FT over one month of continuous operation in CLAS12 [5]. Although this dose is imparted at a much higher rate than will be expected in CLAS12, this allowed all available crystals to be tested in a practical timeframe and within the constraints of the FT-Cal construction schedule. The dose rate dependency of radiation damage becomes less important as the *dk* values computed are used to select the highest-performing crystals from the acquired batch, rather than perform crystal rejection based upon expected radiation conditions in CLAS12.

2.1. The irradiation facility at Gießen University

The biotechnical operating unit of the University of Gießen has an irradiation facility, the *Strahlenzentrum*, used by researchers in a variety of disciplines. The facility has ^{60}Co sources, which can be used in gamma ray irradiation studies and have been utilised by the II Physikalisches Institut of the university in studies of $PbWO_4$ crystals for the PANDA EM calorimeter.

The irradiation station at the *Strahlenzentrum* used for crystal studies is equipped with a Cary 4000 spectrophotometer, using a Hamamatsu R928 PMT as a photo-detector, and featuring a customised enclosure into which crystals are loaded for measurements of the light transmission along their longitudinal axis. The spectrophotometer is controlled by a PC running Cary WinUV software that allows the viewing and saving of spectra and provides options for the export of data to various formats for offline analysis. This is located close to the irradiation chamber, into which the crystals are placed for irradiation. The irradiation chamber contains 6 volume sources, with superposition between the sources enabling irradiation of the entire crystal sample. Any position effects regarding dose imparted within the chamber are considered to be negligible, as seen in multiple irradiation cycles of FT crystals, and in previous work by the PANDA collaboration at the *Strahlenzentrum*. A 30 Gy dose is imparted to the crystals in approximately 15 min, representing a rate of 120 Gy/h.

2.2. Crystal testing procedure

Before irradiation, measurements were made of the longitudinal light transmission of the crystals. Crystals were then irradiated with a 30 Gy dose from the ^{60}Co sources and stored for 30 min in a dark environment to allow the fast recovery component of the crystal to take effect without interference from optically-stimulated recovery effects. They are then measured a second time, with the same alignment and orientation in the spectrophotometer as the initial measurement in order to minimise changes in the light transmission due to crystal positioning and the presence of dust, dirt, and imperfections on the crystal surface. All 370 SICCAS crystals, the 51 replacement crystals, and the BTCP crystals from both the HPS ECal and the FT-Cal prototype, were measured in this way at least once.

2.3. Further studies of crystal properties

In addition to the “once-through” irradiation procedure described above, several crystals were used for more detailed studies. This involved exposure to multiples of the 30 Gy dose, as well as repeat measurements of the “once-through” irradiation procedure after thermal annealing of the crystals, the latter being performed as a consistency check of the reproducibility of measurements. A separate facility at the University of Gießen was also used to study crystal light yield, in order to verify ACCOS results obtained during the preliminary crystal assessment procedure referred to earlier in this section. No significant variation in the light yield measurements was seen in comparison to the ACCOS studies, or the quoted values from the manufacturer, therefore all crystals tested in this work for radiation hardness are considered to have met the light yield requirements of the FT-Cal. Also performed were tests of recovery of radiation damage via optical annealing, discussed in the next section.

3. Recovery of radiation damage by LED illumination

Except in cases of prolonged high doses, for example in high energy collider experiments such as CMS, where large levels of radiation damage will accumulate, $PbWO_4$ crystals will typically recover most of the damage to their light transmission on their own at room temperature over an extended timescale. The colour centres formed around defects in the crystal release their captured electrons and/or holes, and the crystal will exhibit similar light transmission properties to those it had before irradiation. Crystals can also be fully recovered by thermal annealing, as the probability of releasing charge carriers from colour centres depends exponentially on temperature, allowing the recovery process to be performed in a period of several hours at temperatures of around 200 °C.

In addition to these processes, illumination from visible light is able to induce crystal recovery, by optically-stimulating the restoration of the colour centres in the crystals, a process observed in several types of scintillating crystals [10,15–18]. During the program of crystal tests performed in Gießen, irradiated examples of $PbWO_4$ crystals of the SICCAS and BTCP types were exposed to varying degrees of illumination, both from LEDs planned for use in the gain monitoring system of the FT-Cal, and from readily-available sources of light in the *Strahlenzentrum*. The results of these studies using the LEDs from the FT-Cal monitoring system on the SICCAS and BTCP $PbWO_4$ crystals are discussed in Section 4.2.

4. Analysis and results

Light transmission measurements before and after irradiation, as well as all multiply-irradiated, annealed and re-irradiated crystals, and LED illumination studies were saved as .csv text files from the spectrophotometer control software and subjected to offline analysis. This analysis collated light transmission measurements at three wavelengths, 360 nm, 420 nm and 620 nm, computed *dk* at 420 nm for all irradiated crystals, and examined the LED-stimulated recovery properties of the SICCAS and BTCP crystals.

Also considered were possible systematic effects, and data normalisation issues. The spectrophotometer is automatically set up to subtract baseline measurements, a reference measurement taken with no crystal sample installed and no illumination of the photodetector within the device. Changes in this baseline are primarily due to thermal fluctuations, and are mitigated by maintaining a stable ambient temperature in the *Strahlenzentrum* and regularly updating the baseline spectrum used, particularly after longer periods where the spectrophotometer was not in use. The reproducibility of crystal positioning is the other major systematic effect in these measurements, with even small misalignments of the crystal having an appreciable effect on the measured values of light transmission. All crystals had a small identifying mark on one surface of the crystal, and this was used to ensure that every crystal had the same orientation each time it was measured in the spectrophotometer. Several crystals were measured multiple times and their spectra compared, in order to ensure that crystal positioning was sufficiently reproducible and would have minimal effect on the spectra measured. The total systematic error in these measurements is estimated to be 1–2%, resulting in an error in *dk* between 0.1 and 0.2 m^{-1}. For this reason, the requirement for *dk* was increased to accept crystals with $dk \leq 1.3\ \mathrm{m}^{-1}$.

4.1. SICCAS $PbWO_4$ crystal results

In Fig. 2, the light transmission spectra before and after irradiation are shown for two examples of the SICCAS-type crystal, demonstrating a range of behaviours under irradiation. Damage due to the irradiation is seen across the visible spectrum for both crystals, with the right hand plot representing a fairly resistant example, accepted for use in the FT-Cal and the left hand plot typical of a badly-damaged example, which was rejected.

Figs. 3–5 show the light transmission measurements at 360 nm, 420 nm, and 720 nm, before and after irradiation for all the SICCAS crystals tested, highlighting the spread in physical properties of the crystals supplied. The corresponding mean and standard deviation values of light transmission are given in Table 2.

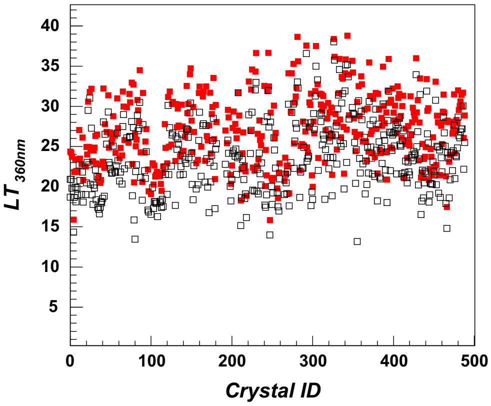

Fig. 3. Light transmission measurements at 360 nm for all SICCAS-type $PbWO_4$ crystals tested in Gießen. Filled squares are measurements before irradiation and open squares from measurements made after irradiation with 30 Gy. “Crystal ID” is an internal numbering scheme used to track the crystals.

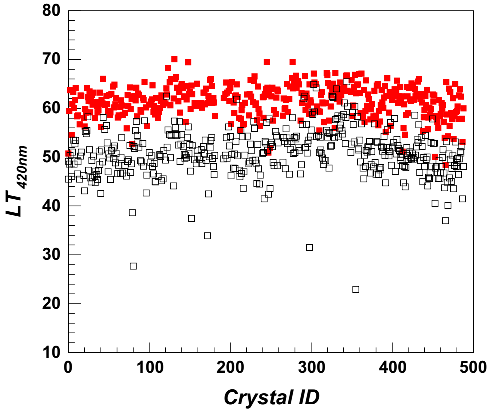

Fig. 4. Light transmission measurements at 420 nm for all SICCAS-type $PbWO_4$ crystals tested in Gießen. Filled squares are measurements before irradiation and open squares from measurements made after irradiation with 30 Gy. “Crystal ID” is an internal numbering scheme used to track the crystals.

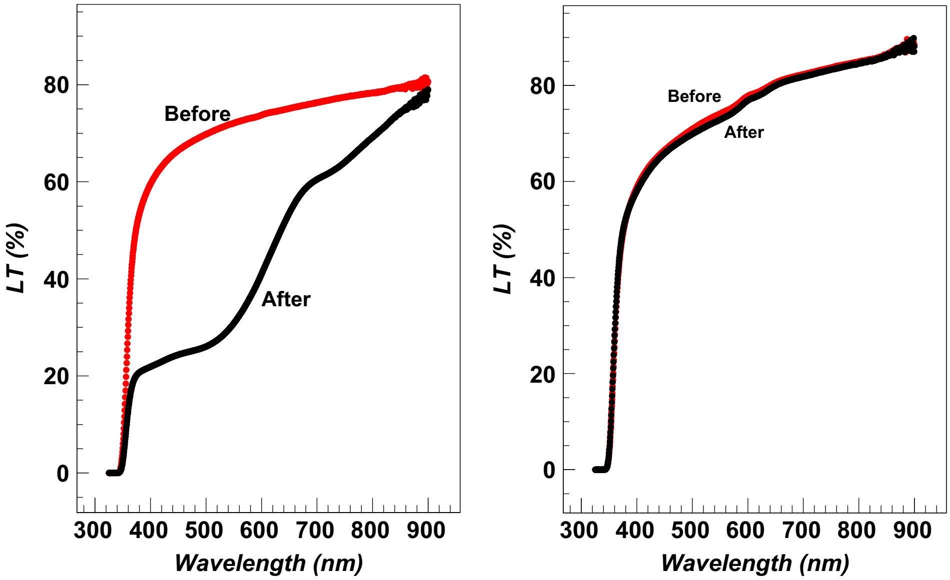

Fig. 2. Longitudinal light transmission for SICCAS-type $PbWO_4$ crystals, before and after 30 Gy gamma irradiation. Irradiated spectra exhibit lower light transmission, particularly around 400–600 nm. The plot on the right represents good response of the SICCAS crystal to irradiation, while the plot on the left is typical of a very poorly performing crystal.

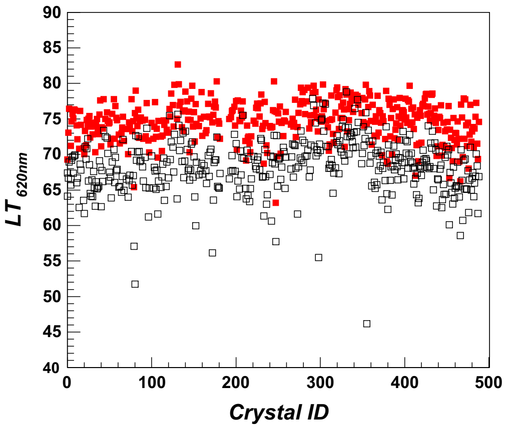

Fig. 5. Light transmission measurements at 620 nm for all SICCAS-type $PbWO_4$ crystals tested in Gießen. Filled squares are measurements before irradiation and open squares from measurements made after irradiation with 30 Gy. “Crystal ID” is an internal numbering scheme used to track the crystals.

Table 2
Average and standard deviation of light transmission values before and after irradiation of the SICCAS $PbWO_4$ crystals acquired for the FT-Cal.

Property	Mean	σ
LT before irradiation (360 nm, %)	27.1 ± 0.2	4.3
LT after irradiation (360 nm, %)	23.7 ± 0.2	4.4
LT before irradiation (420 nm, %)	61.5 ± 0.2	3.2
LT after irradiation (420 nm, %)	50.8 ± 0.2	4.9
LT before irradiation (620 nm, %)	74.7 ± 0.1	2.7
LT after irradiation (620 nm, %)	68.3 ± 0.2	3.7

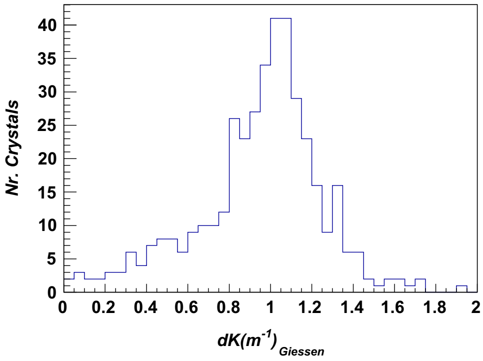

Fig. 6. Histogram of the radiation induced absorption coefficient, *dk*, for all SICCAS-type $PbWO_4$ crystals tested in Gießen. Crystals with a radiation induced absorption coefficient greater than 1.3 m^{-1} were rejected.

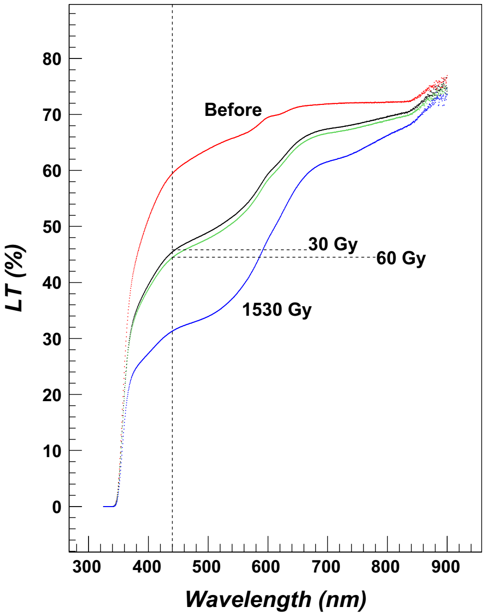

Fig. 7. Light transmission measurements for multiply irradiated SICCAS crystal ‘A’. The crystal was subjected to sequential doses of 30 Gy totalling 1 (30 Gy), 2 (60 Gy), and 51 (1530 Gy) times the representative dose expected during one month of FT-Cal operation. Greater reductions in light transmission are seen as the dose received increases. Labels show intersections of these curves with a line at 440 nm.

The collected statistics for all crystals with respect to *dk* at 420 nm are shown in Fig. 6. Crystals with a *dk* higher than 1.3 m^{-1} were rejected.

Two crystals, referred to here as A and B, were subjected to multiple exposures to the 30 Gy irradiation, totalling 1, 2, 4, and 51 times a single dose, allowed 30 min in a dark environment for fast recovery, then re-measured in the spectrophotometer. The results of these studies are shown in Figs. 7 and 8. The two crystals show different responses to the irradiation, with crystal B experiencing less reduction in light transmission as a result of radiation damage. However, after the 51 × dose, the degradation in light transmission is severe for both crystals, indicating that under sufficient gamma irradiation, all SICCAS-type crystals will suffer appreciable levels of light transmission damage.

4.1.1. Comparison with BTCP crystal from HPS calorimeter

Spectra for the BTCP crystal from the HPS ECal and an example FT-Cal SICCAS crystal, both before and after irradiation, are compared in Fig. 9. The BTCP crystal is notable for having a greater overall light transmission at all wavelengths, and a less pronounced “wiggle” feature which is clearly seen around 600 nm in the SICCAS spectra. The BTCP crystal also displays a far lower degree of radiation damage across the visible spectrum, resulting in a lower value of $dk = 0.6\ m^{-1}$ being computed from the light transmission measurements at 420 nm.

4.1.2. Comparison with BTCP crystals from FT-Cal prototype

The BTCP crystals show a narrower range of values of *dk* than is seen in the SICCAS crystals, and all have *dk* less than 1.0 m^{-1}, the originally-specified value for the FT-Cal. The induced radiation absorption coefficients for the 8 BTCP sample crystals are shown in Fig. 10, alongside the SICCAS crystals which have *dk* less than 1.0 m^{-1}. Together with the greater light transmission at visible wavelengths when compared to the SICCAS crystals, the superior performance of the BTCP crystals has resulted in the available samples being considered for use in the regions of the FT-Cal expected to receive the highest rates of radiation.

4.2. LED recovery results

As shown in the previous section, and in Figs. 7 and 8, even the most resistant of the SICCAS-type crystals will suffer degradation to their light transmission under sufficient irradiation. When deployed in the FT-Cal, thermal annealing will not be a practical option for recovering this damage, as it would require either the dismounting of all 332 crystals, or the capability to heat the calorimeter to a sufficient temperature to significantly speed up the recovery process without causing damage to the surrounding components of the FT, or indeed to CLAS12. Such thermal annealing will be possible during certain shutdown periods of CLAS12 operations, but mitigating the accumulation of radiation damage between these available maintenance windows is desirable.

One alternative is to use LED illumination, available in the FT-Cal from the light monitoring system, to recover radiation damage to the crystals. This use of LED illumination to recover radiation damage was studied for both the SICCAS and BTCP type crystals. Irradiated samples of the two crystal types were illuminated with blue light from a single-colour NICHIA NSBP500AS LED [19], and the light transmission recovery effect observed.

4.2.1. Results for SICCAS crystals

Three SICCAS crystals, A and B, from Section 4.1, and a third crystal, referred to here as crystal C, were all used for LED recovery studies. All three crystals were subjected to the “once-through” irradiation procedure described in Section 2.2. Additionally, crystals A and B were subjected to multiple irradiations, already discussed in Section 4.1. Following their respective maximum irradiations, 1 × 30 Gy dose for crystal C, 51 × 30 Gy dose for crystals A and B, the crystals were then exposed to LED illumination, and the recovery effects observed. For the single 30 Gy dose irradiation, just 30 s of LED illumination is sufficient to begin to observe recovery in light transmission, with significant recovery observed after several minutes of illumination. Fig. 11 shows the light transmission curves for SICCAS crystal C after a series of 30 s illuminations from LED light, demonstrating the fast rate of recovery possible via LED illumination.

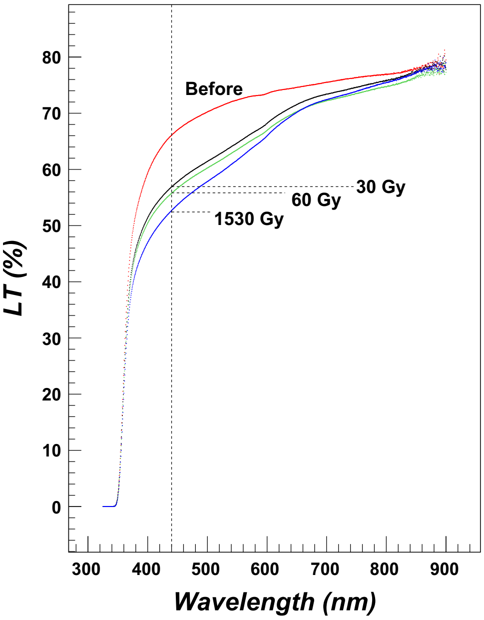

Fig. 8. Light transmission measurements for multiply irradiated SICCAS crystal ‘B’. The crystal was subjected to sequential doses of 30 Gy totalling 1 (30 Gy), 2 (60 Gy), and 51 (1530 Gy) times the representative dose expected during one month of FT-Cal operation. Greater reductions in light transmission are seen as the dose received increases. Labels show intersections of these curves with a line at 440 nm.

For the crystals receiving higher doses, much longer illumination times, of order several hours, are required to see any significant recovery effect, demonstrated in Fig. 12, which shows the light transmission recovery after 4 h illumination.

It is expected that the light monitoring system of the FT-Cal will be used to regularly optically anneal the crystals, usually between experiments. The doses accumulated over the course of an experiment are not expected to cause significant damage to the crystals, and a few minutes of illumination should be sufficient for recovery. The possibility also exists to illuminate crystals between

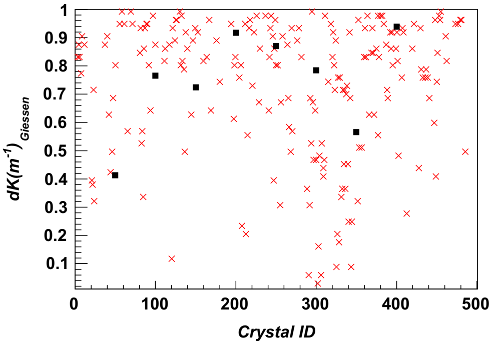

Fig. 10. Induced absorption coefficient, *dk*, for BTCP sample crystals (squares), shown alongside all SICCAS crystals with *dk* less than 1.0 m^{-1} (crosses), the originally-specified value for the FT-Cal. Both crystal types shown have the same 200 × 15 × 15 mm geometry, allowing these BTCP samples to be deployed alongside SICCAS crystals in the Forward Tagger.

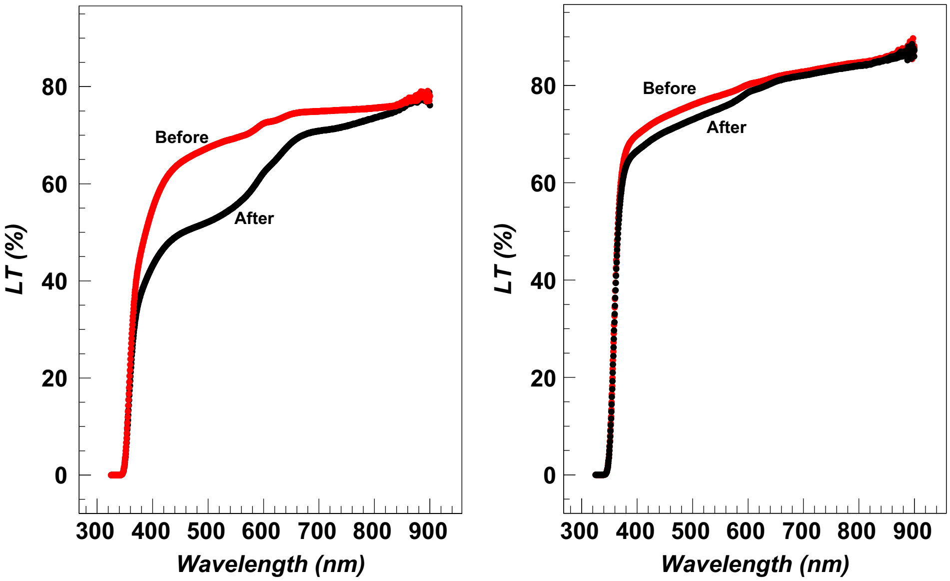

Fig. 9. Light transmission measurements for a single SICCAS $PbWO_4$ crystal, before and after irradiation (left), alongside similar measurements performed for a BTCP crystal (right). The irradiated spectra exhibit lower light transmission, particularly around 400–600 nm, however the BTCP-type crystal exhibits a greater resistance to light transmission damage under irradiation.

runs during an experiment if necessary, provided the opportunity to do so arises through beam operations or configuration changes in the experimental hall.

4.2.2. Results for HPS BTCP crystal

In a similar programme of tests to the SICCAS crystals, the BTCP crystal from the HPS calorimeter was also subjected to LED illumination. Like SICCAS crystal C, a "once-through" irradiation procedure was performed on the crystal, and exposure to varying degrees of LED illumination used to realise light transmission recovery. After 35 min of illumination, almost complete recovery of the light transmission is observed, shown in Fig. 13.

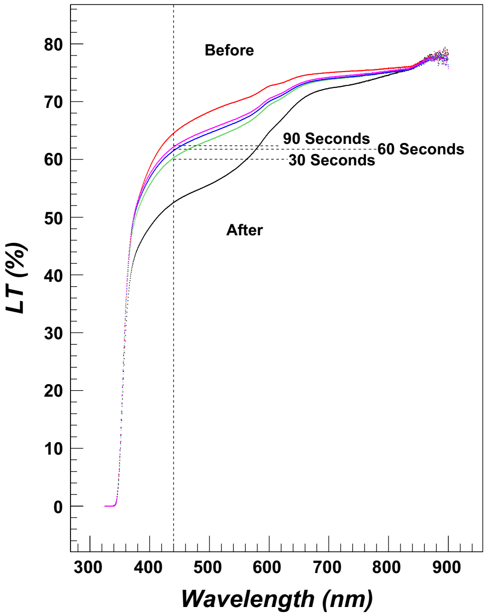

Fig. 11. Light transmission measurements for SICCAS-type $PbWO_4$ crystal C, irradiated with 30 Gy ('After' curve) and recovered using LED illumination. Initial recovery of light transmission can be seen after 30 s illumination (green curve). Successive 30-second illuminations show significant recovery of light transmission is possible after a few minutes (further curves shown representing 60 s accumulated illumination, and 90 s). Labels show intersections of curves with a line at 440 nm. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

5. Conclusions and outlook

The demanding specifications of the Forward Tagger calorimeter has proven to be a challenge with respect to acquiring Lead Tungstate crystals with sufficient performance for deployment in the device. Of particular concern was the degradation in light transmission under irradiation. The program of crystal assay undertaken at the University of Gießen has enabled an informed selection to be made of those crystals requiring replacement, and the positioning of the selected crystals within the calorimeter

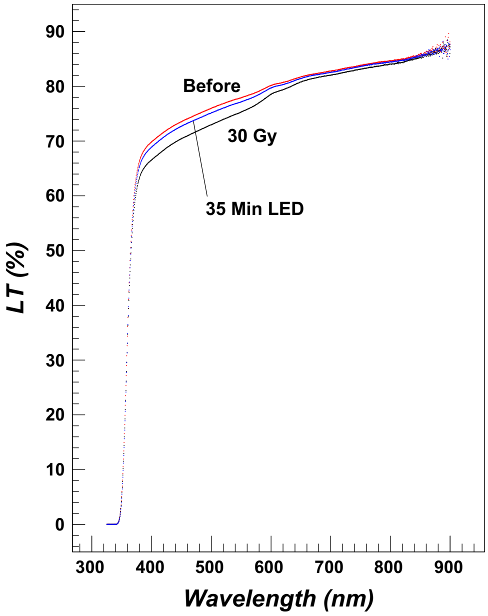

Fig. 13. Light transmission measurements for BTCP-type $PbWO_4$ crystal, before and after irradiation with 30 Gy, and recovered using LED illumination totalling 35 min. After this illumination, almost complete recovery of the light transmission is observed.

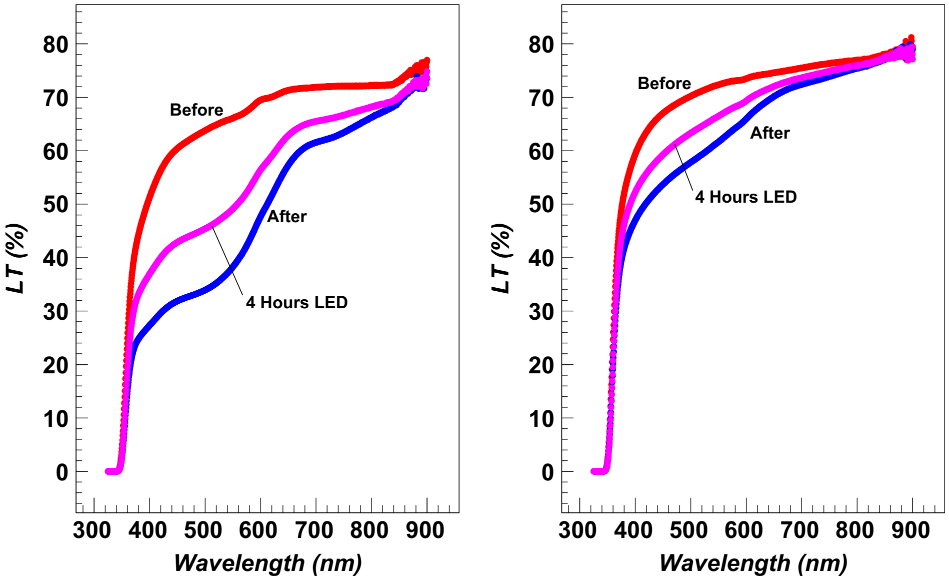

Fig. 12. Light transmission measurements for multiply irradiated SICCAS crystals A (left) and B (right), showing pre-irradiated measurements, irradiated spectra for a 51 times 30 Gy dose, and the effect of 4 h LED illumination on the recovery of light transmission. After such heavy doses, crystal recovery via LED illumination is more difficult.

according to their radiation hardness. Studies of possible recovery of radiation damage to the crystals by means of LED illumination were also performed, leading to greater confidence that the LED-based light monitoring system of the FT-Cal, designed for preliminary gain equalisation, can also be applied to the optically-stimulated recovery of radiation damage to the crystals, rather than the time-consuming alternative of dismounting the calorimeter for thermal annealing.

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The proposed application of the Forward Tagger light monitoring system to perform stimulated recovery of radiation damage via external light on a quasi-online basis (i.e. without dismantling the calorimeter for annealing between experiments) was discovered and developed as a result of research and development on $PbWO_4$ crystals for PANDA. This application is described in reference [10], and can be performed with infrared or visible light. A European patent for a device providing external light for this purpose is held by the University of Gießen.

References

[1] The CERN Large Hadron Collider: Accelerator and Experiments, vols. 1–2, CERN, Geneva, 2009.
[2] A.A. Annenkov, et al., Nuclear Instruments and Methods in Physics Research Section A 490 (2001) 30.
[3] PANDA Electromagnetic Calorimeter (EMC), Technical Design Report, ⟨http://www-panda.gsi.de/archive/public/panda_tdr_EMC.pdf⟩.
[4] Deeply Virtual Compton Scattering with CLAS at 6 GeV, Experimental Proposal ⟨http://www.jlab.org/exp_prog/proposals/01/PR01-113.pdf⟩, 2001.
[5] M. Battaglieri, et al., CLAS Collaboration, The CLAS12 Forward Tagger, Technical Design Report, ⟨http://www.ge.infn.it/~batta/jlab/ft-tdr.2.0.pdf⟩, 2012.
[6] P. Adzic, et al., Journal of Instrumentation 5 (2010) 03010.
[7] X. Qu, et al., Nuclear Instruments and Methods in Physics Research Section A 480 (2002) 470.
[8] Heavy Photon Search – A Proposal to Search for Massive Photons at Jefferson Laboratory, experimental Proposal, ⟨http://www.jlab.org/exp_prog/proposals/11/PR12-11-006.pdf⟩, 2011.
[9] P. Lecoq, et al., Nuclear Instruments and Methods in Physics Research Section A 365 (1995) 291.
[10] V. Dormenev, et al., Nuclear Instruments and Methods in Physics Research Section A 623 (2010) 1082.
[11] R.Y. Zhu, et al., Nuclear Instruments and Methods in Physics Research Section A 413 (1998) 297.
[12] R. Mao, et al., IEEE Transactions on Nuclear Science NS-51 (2004) 1777.
[13] F. Yang, et al., IEEE Transactions on Nuclear Science NS-60 (2013) 2336.
[14] E. Auffray, et al., Nuclear Instruments and Methods in Physics Research Section A 456 (2001) 325.
[15] D. Ma, et al., Nuclear Instruments and Methods in Physics Research Section A 332 (1993) 113.
[16] R.Y. Zhu, Nuclear Instruments and Methods in Physics Research Section A 340 (1994) 442.
[17] R.Y. Zhu, et al., Nuclear Instruments and Methods in Physics Research Section A 356 (1995) 309.
[18] R.Y. Zhu, et al., Nuclear Instruments and Methods in Physics Research Section A 376 (1996) 319.
[19] NICHIA Corportation, Technical Specifications for NICHIA Blue LED NSPB500AS.