Nuclear Instruments and Methods in Physics Research A 789 (2015) 101–108

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

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

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ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form
23 March 2015
Accepted 24 March 2015
Available online 8 April 2015

Keywords:
Electromagnetic calorimetry
Lead tungstate scintillators
Radiation hardness
Optical transmission
Stimulated recovery of radiation damage

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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http://dx.doi.org/10.1016/j.nima.2015.03.073

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 $200 \times 15 \times 15$ 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:

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

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	≤ 1.0 m^{-1}