Nuclear Instruments and Methods in Physics Research A 787 (2015) 144–147

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Simulation studies of crystal-photodetector assemblies for the Turkish accelerator center particle factory electromagnetic calorimeter

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ARTICLE INFO

Available online 26 November 2014

Keywords:
Scintillation crystals
Photodetectors
Calorimeters
GEANT4 simulation

ABSTRACT

The Turkish Accelerator Center Particle Factory detector will be constructed for the detection of the produced particles from the collision of a 1 GeV electron beam against a 3.6 GeV positron beam. $PbWO_4$ and CsI(Tl) crystals are considered for the construction of the electromagnetic calorimeter part of the detector. The generated optical photons in these crystals are detected by avalanche or PIN photodiodes. Geant4 simulation code has been used to estimate the energy resolution of the calorimeter for these crystal–photodiode assemblies.

1. Introduction

The Turkish Accelerator Center (TAC) [1] project was planned a regional facility for accelerator based fundamental and applied physics research in Turkey. One of the main parts of the TAC project is the electron–positron collider as a super charm factory consisting of a 1 GeV electron linac and a 3.6 GeV positron ring for linac on ring type [2] and a detector to search for charm physics, mainly the CP violation and mixings of D^0-mesons, as well as new physics effects in the rare decays. The main components of the preliminary design of the TAC Particle Factory detector are tracker (SiT), time of flight (ToF), calorimeter (ECAL), and muon system (MUON). The aim of this paper is to investigate the possible effects to the electromagnetic energy resolution due to different crystal-photodetector systems for the calorimeter.

In order to get good energy and position resolution, $PbWO_4$ (PWO) and CsI(Tl) crystals are considered to use for the calorimeter. PWO crystals are high density inorganic scintillators with short decay time (about 80% of the scintillation light is emitted in 25 ns). The drawbacks of this crystal are a high sensitivity to a temperature variation and poor light yield [3]. CsI(Tl) crystals are also used widely due to their high light output, good mechanical properties and moderate price, but these crystals are relatively slow scintillators (about 64% of the light is emitted in 680 ns) [4,5]. While the generated photons in the PWO crystal are emitted in the wavelength region of 320–600 nm peaking at around 420 nm, the generated photons in the CsI(Tl) crystal are emitted in the wavelength region of 350–800 nm peaking at around 550 nm. The photons generated from incident particles in these crystals could be detected from a pair of Hamamatsu S2744-08 PIN diode or Hamamatsu S8664-55 avalanche photodiode (APD). As Hamamatsu S2744-08 PIN diodes are used as photo-detectors for the BaBar [6], BELLE [7] and BES III [5] CsI(Tl) calorimeters, Hamamatsu S8664-55 APDs are used for the CMS [8] PWO calorimeter. Both can be used as photodetectors for the electromagnetic calorimeter of the proposed TAC Particle Factory detector.

2. Energy resolution

The energy resolution of a calorimeter can be parameterized as $\sigma(E)/E = a/\sqrt{E} \oplus b \oplus c/E$, where a is the stochastic term, b is the constant term, c is the noise term, E is the incident particle energy in GeV and $\oplus$ represents addition in quadrature. The stochastic term of the energy resolution for crystal–photodiode combination is composed of a contribution from event to event fluctuations in the lateral shower containment ($a_{lateral}$) and a contribution from photoelectron statistics (a_{pe}) or photostatistics given as $a = a_{lateral} \oplus a_{pe}$. The photoelectron statistics contribution is related to fluctuations in the photodetector signal [9]:

$$a_{pe} = \sqrt{\frac{\overline{F}}{N_{pe}}} \tag{1}$$

Here, $\overline{F}$ is the emission weighted excess noise factor coming from the fluctuations in the avalanche gain process:

$$\overline{F} = \frac{\int F(\lambda)Em(\lambda)\, d\lambda}{\int Em(\lambda)\, d\lambda} \tag{2}$$

where $F(\lambda)$ and $Em(\lambda)$ are the excess noise factor of the photodetector as a function of the wavelength and the emission spectrum of the

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http://dx.doi.org/10.1016/j.nima.2014.11.077
0168-9002/

crystal. Since the PIN photodetectors have no internal gain, there is no excess noise ($F=1$). N_{pe} is the number of primary photoelectrons resulted from photoabsorption in the photodiode and calculated from

$$N_{pe} = N_{ph} \cdot \overline{QE} \tag{3}$$

here, N_{ph} is the number of incident photons collected by the photodiode which is related to the number of photons leaving at the end of the crystal. $\overline{QE}$ is the emission weighted quantum efficiency calculated according to

$$\overline{QE} = \frac{\int QE(\lambda)Em(\lambda)\,d\lambda}{\int Em(\lambda)\,d\lambda} \tag{4}$$

where $QE(\lambda)$ and $Em(\lambda)$ are the quantum efficiency of the photodetector as a function of the wavelength and the emission spectrum of the crystal [10].

3. Geant4 simulation and results

Geant4 simulation code [11] was used to simulate photons at the different energies passing through the PWO and CsI(Tl) crystal, arranged in 5×5 matrices. Each PWO crystal has a cross-section of 20×20 mm^2 and a length of 200 mm (22 X_0). The cross-section of CsI(Tl) crystal is 55×55 mm^2 at the front surface and 60×60 mm^2 at the rear surface; the length of crystal is 300 mm or 16.2 X_0.

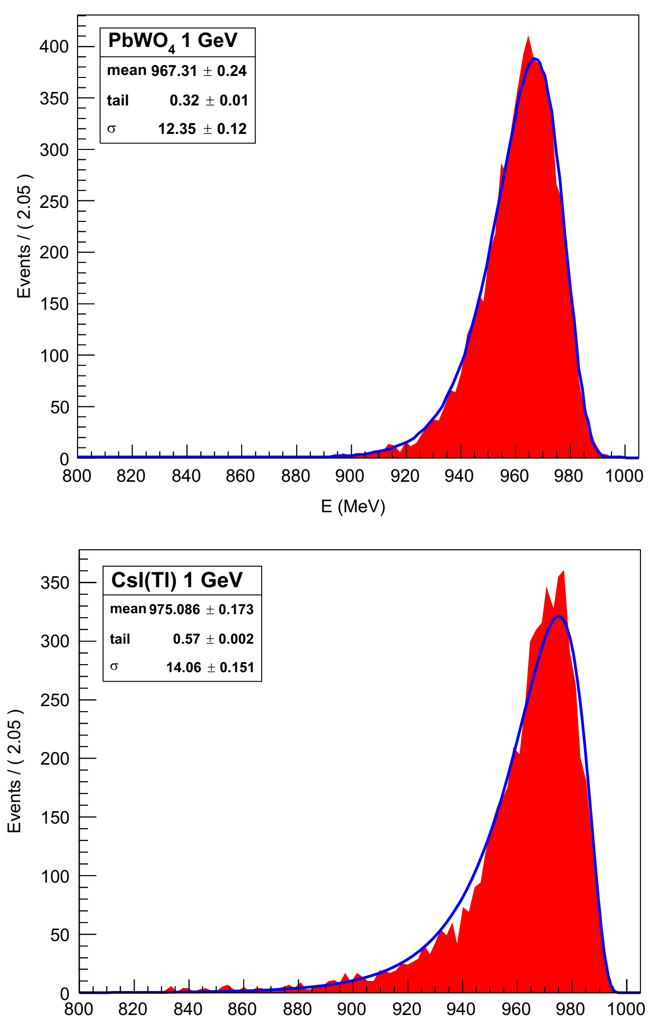

Fig. 1. Energy spectra of the 5×5 PWO and CsI(Tl) crystal matrices for 1 GeV photons injected into the central crystal. Solid curves are the results of the fits with a Novosibirsk function. The obtained fit values are also given.

Some properties of these crystals can be found in Ref. [12]. Photons in the energy region from 50 MeV to 2 GeV were injected into the center of central crystal of 5×5 matrix. Some part of this study related to PWO crystal was published in Ref. [13].

When directing the photon towards a crystal matrix, the photon initiates an electromagnetic shower. The energy of the incident photon is deposited in active medium of the crystal matrix. Energy deposition spectra have a Gaussian with an asymmetric tail towards lower energies, as can be seen in Fig. 1. These spectra were fitted with Novosibirsk function which is defined by [15]:

$$f(E) = A_s \exp(-0.5\ln^2[1+\Lambda\tau \cdot (E-E_0)]/\tau^2+\tau^2) \tag{5}$$

where $\Lambda = \sinh(\tau\sqrt{\ln 4})/(\sigma\tau\sqrt{\ln 4})$, E_0 the peak position, σ the width, and τ the tail parameter. As a result of this fit, the energy resolutions were obtained as 1.3% and 1.4% for the 5×5 PWO and CsI(Tl) crystal matrices at 1 GeV photons, respectively.

Fig. 2 shows simulated energy resolution results for PWO and CsI(Tl) crystal matrices as a function of the incident photon energy. These results are consistent with the previous studies [14,15]. The resolution of the simulated response function includes the effect of the shower fluctuations and the leakage out of the crystal volumes. A larger crystal matrix size significantly improves the energy resolution since the transverse leakage dominates at energies below 1 GeV. Mostly the shower leakages in the transverse directions outside the crystal matrix contribute to stochastic term while the shower leakages from back of the crystals contribute to constant term. In order to estimate the photostatistical

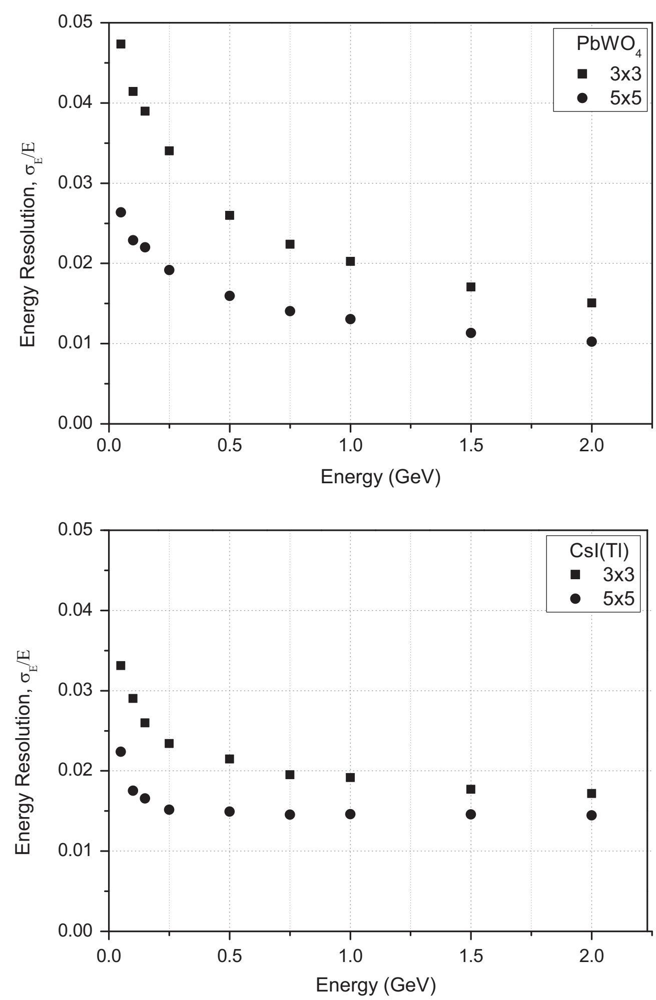

Fig. 2. Energy resolutions as a function of incident photon energies for PWO and CsI(Tl) crystal matrices.