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Simulation work on calorimetric energy resolution for the TAC-PF Detector

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Abstract. According to the Turkish Accelerator Center (TAC) project, a tau-charm factory is proposed based on colliding a 1 GeV electron beam against a 3.5 GeV positron beam. The Particle Factory (TAC-PF) detector will be constructed for the detection of the producing particles from this collision. $PbWO_4$ and CsI(Tl) crystals are considered for the construction of the electromagnetic calorimeter. The photons generated from incident particles in the crystal material are detected by Avalanche photodiodes (APD) or PIN photodiodes placed at the end of the crystal. In this work, the contribution to the calorimetric energy resolution from both the shower fluctuations in the crystal and photoelectron statistics in the detectors have been simulated for $PbWO_4$-APD and $PbWO_4$-PIN combinations.

1. Introduction

The Turkish Accelerator Center project was started as a regional facility for accelerator based fundamental and applied research [1]. The project has been ongoing by eleven Turkish Universities collaboration with the support of State Planning Organization (DPT). The TAC project will include: light sources (synchrotron radiation and free electron laser), an electron-positron collider, a GeV scale proton accelerator. A proposed tau-charm factory will be based on colliding a 1 GeV electron beam against a 3.5 GeV positron beam. This factory will have an important role in the TAC project for a deeper understanding of QCD, as well as for detailed investigations of new physics. On the other hand, detector design studies are ongoing for the factory.

Electromagnetic calorimeters made of the crystals have been used in many years for their good energy resolutions. For this reason, $PbWO_4$ (PWO) and CsI(Tl) crystals are considered to use for the electromagnetic calorimeter part of the TAC-PF detector. PWO is a high density inorganic scintillator with sufficient energy and time resolution. The drawbacks of this crystal are a high sensitivity to a temperature variation and poor light yield. CsI(Tl) is widely used in the calorimeters due to the its high light output, short radiation length, small Molière radius and good mechanical properties.

The crystals act as both the shower development medium and light producer. The produced photons from incident particles in these crystals could be detected from a Hamamatsu S2744-08 PIN photodiode or a Hamamatsu S8664-55 (S8148) avalanche photodiode (APD) which is attached at the rear end of the crystals. While Hamamatsu S2744-08 PIN photodiodes are used as photodetectors for the BaBar [2], BELLE [3] and BES III [4] CsI(Tl) calorimeters, Hamamatsu S8664-55 APDs are used for the CMS [5] PWO calorimeter. Active area of the PIN photodiode is 1 x 2 cm^2 and the thickness of depletion region is 300 μm. For the APD, active area is 5 x 5 mm^2 and the thickness of depletion region is 50 μm which have a 5 μm thick high field avalanche region and a 45 μm thick low field drift region [6]. Both type of the photodiodes can also be used as photodetectors for the proposed the TAC-PF electromagnetic calorimeter.

2. Calorimetric 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}) given as $a = a_{lateral} \oplus a_{pe}$. The lateral shower shape determines the distribution of the energy deposition in a cluster of crystals around the impact point. The photoelectron statistics contribution is related with fluctuations in the photodetector signal [7]:

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

Here, F is the emission weighted excess noise factor of the APD coming from the fluctuations in the avalanche gain process. Since the PIN photodiode has 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:

$$N_{pe} = N_{ph} \cdot QE \tag{2}$$

N_{pe} 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 and QE is the emission weighted quantum efficiency.

3. Simulation and Results

Geant4 simulation code [8] has been used to simulate photons at the different energies passing through the PWO crystals. The PWO crystal has a 200 mm length with cross section 20x20 mm^2 (22X$_0$). Photons in the energy region from 250 MeV to 2 GeV were injected into the central crystal of the matrice as shown in figure 1.

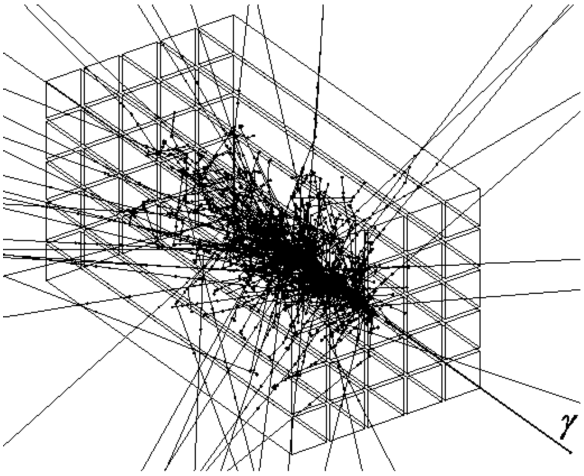

Figure 1. Electromagnetic shower for a single incident photon at 2 GeV

The energy of the incident particle is deposited in active medium of the crystals. Figure 2 shows the energy deposition spectra in PWO crystal matrices, at 2 GeV for example, obtained in the nine and twenty-five crystals.

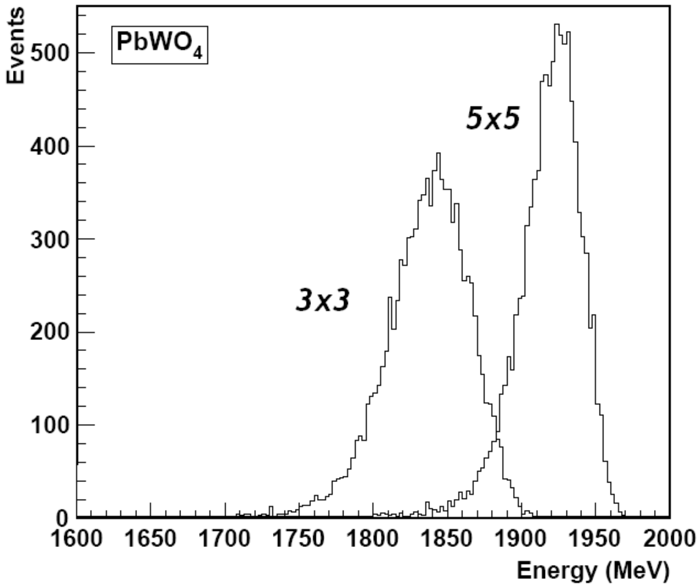

Figure 2. Energy spectra of PWO crystal matrices for 2 GeV photons injected into the center of the central crystal.

The energy resolution (σ_E / E) can be directly obtained from the simulated response functions as shown in figure 2. Figure 3 shows simulated energy resolutions for PWO crystal matrices as a function of incident photon energy. The resolution of the simulated response function includes the effect of the shower fluctuations and the leakage out of the crystal volumes. 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. Monte Carlo simulations show that the shower leakages for 5x5 PWO crystal matrix contribute to constant term 0.5%. The results are consistent with Ref. [9].

Monte Carlo simulations show that shower fluctuations give a contribution of 1.11% to stochastic term for 5x5 PWO crystal matrix. To estimate the other major contribution in the stochastic term we need to know the excess noise factor for the crystal-APD combination and the photoelectron yields. Combining these contributions we would estimate the stochastic term. The emission weighted APD excess noise factor has been calculated as 2.2 for the PWO emission spectrum. Here, the wavelength-dependent APD excess noise value obtained from Ref. [10]. In order to get photoelectron yields contribution to the stochastic term, photons at 1 GeV energies were also injected from the front side of the crystal. The photons produce charged particles in the crystal which interact with the crystal and emit scintillation photons. The number of collected photons at the rear end of the PWO crystal are 71 photons/MeV. The number of primary photoelectrons (N_{pe}) in the photodetector can be calculated by considering back face cross section of the crystals, active area of a pair photodetectors and quantum efficiency of the photodetector. The emission weighted APD and PIN quantum efficiencies have been calculated as 77% and 61% for the PWO emission spectrum at the rear end of the crystal. The calculated emission weighted quantum efficiency value for the crystal-APD system is consistent with the experimental measurements given in Ref. [5]. So the photoelectron statistics contributions on the stochastic term have been calculated as 1.8% for PWO-APD, 0.48% for PWO-PIN combinations by using Eq.1.

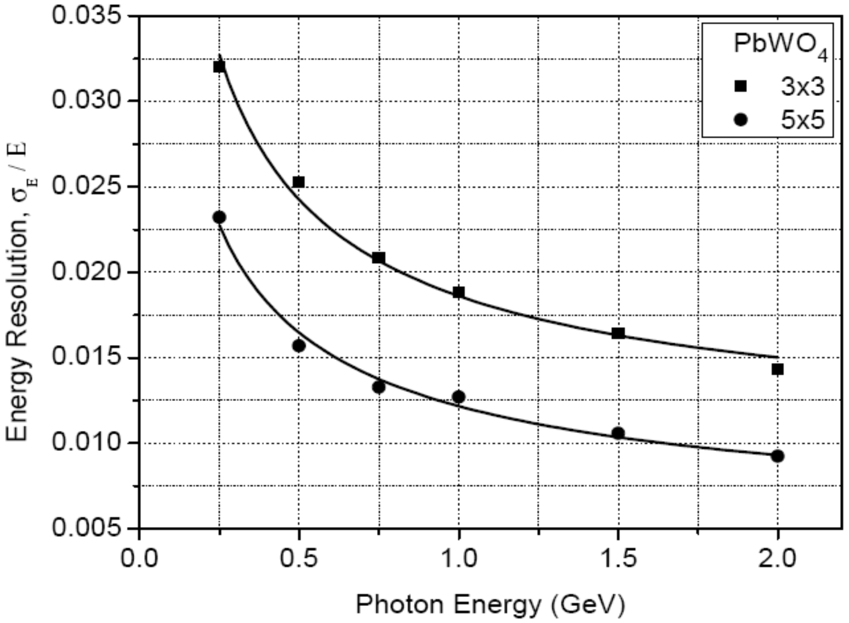

Figure 3. Energy resolutions as a function of incident photon energies for PWO crystal matrices. Results of Geant4 simulations incorporate only the pure energy deposit. Solid lines are the results of fits.

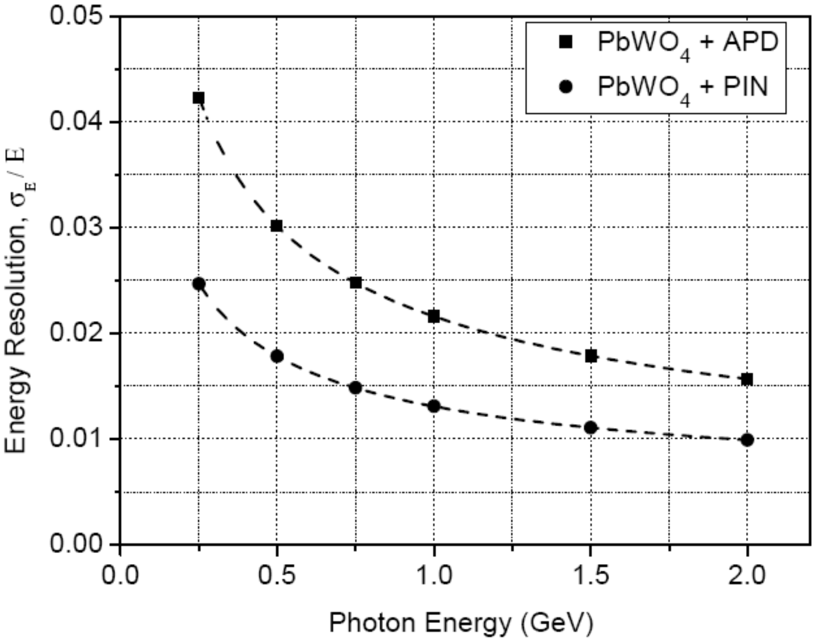

Figure 4. Energy resolutions as a function of incident photon energies for the different photodiode combinations.

Thus, the stochastic term have been calculated by adding photoelectron statistics contributions to the shower fluctuations and plotted in figure 4. Then results of the energy resolution have been obtained as $\sigma_E/E = 2.11\%/\sqrt{E} \oplus 0.5\%$ for the PWO-APD combination and $\sigma_E/E = 1.21\%/\sqrt{E} \oplus 0.5\%$ for the PWO-PIN combination.

As the APD has lower active area and bigger excess noise factor, the photoelectron statistics contribution to the stochastic term is bigger for PWO-APD combination. So that PWO-PIN combination gives better energy resolution values. In order to compare these results, similar studies should be made for CSI-APD and CSI-PIN combinations for the TAC-PF electromagnetic calorimeter.

Acknowledgment

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