Monte-Carlo simulation of a compact gamma-ray detector using wavelength-shifting fibers coupled to a YAP scintillation crystal*

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Abstract The production and transportation of fluorescent light produced in wavelength-shifting fibers (WSFs) coupled to YAP scintillation crystal is simulated using the GEANT4 codes. An advantage of the wavelength-shifting fiber readout technique over a direct readout with a position-sensitive photo-sensor is the reduced requirement for position sensitive photomultiplier tube photocathode area. With this gamma-ray detector, the gamma camera is small and flexible and has larger effective field of view and low cost. Simulation results show that a) a mean 12 of photons per 59.5 keV gamma ray interaction is produced in the WSF located nearest to the incident gamma ray, and a spatial resolution of 3.6 mm FWHM is obtained, b) a mean 27 of photons per 140 keV gamma ray interaction is produced and a spatial resolution of 3.1 mm FWHM is obtained. Results demonstrate the feasibility of this concept of a compact gamma-ray detector based on wavelength-shifting fibers readout. However, since the very low photoelectron levels, it is very important to use a photon counting device with good single photo-electron response to readout the WSFs.

Key words Monte-Carlo simulation, WSF, spatial resolution

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1 Introduction

Gamma cameras have been in wide use in the field of nuclear medicine. In recent years, considerable effort has gone into the development of compact gamma cameras in order to improve nuclear medical imaging[1, 2]. A small and flexible gamma camera with good spatial resolution would have widespread applications. To achieve clearer images, the gamma-ray detector of the camera should be small and flexible with good spatial resolution. At present, gamma-ray detectors for gamma cameras use planar crystals coupled to position sensitive photomultiplier tubes (PSPMT[3]), which provides better spatial resolution than gamma-ray detectors that use a conventional Anger camera[4]. However, the large light spread produced by the planar crystal produces distortion in the region (2 to 3 cm) near the PSPMT boundaries[5]. As a result, the effective field of view of the camera is relatively small and the spatial resolution is only 4 to 5 mm. Gamma cameras that use planar crystal coupling with position sensitive photomultiplier tubes also suffer from the PSPMT's relatively high cost per unit of photocathode area. In an attempt to address these issues, we are studying a gamma-ray detector where the position of interaction of gamma rays in a scintillation crystal is obtained by measuring the profiles of light trapped inside ribbons of wavelength-shifting fibers (WSFs) coupled to a planar crystal. The fibers are placed in orthogonal directions (X and Y) on each side of the crystal. By using a coincidence signal from the X and Y readouts, position information of gamma ray can be obtained. Compared with direct PSPMT readout, the wavelength-shifting fibers readout can decrease the required position sensitive photomultiplier tube photocathode area. In other words, the same area of PSPMT could be used for large image area. By using

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this gamma-ray detector, the gamma camera is compact, has a larger effective field of view and a lower cost. In this paper, a simulation model for a compact gamma-ray detector with WSFs coupled to planar scintillation crystal developed using the GEANT4 codes is described. The performance is assessed in terms of mean number of photons and spatial resolution.

2 Materials and description of the simulation

2.1 YAP and WSF and PSPMT

YAP: Ce scintillation crystals are already used in high-resolution gamma-ray imaging applications[6]. YAP: Ce exhibits a fast scintillation, a high light yield and very good mechanical and chemical properties. Its emission spectrum peaks at ∼370 nm and its scintillation decay time is ∼30 ns. The light output is about 17000 photons/MeV. It also has a higher density and higher effective atomic number than NaI(TI), so thin slabs can be used. It can focus the produced light on to a small number of fibers. The properties of this scintillator allow it to be used in gamma-ray imaging systems with very high spatial and time resolution for nuclear medicine applications. The size of the YAP scintillation crystal in our simulation is 20 mm×20 mm×4 mm.

WSFs are widely used in high-energy physics to concentrate light from large areas onto smaller photosensors. The SCSF-38 WSFs[7] has an absorption spectrum that peaks at ∼390 nm and an emission spectrum that peaks at ∼440 nm. The WSF can efficiently absorb a short-wavelength incident photon, and then isotropically emit a secondary longer-wavelength photon. Since the WSFs absorption spectrum nearly completely overlaps the YAP emission spectrum, most of the light escaping from the YAP crystal is directly collected by the fibers. The core refractive index of SCSF-38 WSFs is 1.59, while that of the cladding is 1.49. The diameter of WSFs is 2 mm, and the length is 300 mm.

PSPMTs are opening new frontiers in the development of advanced position sensitive detectors for nuclear medicine, such as in Single Photon Emission Computerized Tomography (SPECT) and Positron Emission Computerized Tomography (PET). PSPMTs are based on the principle of multiplication of a charge cloud around the original position in which the photoelectron is generated on photocathode. The charge cloud had a wide intrinsic spread during the process of the multiplication inside the PSPMT. This results in a deterioration of the spatial resolution of the entire detector system. The type of PSPMT used in our simulation is the Hamamateu PSPMT R2486. This tube consists of a ϕ60 mm PMT with a bi-alkali photo cathode, 12 stages of proximity-mesh dynodes and a 16×16 crossed wire anode for X and Y position respectively. The R2486 has a quantum efficiency of about 20% at 440 nm and a photoelectron collection efficiency of about 65%. The gain is 10^5 for an applied high voltage of 1250 V. The intrinsic spread of the charge cloud during the process of the multiplication is 4 mm (FWHM)[8].

2.2 Description of the simulation

The simulation uses the GEANT4 program library developed at CERN. The geometric description of the simulation prototype is shown in Fig. 1. Two ribbons of SCSF-38 WSFs are coupled via a silicone gel to opposite sides of a YAP slab. In our previous simulation studies[9], we confirmed that the number of photons is higher when silicone gel is used to couple the fibers to the crystal. Each ribbon has 10 WSFs. The fiber ribbons are placed in orthogonal directions (X and Y) on each side of the crystal in order to provide position information for both dimensions. The top surface is X (WSF-X) and the bottom surface is Y (WSF-Y). Since we only read out one end of each fiber, the other end was aluminized to improve light collection at the PSPMT.

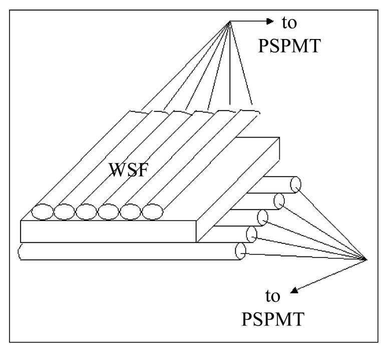

Fig. 1. A schematic diagram of the simulation prototype.

In the simulation, the beam of gamma rays is propagated perpendicularly into the crystal. The simulation program is carried out as follows: (1) Tracing the ith gamma-ray event and marking the interaction coordinates; (2) Calculating the energy deposit of the secondary electrons; (3) Converting the deposited energy to scintillation photons that propagate isotropically; (4) Some of photons are absorbed by the WSFs and reemitted isotropically; (5) Tracing the scintillation photons according to the Fresnel relations until they hit the photocathode of PSPMT and are converted to photoelectrons with a quantum efficiency of 20% and a photoelectron collection efficiency of 65%; (6) The produced charge cloud will multiply until they hit the cross wire anode inside the

PSPMT, which has an intrinsic spread of 4 mm; (7) Calculating the coordinate of the charge cloud centroid (x_{ij}, y_{ij}); (8) Recording the coordinate of the charge cloud centroid (x_{ij}, y_{ij}) and the interaction coordinate of the ith gamma photon, calculated with the formula $X_i = \sum_{j=1}^{m_i} x_{ij} \Big/ m_i$, $Y_i = \sum_{j=1}^{m_i} y_{ij} \Big/ m_i$. Here m_i is the total count of the photoelectrons that are detected in the ith gamma-ray event. The transmission of the light during the propagation is as follows: An incident photon interacts with the YAP crystal and deposits some of its energy and produces scintillation light. Some of the scintillation light is absorbed by the WSFs followed by isotropic emission of photons with a longer wavelength. Depending on the relative angle with respect to the fiber axis, a fraction of the re-emitted photons are trapped inside the WSF and piped to the fiber ends. At last, the photons strike the photocathode of the PSPMT and liberate photoelectrons. All the light transmission efficiencies during the propagation are summarized in Table 1.

Table 1. Summary of the expected light transmission efficiency in the YAP-fibers system.

energy deposit efficiency	50%
escaping from the YAP surface (light not absorbed in YAP)	85%
light transmitted at the YAP-silicone gel interface	93%
light transmitted at the silicone gel-fiber interface	93%
YAP emission-fiber absorption overlapping	84%[10]
fiber quantum efficiency	80%[10]
fiber trapping efficiency in air	18.5%[10]
escaping from the fiber end (light not absorbed in fiber)	25%[10]

3 Results and discussion

In order to study the effect of the gamma ray energy, we made simulation studies where 100 000 59.5 keV gamma-ray events and 100 000 140 keV gamma-ray events enter the surface of a crystal perpendicularly with coordinates of (11 mm, 11 mm), respectively. Thus, the interaction position is approximately located above WSFs-X_6 and WSFs-Y_6.

3.1 Mean number of photons produced by WSFs

Figure 2(a) shows the number of photons trapped in the WSF nearest the incident 59.5 keV gamma ray; the mean value is 12. Fig. 2(b) shows the same distribution for 140 keV gamma ray; here the mean number of trapped photons is 27.

From Fig. 2, the following conclusions can be obtained: (1) A mean 12 of photons per gamma ray interaction of 59.5 keV and a mean 27 of photons per gamma ray interaction of 140 keV is produced in the corresponding WSF located nearest the beam of gamma rays. By using a quantum efficiency of 20% and a photoelectron collection efficiency of 65% of the PSPMT, we infer the mean numbers of photoelectrons on the photocathode are 1.6 and 3.5. This shows both the detection efficiency of this arrangement for 59.5 keV and 140 keV gamma ray is very low. Because of the very low photoelectron levels, it is very important to use a photon counting device with good single electron response to readout the WSFs. (2) Near the hit point of gamma ray only few of WSFs contain position information. This improves the spatial resolution of the gamma-ray detector when the position of the gamma ray interaction is determined by a centroid calculation. (3) The mean number of photons detected is higher for 140 keV gamma ray that strike perpendicular to the surface of the crystal. In addition, the distributions of mean number of photons are narrower. In our subsequent simulation study we could confirm the spatial resolution is improved for 140 keV normally incident gamma ray. This demonstrates the importance of increasing the mean number of photons and of reducing the width of the light distribution over the WSFs.

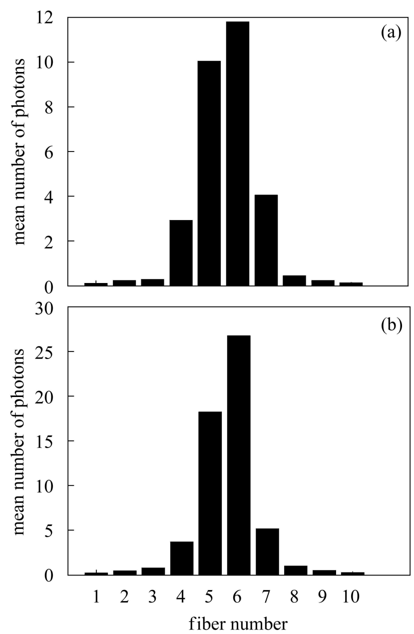

Fig. 2. Mean number of photons produced by WSFs on coordinate of (11 mm, 11 mm): (a) 59.5 keV and (b) 140 keV.

3.2 Spatial resolution

Figure 3 shows the image obtained for 59.5 keV gamma rays. The interaction position is located approximately above WSF-X_6 and WSF-Y_6. Fig. 4 shows the Point Spread Function (PSF) of 59.5 keV gamma rays. By fitting a Gaussian curve to the Point Spread Function of the image, a spatial resolution of 3.6 mm FWHM is obtained for both the x and the y directions.

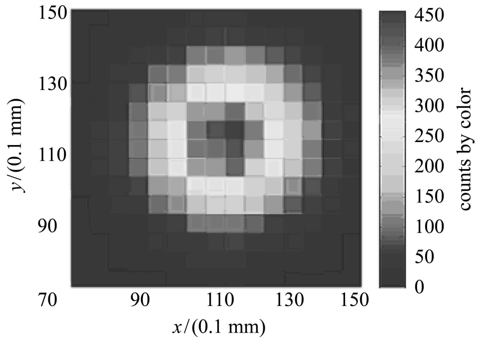

Fig. 3. Image of 59.5 keV gamma rays.

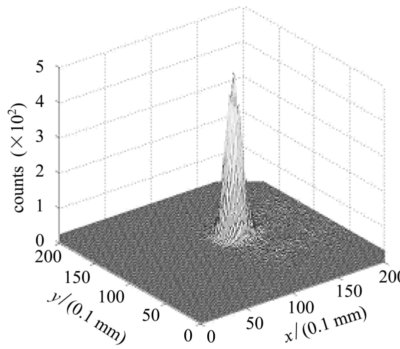

Fig. 4. Point Spread Function of 59.5 keV gamma rays. A spatial resolution of 3.6 mm FWHM is obtained.

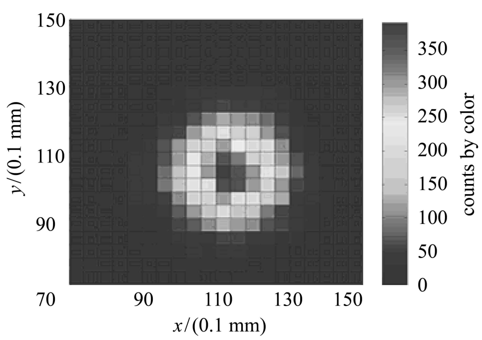

Fig. 5. Image of 140 keV gamma rays.

Figure 5 shows the image obtained for 140 keV gamma rays. The interaction position is located approximately above WSF-X_6 and WSF-Y_6. Fig. 6 shows the Point Spread Function (PSF) of 140 keV gamma rays. A spatial resolution of 3.1 mm FWHM is obtained for both the x and the y directions, which demonstrates the importance of increasing the mean number of photons and of reducing the width of the light distribution over the WSFs. It also shows that the spatial resolution is mainly determined by the light spread over the WSFs ribbons when the position of the gamma ray interaction is estimated by a centroid calculation.

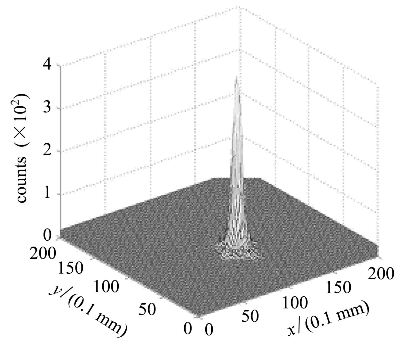

Fig. 6. Point Spread Function of 140 keV gamma rays. A spatial resolution of 3.1 mm FWHM is obtained.

4 Conclusions

A compact gamma-ray detector using wavelength-shifting fibers coupled to a YAP planar scintillation crystal has been studied via computer Monte-Carlo simulations. Results demonstrate the feasibility of the concept of the compact gamma-ray detector based on wavelength-shifting fibers readout. However, since the photoelectron levels are very low, it is very important to use a photon counting device with good single electron response to read out the WSFs (The 64 channel Hamamatau H8500 Flat Panel PMT based on a metal channel dynode for electron multiplication, for example). Spatial resolutions of 3.6 mm FWHM for 59.5 keV gamma rays and 3.1 mm FWHM for 140 keV gamma rays are obtained The simulations also demonstrate the importance of increasing the mean number of photons in order to achieve better spatial resolution. An immediate way of increasing the number of photons is by coupling both ends of the WSFs to the PSPMT. In the future Monte-Carlo simulations, we will continue to investigate such optimizations, using a variety of scintillators, wavelength-shifting fibers, and photosenors.

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