Monte-Carlo simulation to determine detector efficiency of plastic scintillating fiber

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Abstract Fundamental characteristics of the plastic scintillating fiber (PSF) as a detector for electromagnetic radiation (X & γ) are obtained by GEANT4 detector simulation tool package. The detector response to radiation with energy of 10~400 keV is found out. Energy deposition as well as detector efficiency (DE) of the PSF are studied. In order to make linear array of the PSF for imaging purpose, the optimum length of fiber is also estimated.

Keyword Plastic scintillating fiber, Imaging, Detector’s quantum efficiency, Geant 4.
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1 Introduction

The plastic scintillating fiber (PSF) has many applications in different fields such as particle tracking in high-energy particle physics, calorimeters, etc., but using PSF as an imaging detector is the main goal of this research. Therefore, we selected 10~400 keV mono-energy electromagnetic radiation that is used in medical and non-medical imaging (e.g. non destructive testing).

Some scintillation characteristics of plastic scintillating optic fiber have been discovered by experiment.[1] We tried to use the properties of the typical round PSF which is available in market such as BCF-20 (supplied by Bicron Corporation) having a diameter of 0.25 mm. All material compositions used in the simulation code are according to information released by Bicron Company.[2] The peak wavelength of scintillation light is 492 nm.[3] The experimental setup defined in Geant 4 simulator is shown in Fig.1. The radiation source is treated as a point source.

2 Scintillation characteristics of PSF

In order to estimate the optimum length of the fiber, we irradiated it along its axis under different energy of incident photon. As it is shown in Fig.2, the energy deposit reaches to a saturation level when the length of fiber is more than 10~12 cm. This is in good agreement with the experiment which was done some time ago.[4]

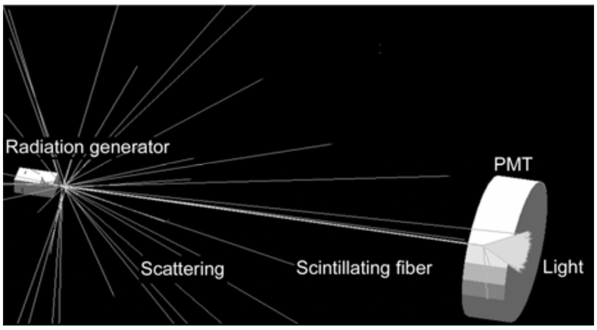

Fig.1 Experimental setup defined for simulation

To avoid poor spatial resolution of the image, the length of the fiber, or in the other word, the length of the detector must be as small as possible, so according to Fig.2 it is no need to use long fiber for increasing energy deposition. In fact, at low energy most of the particles would loss their full energy via photoelectric interaction in a few centimeter after passing through the fiber, and for a little bit high energy the secondary particles created via Compton interaction would leave the fiber.

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As a next step we tried to find out how the intrinsic efficiency of the scintillating material would vary under different incident gamma energies. The results are shown in Fig.3.

The core material of the fiber (polystyrene) is a light material, so we can see, from Fig.3 that, even for low energy (10 keV) the efficiency of the PSF could not be more than 85% and it falls down rapidly when energy of incident gamma ray is going to be larger than 100keV.

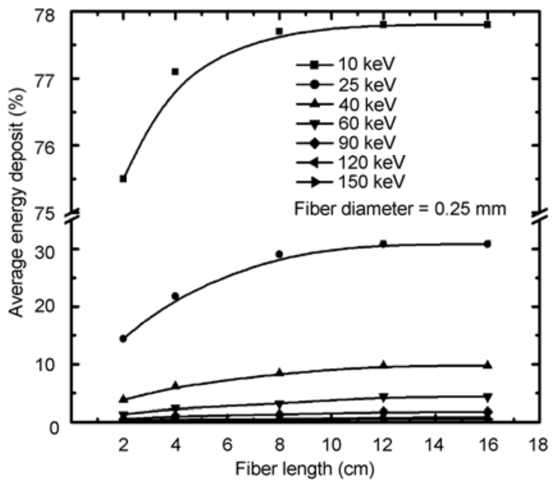

Fig.2 Determination of the optimal fiber length for different energies of incident photons

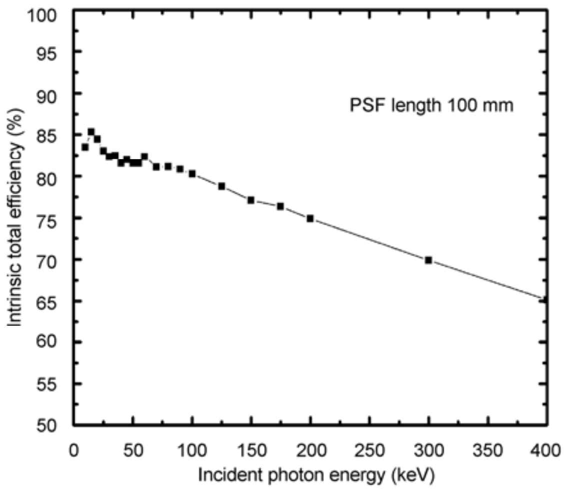

Fig.3 Total intrinsic efficiency of the PSF with 0.25 mm diameter

Obviously, dominant interaction at low energy is photoelectric effect and the peak to total ratio of the interaction help us to better understand this matter. This is shown in Fig.4 for different lengths of fiber.

3 Quantum efficiency (QE)

Quantum efficiency, or the overall scintillating detector efficiency, is defined as QE = (scintillation output energy) / (photon input energy), or QE=$T_a T_c T_t$ where T_a is the absorption efficiency, defined by the ratio of absorbed photon energy to incident photon energy; T_c is the light conversion efficiency, defined by the ratio of generated scintillation light energy to absorbed photon energy; and T_t is the transmission efficiency, defined by the ratio of output scintillation light energy to generated light energy.[4]

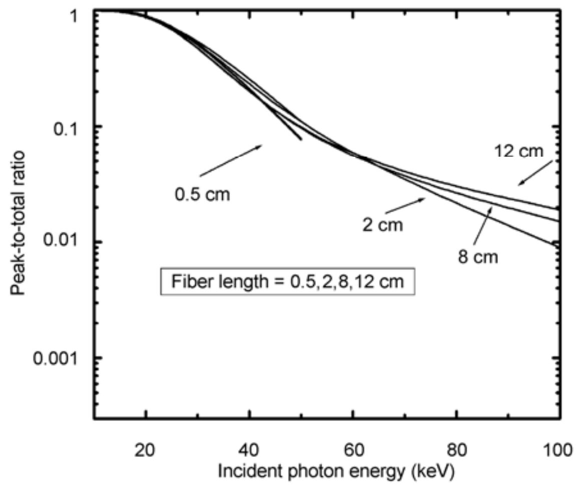

Fig.4 Peak to total ratio

We obtain the energy deposit for various incident photon energy in plastic scintillating fiber from the output of Geant 4 program, so we could consider their ratio as T_a. Fig.5 shows that the minimum percentage

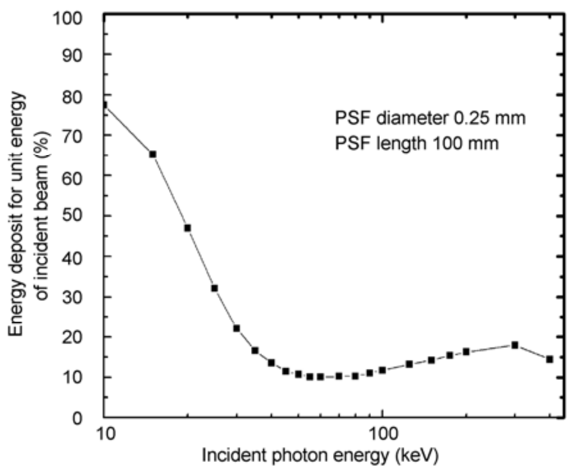

Fig.5 Percentage of energy deposit for unit energy of incident gamma ray

of energy deposit would occur in the energy range of 50~80 keV.

Small fraction of the kinetic energy is got lost due to the charged particle in scintillation being converted into fluorescent energy. The remainder is dissipated nonradiatively, primarily in the form of lattice vibrations and heat.[5] For BCF-20, the energy of the visible photon is 2.5eV. By multiplying this value by the total number of photons produced in the fiber, one can find the fraction of the kinetic energy converted into light energy. For all scintillators, the scintillation efficiency or amount of light generated per unit energy loss (dL/dE) depends on both particle type and its kinetic energy. In the ideal case dL/dE would be a constant independent of the particle energy.

The total light yield will then be directly proportional to the energy of incident particles and the response of the scintillator would be perfectly linear.[5]

The light photons in fiber emitted by the interaction are distributed isotropically. All the photons in solid angle θ (critical angle) could be trapped by the fiber. With the values of the refraction indexes of the fiber core and cladding, one can easily derive the trapping efficiency of the fiber from formula T_{trap}=[1-(n_{clad} / n_{core})]/2. The refraction indexes of our fiber (BCF-20) are n_{core}=1.6 and n_{clad}=1.49 respectively. So the trapping efficiency of the fiber would be 3.4%. In addition the light energy transmitted along the fiber to the photo-detector is attenuated by absorption in the fiber core and light scattering.

We have to notice that only small amount of light photons would be trapped into fiber due to internal conversion phenomenon. The output light, which is obtained from program code, is the attenuated light trapped into fiber and traveling along the PSF. Then the output light efficiency should be $T_c \cdot T_t$.

By linear fitting of the curve in Fig.6, we get the average value of the $T_c \cdot T_t$ being about 0.9 (light photon per unit energy of photoelectron).

Now we are able to get QE of the PSF. Fig.7 shows the QE for different energy of the incident beam. As it is seen from Fig.7, the main line shape of the QE is very similar to that in Fig.5, so the main important factor in quantum efficiency of the detector is the absorption efficiency of the scintillating material. On the other hand, $T_c \cdot T_t$ is almost constant in the incident photon energy range of 10~400 keV.

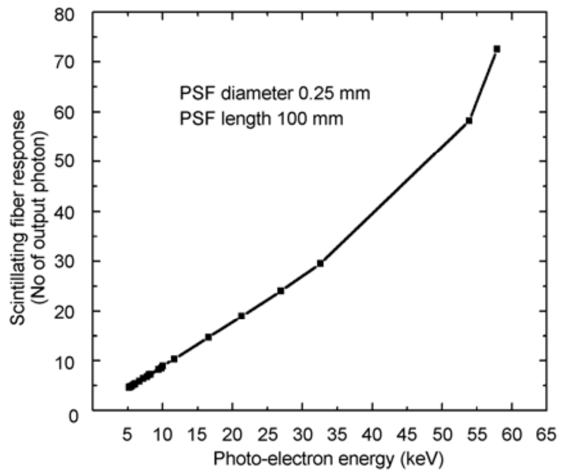

Fig.6 Scintillator response versus energy of photo-electrons

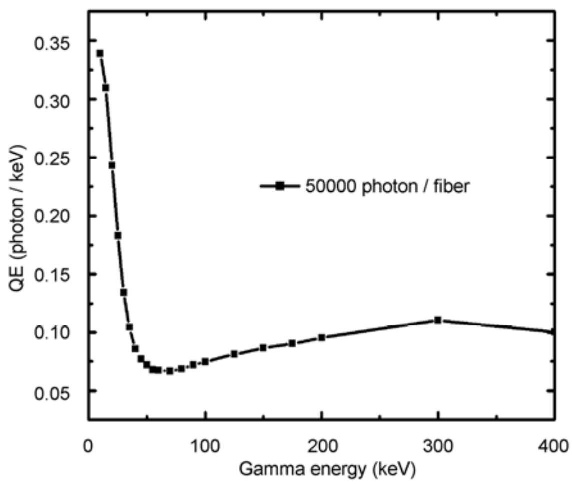

Fig.7 Quantum efficiency

In this research we did not consider the photosensitive detector efficiency. But each photosensitive detector such as photomultiplier or CCD has its own detective efficiency value, that can finally make the quantum efficiency of whole imaging system further worse.

4 Results and discussion

In summary, the detector efficiency of scintillating fiber for incident X-rays in very low energy of 10~40 keV is higher than that in higher X ray energy region. It means that PSF with very low incident X ray energy is a good detector for taking image of small specimen or soft and thin tissue. Although the QE value is improved a little bit with incident gamma ray energy around 300 keV, we must notice the small ratio of signal to noise, and take into account stronger effects from Compton scattering of the gamma ray at high energy region.

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