Monte-Carlo simulation for determining SNR and DQE of linear array plastic scintillating fiber

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Abstract Fundamental characteristics of the plastic-scintillating fiber (PSF) for wide energy range of electromagnetic radiation (X & γ) have been studied to evaluate possibility of using the PSF as an imaging detector for industrial purposes. Monte-Carlo simulation program (GEANT4.5.1, 2003) was used to generate the data. In order to evaluate image quality of the detector, fiber array was irradiated under various energy and fluxes. Signal to noise ratio (SNR) as well as detector quantum efficiency (DQE) were obtained.

Keywords SNR, DQE, Scintillating fiber array, Imaging detector
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1 Introduction

Radiation imaging detector can be designed in either one or two dimension. Each kind of them has its own advantages and disadvantages. One of the advantages of linear array detectors is its less effects of scattering and crosstalk between pixels. These two effects are very important to make an image with high or low quality. This is the main reason for choosing linear array in our research.

So these effects can be shown in contrast and spatial resolution, which are crucial criteria to evaluate the quantity of an image. GEANT4 allows us to trace light photon, which is created via scintillation process in PSF. Then the light photons, which reach to photosensitive detector (such as PMT and CCD), can be taken into consideration to calculate the output signal and noise of the detector. The properties of the PSF in this simulation work are almost the same as BCF-20.[1] The BCF-20 is a round fiber, which has 0.25 mm diameter and emits 2.5 eV green light. So pixel size is almost enough for NDT application and also we do not need to take care of the rate of the radiation dose. To avoid high scattering radiation from object under investigation, linear array receptor (slit scan detectors) is a good choice in industrial imaging, especially CT-scan, and utilization of the fan beam. As is well known, one should spend some time with several shoots of the X-ray tube to take an industrial CT image. Because of the efficiency variation of the tube, it is better to use a stable source with a good collimation for this imaging device. Therefore, in our virtual experiment we used mono-energetic source of radiation with a fan shape. It means we ignored any unstable states of the source.

2 SNR and DQE

In any radiation imaging systems, signal and noise always play an important role in shaping final image. According to the nature of photon emission of the source, there is an uncertainty in the amount of radiation exposed on a unit of detection area. In addition, object contrast has a strong effect on SNR. The dominant factors, which determine the SNR, are the number of photons transmitted through the objective, the absorption efficiency of the detector and the utilization of the captured photons to record the image.[2] SNR can be defined for both input information to the detector ($SNR_i = S_i / N_i$) and output information from

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the detector ($SNR_o = S_o / N_o$), where S_i, N_i and S_o are the average number of input quanta, the r.m.s. value of the input noise and the average number of output quanta, respectively, while N_o is the r.m.s. value of the output noise.[3]

In above definitions of SNR_i and SNR_o we are dealing with the statistics of the input photon flux (number of incident photons) and the output quanta (number of interacted particle or good events). The number of good events or the particle-induced interaction with scintillating material is dependent on both photoelectric effect (PE) and Compton effect (CE) of low and medium energy gamma rays. The fluctuation of energy absorption causes noise. Indeed, absorption noise is also one of the effective parameters in imaging process. It means that if one could separate PE from CE in output signals, then it could be possible to measure absorption noise (there is no characteristic X-ray in our energy region of interest for this kind of fiber).

The detector quantum efficiency is a very useful parameter of the imaging detectors. If one gives care to the quantity of the radiation quanta and the fluctuation of the signal and noise, then the only source of noise in the image would be fluctuations in the number of impinging photons with a Poissonian distribution. Eq.(1) is a good expression for the definition of DQE:

$$DQE = (SNR_o)^2 / (SNR_i)^2 \qquad (1)$$

The other approach is to determine the absorbed energy of the incident beam and its relation with the output photons. For scintillating fiber under investigation in this work, we attempted to find out, in addition to the DQE defined by Eq.(1), the DE (detector efficiency)[4] that could be expressed as

$$DE = T_a \, T_c \, T_t \qquad (2)$$

where DE simply means the scintillation output (light) energy over photon input (X or γ) energy; T_a, T_c and T_t are absorption, conversion and transmission efficiencies, respectively.

Of course both of the DQE and DE in Eq.(1) and Eq.(2) are defined for a single pixel of the detector and here, a pixel corresponds to one fiber. In general, DQE is always less than one (DQE < 1), i.e. the detector quantum efficiency of a real detector is always less than that of an ideal detector (for ideal one DQE = 1). The contrast in image is particularly important to evaluate quality of the image.

The main goal for measuring DQE is to study capability of the detector to show different contrast of the imaged object and also to evaluate the behavior of noise in the system and final image (quantum mottle).

3 Virtual experiment set-up

Fig.1 shows the experiment set-up defined in GEANT4.[5] It is seen that a fiber array has been arranged in a trapezoid shape so the angle between every two fiber is fixed. Indeed the short source to fiber distance (SFD=20cm) is the only reason to select trapezoid shape for arranging the fibers. The length of the fiber is 10cm (optimum length for fiber[6]).

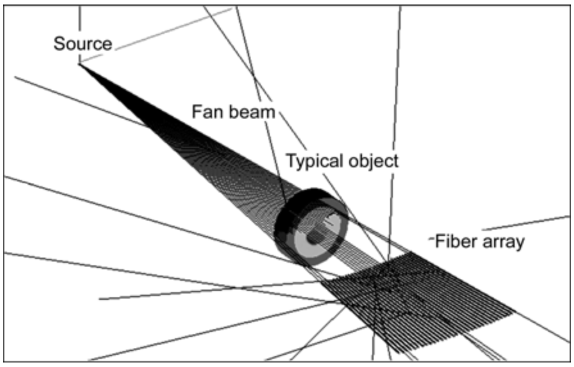

Fig.1 Experiment set-up.

4 Results and conclusion

The fiber array was irradiated by gamma rays with different energies and various fluxes. Fig.2 shows the fluctuation of signal and noise for 1000 gamma particles with 50keV energy that exposed straight to center of the fiber.

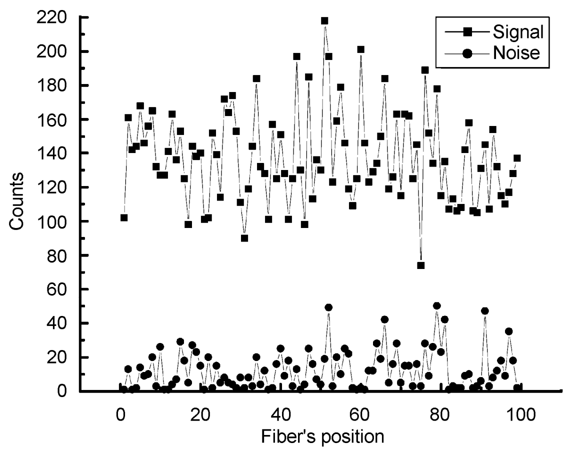

Fig.2 Fluctuation of the signal and noise in fiber array.

Relative uncertainty or the ratio of noise to signal for different dose rate is shown in Fig.3. In general, for fiber array detector the relative uncertainty for high photon energy and especially for low flux is far from an ideal detector. According to Fig.3 for high dose rate, uncertainty can be almost constant over a wide range of photon energy (20~200keV).

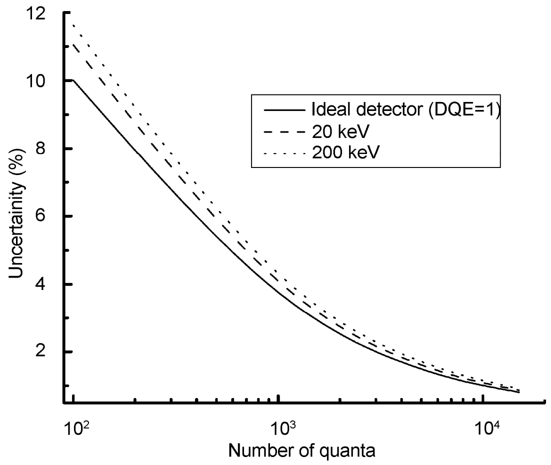

Fig.3 Relative uncertainties of fiber array detector for different photon energies in comparison with ideal detector

Fig.4 represents the variation of SNR_o with the dose rates. With increment of photon energy, SNR_o decreases quantitatively. Therefore, we can conclude that the imaging system with low energy and high fluxes of incident gamma ray can present better SNR_o.

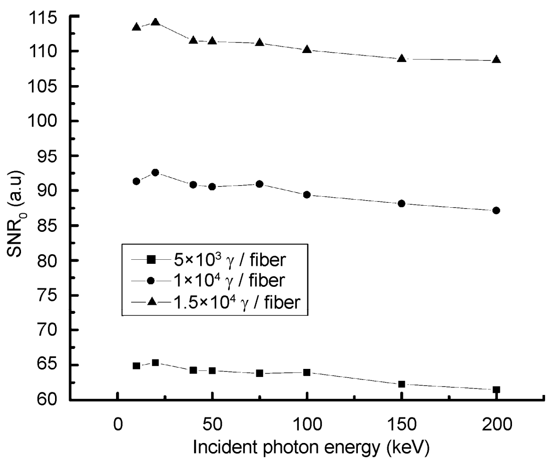

Fig.4 Output signal to noise ratio for different energies.

Eq.(1) shows that our DQE is defined at zero frequency for the imaging detector. DQE is dependent on the average input signal, because when the intensity of signal is increased, the detector noise becomes more and more insignificant (assuming Poisson statistics for the incoming quanta) and DQE approaches to its maximum.[7] Fig.5 shows the variation of DQE with incident photon energy. At low photon energy up to about 60keV, DQE can increase significantly with increment of flux. For the photon energies from 60keV to about 150keV, the DQE's discrepancies for different flux values are relative small. But when the photon energy is higher than 150keV and flux is 1.5×10^4 γ (quanta)/fiber, the DQE is going to be better.

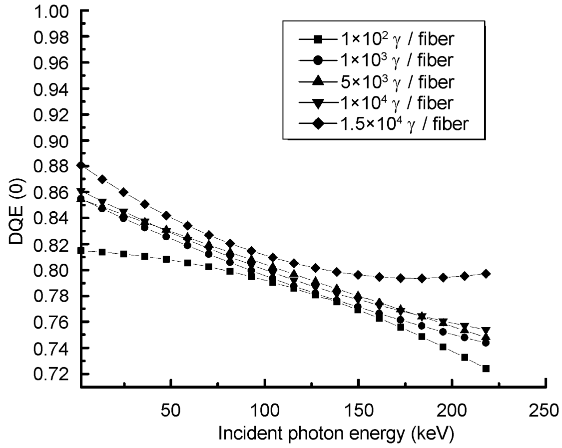

Fig.5 Variation of DQE (0) under different exposures with the photon energy

In order to find out the behavior of the fiber under various exposures and energies of the incident gamma ray, we irradiated the fiber in different conditions. According to Eq.(2) DE (detector efficiency) can be determined for each of the particular energy. Fig.6 shows that DE, which is defined as the number of output photons per unit energy of incident particles, is relative large at low photon energy but it is falling down very fast when increasing energy.

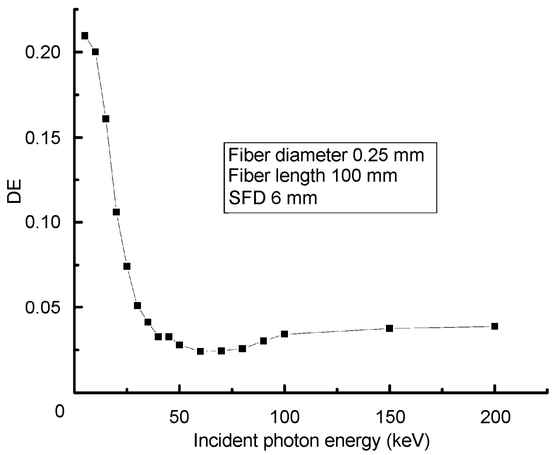

Fig.6 Detector efficiency versus incident photon energy.

The high DE at low photon energy can be attributed to the photoelectric effect. When the photon energy is higher than about 60keV, DE generally is low, although it can increase smoothly for a little high energy.

From simulation results, some conclusions have been extracted:

1) By adopting low energy (under 40keV) incident beam with high flux, we can get the better DQE at zero frequency.

2) There is no any significant variation in DQE under different exposures for energy range of 60~150keV.

3) The poor detection efficiency or the number of output light photons is the main problem for PSF and the situation will be improved by using an image intensifier.

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