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Some characteristics of X-ray imaging for energy region of over 100 keV using plastic scintillation fiber array

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Abstract In this work, characteristics of using PSFs (plastic scintillation fibers) coupled with CCD (charge-coupled devices) to build area detectors for high energy X-ray imaging are studied with a Monte Carlo simulation, which cover an energy range of a few hundred keV to about 20 MeV. It was found that the efficiency of PSF in detecting X-ray with energy above a few hundred keV is low. We can use large incident flux to increase the output signal to noise ratio (SNR). The performance can also be improved by coating PSF with X-ray absorption layers and the MTF of the system is presented. By optimizing the absorption layer thickness, the crosstalk of the area detector built with PSF decreases.

Key words Plastic scintillating fiber (PSF), X-ray imaging, Geant4, Signal to noise ratio (SNR), Cross talk

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1 Introduction

Digital X-ray imaging, as an important diagnostic and characterizing tool, has been increasingly used in many fields such as medicine, biology, security, industrial testing and evaluations.[1] The most commonly used detector for digital X-ray imaging relies on scintillation technology. It converts X-rays into visible lights through scintillation materials and the lights are detected by a CCD imager.[2] To increase the efficiency or sensitivity, a thicker scintillation material is usually desired. However, an increased thickness of the scintillator would result in a larger isotropic spreading of light generated in the scintillation materials, hence a reduced spatial resolution of the imager.

An alternative approach in constructing an X-ray digital imager is to use plastic scintillating fibers (PSFs) to build an array plate that is directly coupled with a CCD.[3-5] In a scintillating fiber of the X-ray detector, a portion of light converted from incoming X-rays is channeled along the fiber through internal total reflection, and an Extra Mural Absorber (EMA) absorbs the remainder.[6] The scattered radiation via Compton scattering in the fiber causes a uniform background. Such a design, in principle, does not require any compromise of the length of fiber and the spatial resolution. More importantly, PSFs are flexible and can be easily built into an area detector with geometry best matched with the object to be imaged to achieve maximum efficiency.

Early results indicate that scintillating fiber arrays can achieve excellent imaging resolution and sensitivity for X-rays below 50 keV.[7] With further increase of the X-ray energy, the resolution and sensitivity deteriorates quite rapidly, due to insufficient absorption of the X-rays and cross talk between adjacent fibers.

Radiographic techniques, especially X-rays imaging, are historically and currently one of the most common methods of nondestructive evaluation (NDE). With the increasing demand of NDE for dense and large objects, great efforts are made to improve the performance of high energy X-ray (usually from a few

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hundred keV to about ten MeV) imaging system. In this work, we used Monte Carlo simulation to evaluate energy deposition and cross talk between the fibers of a scintillation fiber area detector for imaging X-rays in such energy region. We focus primarily on the approaches in enhancing the imaging feasibility of the fibers to hard X-rays.

2 Computer simulation

The simulation was carried out using a Monte-Carlo program, GEANT4, which is a toolkit package developed at the European Organization for Nuclear Research (CERN) for simulating performance of detectors used in nuclear and high energy physics experiments. The program, available on the Internet,[9,10] has been applied to other areas, such as fluid dynamics and medical physics.[8] It can be used to trace trajectories of particles and their interactions with the materials. After careful test, GEANT4 was used in this study and the results are consistent with those in Ref.[9].

When an X-ray enters a material, the photon interacts with the materials through physical processes of photoelectric effect, Compton scattering, Rayleigh effect, bremsstrahlung and ionization.[10] A set of models that describe behaviors of the low energy photons and electrons in matters has been implemented in the toolkit. A minimal energy for the particle-matter interactions is defined as the energy within the validity range of the model. Users can alternatively define a higher threshold for any specific application. Each run takes a few days to about one week on a PC.

A commercially available PSFs, BCF-20,[6,11] was chosen in our simulation. The results should be applicable to other PSFs as well.

3 Simulation results

The simulation covers a relative broad range of energy for incoming X-rays, in a hope to address several issues in our potential use of the scintillation fibers for high energy X-ray imaging.

In a radiation imaging system, signal to noise ratio (SNR) plays an important role in shaping the final image. According to the nature of photon emission source, there is an uncertainty in the amount of radiation hitting a unit of detection area. In addition, object contrast has a strong effect on SNR. The dominant factors to the SNR are the number of photons transmitting through the objective, the absorption efficiency of the detector and utilization of the captured photons to record the image. SNR can be defined for both input information to the detector ($SNR_i=S_i/N_i$) and output information from the detector ($SNR_o=S_o/N_o$), where S_i, N_i (S_o, N_o) are the average input (output) signal, i.e. the r.m.s. value of the input (output) signal or input (output) noise, respectively.[12] In the simulation, interaction of an X-ray photon with scintillation material generates a good event, and fluctuation in the energy absorption causes noise. Fig.1 plots SNR_o of a PSF array for different incident photon fluxes. We can see that the SNR_o increases with the incident flux and decreases with the incident photon energy.

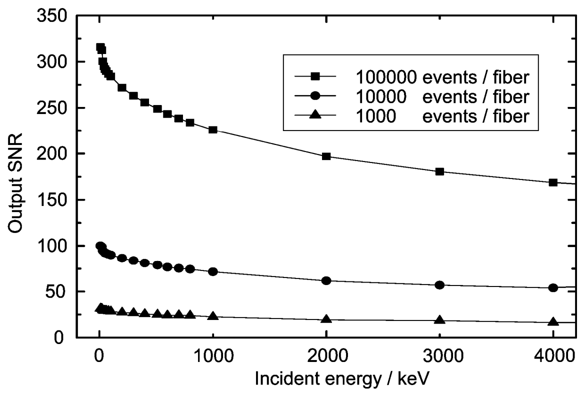

Fig.1 The output SNR of the fiber arrays versus incident photon energy, for different fluxes.

As were reported,[3,4,7] under certain circumstances scintillation fibers were used for low energy X-ray imaging. However, absorption efficiency of the fibers made of mainly low mass elements is greatly reduced for high energy X-rays. Incident photons penetrating the fiber may well enter neighboring fibers, causing cross talk effect between PSFs. And secondary photons generated in random directions inside a fiber may affect neighboring fibers, too. All these produce scintillating signals that are ultimately detected by the CCD to form images. The cross talk between neighboring fibers reduces spatial resolution of the detector and severe cross talk can even render the detector unusable in X-ray imaging.

In order to investigate the extent of cross talk in a fiber array detector, we calculated the total energy deposited in a single fiber as functions of the fiber length and diameter. Typical results are plotted in Fig.2. It shows that for 100 keV incident photons, the total energy deposited in the fiber saturates at about 15 cm, but the deposition percentage is only about 15%-22% in fibers of diameters ranging from 1 to 40 mm. This means that the cross talk effect is significant for hard X-ray photons. Above about 15 cm, the cross talk effect is almost independent of fiber length.

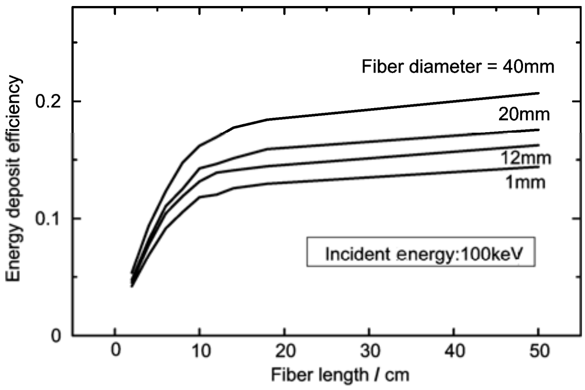

Fig.2 Energy deposition efficiency along fiber length in fibers of different diameters.

One way to reduce the cross talk effect is to coat PSFs with a layer of X-ray absorption material, such as lead. It may prevent secondary photons from passing through the boundary between two fibers. The cross talk ratio, which is defined as energy deposition divided by that in neighboring fibers, for different incident energies are illustrated in Fig.3 and Fig.4, as the function of fiber radius and lead thickness, respectively. One sees that the cross talk problem can be alleviated by coating the fibers with a thin layer of heavy metal.

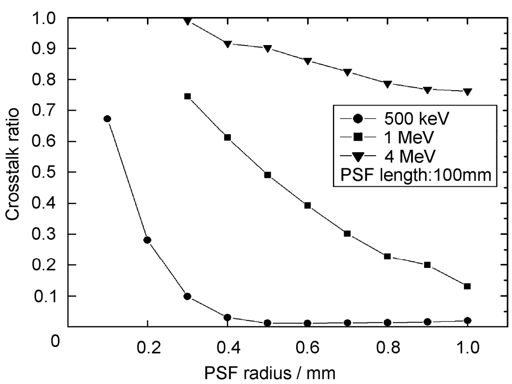

Fig.3 Cross talk ratio versus fiber radius for different incident energies.

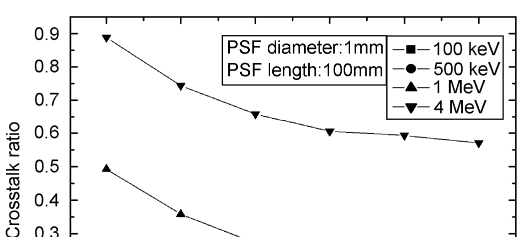

Fig.4 Cross talk ratio versus lead thickness for different incident energies.

In order to quantitatively describe the improvement in resolution by coating PSF with an absorption layer, one needs to calculate the Modulation Transfer Function (MTF) which is a measure of the response to imaging spatial frequency.[13] By definition, MTF is the Fourier transform of the Line-Spread Function (LSF)

$$\mathrm{MTF}(f)=\left|\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\mathrm{LSF}(x)\mathrm{e}^{2\pi i f x}\mathrm{d}x\right|$$

In our previous report[7], we found that MTF is almost independent of the energy of incident X-rays and the fiber length, but depends fairly strongly on the size of the fiber used. Fig.5 plots the MTF of detectors made of the same size of scintillation fibers but with different thickness of adsorption layers. As can be seen, when the lead layer thickness is 10 μm, the MTF is improved quite significantly. But with a layer thickness of 100 μm, the MTF deteriorates. This is because

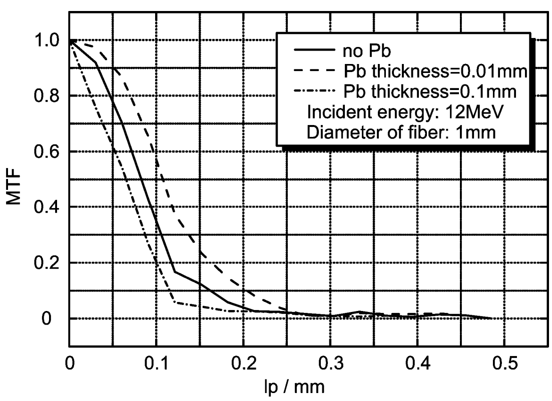

Fig.5 Simulated modulation transfer function (MTF) of a fiber array embedded in a lead matrix.

that a thicker coating layer reduces the effective detecting area of the fiber array detector, which actually can be equal to increase the fiber diameters. These results show that coating PSF will improve the resolution of PSF array detector. However, there is an optimum thickness, above which the resolution will be worse, rather than better, in comparison with the results obtained using uncoated PSFs.

4 Conclusion

In summary, our simulation results demonstrate some characteristics related to plastic scintillation fiber array area detector used for hard X-ray imaging. Due to the low efficiency we can use large incident flux to improve the output SNR. In addition, the image resolution is strongly affected by the cross talks among PSFs in an array at this energy window. To improve the imaging resolution, simulation on imaging with PSFs coated with absorption layers were carried out. The results show that with coating layer, the imaging resolution can be improved. The coating material chosen in this study is lead. Other possible coating materials should be explored, especially those of scintillation materials doped with heavy metals. A more systematic study of several different approaches in improving the detecting efficiency of PSF array matrix is currently underway.

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