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Handy Compton camera using 3D position-sensitive scintillators coupled with large-area monolithic MPPC arrays

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ABSTRACT

The release of radioactive isotopes (mainly ^{137}Cs, ^{134}Cs and ^{131}I) from the crippled Fukushima Daiichi Nuclear Plant remains a serious problem in Japan. To help identify radiation hotspots and ensure effective decontamination operation, we are developing a novel Compton camera weighting only 1 kg and measuring just ~10 cm^2 in size. Despite its compactness, the camera realizes a wide 180° field of vision with a sensitivity about 50 times superior to other cameras being tested in Fukushima. We expect that a hotspot producing a 5 μSv/h dose at a distance of 3 m can be imaged every 10 s, with angular resolution better than 10° (FWHM). The 3D position-sensitive scintillators and thin monolithic MPPC arrays are the key technologies developed here. By measuring the pulse-height ratio of MPPC-arrays coupled at both ends of a Ce:GAGG scintillator block, the depth of interaction (DOI) is obtained for incident gamma rays as well as the usual 2D positions, with accuracy better than 2 mm. By using two identical 10 mm cubic Ce:GAGG scintillators as a scatterer and an absorber, we confirmed that the 3D configuration works well as a high-resolution gamma camera, and also works as spectrometer achieving typical energy resolution of 9.8% (FWHM) for 662 keV gamma rays. We present the current status of the prototype camera (weighting 1.5 kg and measuring $8.5 \times 14 \times 16$ cm^3 in size) being fabricated by Hamamatsu Photonics K. K. Although the camera still operates in non-DOI mode, angular resolution as high as 14° (FWHM) was achieved with an integration time of 30 s for the assumed hotspot described above.

1. Introduction

One year after Japan's nuclear disaster, a large amount of radioactive isotopes were released and still remain a serious problem in Japan. To help identify radiation hotspots that people should avoid, various gamma cameras are now being developed and undergoing careful field tests. One configuration, the so-called pinhole camera as seen in Fig. 1 (top), is the easiest way of imaging gamma rays. However, collimation of gamma rays is generally very difficult without using a thick mechanical collimator made of lead (Pb) or tungsten (W) to avoid contamination by gamma rays coming from outside the detector field of view (FOV). The detection efficiency is also limited by the geometrical area of a pinhole, which must be as small as possible to achieve good angular resolution.

The other model, the so-called the Compton camera as seen in Fig. 1 (bottom), utilizes the kinematics of Compton scattering to contract a source image without using mechanical collimators or coded masks, and features a wide FOV. For example, the concept of the Si/CdTe Compton camera was initially adopted as the key technology for the Soft Gamma-ray Detector [1] onboard Astro-H, Japan's sixth X-ray astronomy mission [2]. Despite their excellent angular resolution [3], thin Si/CdTe devices have poor sensitivity, particularly in ^{137}Cs (662 keV) and ^{134}Cs (604 keV) measurements, meaning that data must be accumulated over tens of minutes to reconstruct an image. Moreover, thousands of readout channels from Si/CdTe pixels and the need for a detector cooling system make the camera system complicated and heavy with a weight of around 10 kg.

As an alternative, we are developing a handy Compton camera weighing only 1 kg and measuring just 10 cm^2 in size. Unlike semiconductor-based Compton cameras, we use thick inorganic scintillators both as the scatterer and the absorber to substantially improve the sensitivity to 604/662 keV gamma rays. We propose a novel design for a module with depth of interaction (DOI) capability for gamma rays as detailed in Section 2.1. Thanks to this innovative approach, the camera realizes a wide 180° field of vision with a sensitivity ≃1% for 662 keV gamma rays, or about 50 times superior to other cameras being tested in Fukushima. We expect that a hotspot producing a 5 μSv/h dose at a distance of

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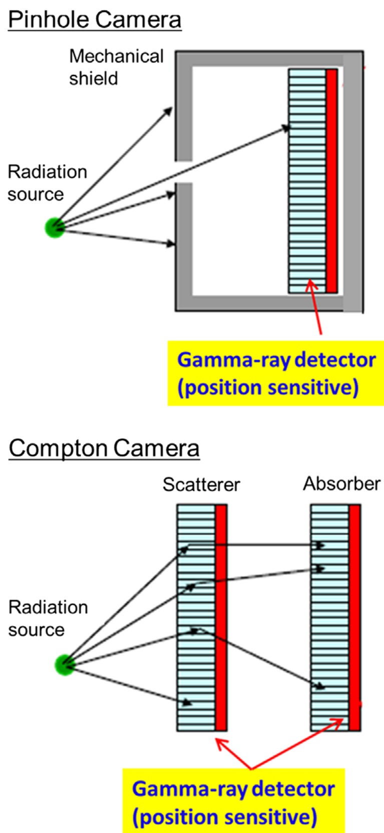

Fig. 1. Conceptual design of two types of gamma cameras. Pinhole camera with thick mechanical collimator (top), Compton camera consisting of scatterer and absorber (bottom).

3 m can be imaged every 10 s with an angular resolution better than $\Delta\theta \simeq 10^\circ$ (FWHM). This paper presents the concept, simulation performance, and initial demonstration of a prototype detector.

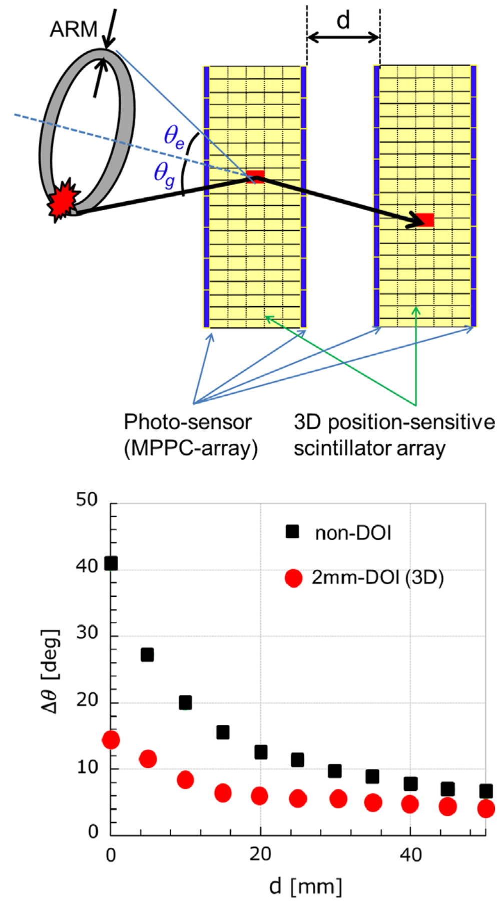

Fig. 2. Conceptual design of the DOI-Compton camera proposed in this paper (top), Geant-4 simulation of the angular resolution $\Delta\theta$ as a function of distance d for DOI and non-DOI configurations, assuming 50×50 mm^2 Ce:GAGG scintillator plates of 10 mm thickness for both the scatterer and the absorber (bottom). An energy resolution of 10% was assumed for 662 keV gamma rays.

2. DOI-Compton camera

2.1. Conceptual design

The concept of a two-plane Compton camera consisting of various scintillating detector materials as a scatterer and an absorber has already been proposed for the location and nuclide identification of remote radiation sources [4]. A similar Compton camera was also applied for the MeV gamma-ray observation of astrophysical sources [5]. When a gamma-ray photon is scattered in one detector and absorbed in another detector, the incident energy of the gamma ray, the scattering angle, and the Angular Resolution Measure (ARM) can be determined as

$$E_{in} = E_1 + E_2 \quad (1)$$

$$\cos\,\theta_e = 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2} \quad (2)$$

$$ARM = \theta_e - \theta_g \quad (3)$$

where E_1 denotes the energy of the recoil electron, E_2 the energy of the scattered photon, and θ_e the scattering angle as calculated from the measured energy deposit. θ_g is calculated from the measured interaction position and the real direction of the source (see also, [3] and Fig. 2 (top)). The angular resolution $\Delta\theta$ of a Compton camera is estimated by the distribution of ARM for sufficient number of events. The detectors having good spectral resolution as well as positional resolution apparently make θ_e and θ_g as close as possible, resulting in good angular resolution $\Delta\theta$.

An obvious advantage of using thick scintillators rather than semiconductor devices as both the scatterer and the absorber is its high sensitivity to gamma rays. The angular resolution of a scintillator-based Compton camera is generally thought not to be good, because the positions of gamma-ray interaction are quite uncertain within the scintillator especially for the DOI direction, leading to large fluctuations in θ_g and the energy resolution is not good, leading to large fluctuations in θ_e. As for the former, we can improve $\Delta\theta$ by taking a large distance d between the scatterer and the absorber, but such a configuration inevitably reduces the overall sensitivity of the Compton camera.

Here we are proposing a novel Compton camera using high resolution and 3D position-sensitive scintillators coupled to a large-area monolithic Multi-pixel Photon Counter (MPPC) array (Fig. 2 (top)). By measuring the DOI of incident gamma-rays, as well as the usual 2D positions, we expect that $\Delta\theta$ is significantly improved, especially when placing the scatterer and absorber closer together (i.e., small d). In fact, Fig. 2 (bottom) shows the variation of $\Delta\theta$ as a function of d for the DOI (circle; 2 mm resolution) and non-DOI (box) configurations. We assumed 50×50 mm^2 Ce-doped $Gd_3Al_2Ga_3O_{12}$ (Ce:GAGG) plates of 10 mm thickness for both the scatterer and the absorber, due to their high light yield and short scintillation decay time [6]. Note that good angular resolution as good as $\Delta\theta < 10^\circ$ can be achieved even with $d = 10$ mm for the DOI configuration.