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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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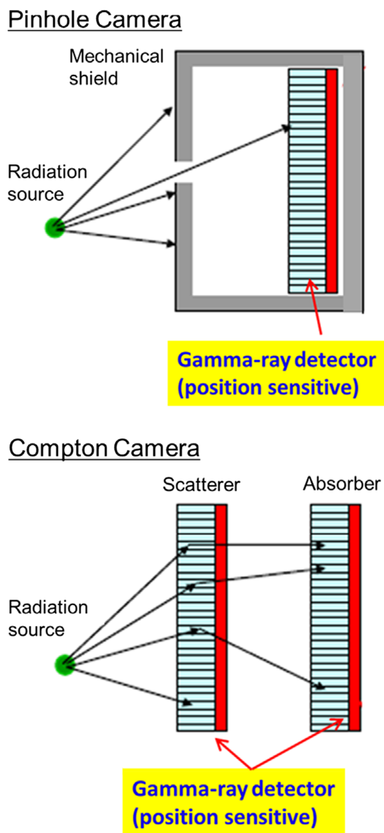

Fig. 1. Conceptual design of two types of gamma cameras. Pinhole camera with thick mechanical collimator (top), Compton camera consisting of scatterer and absorber (bottom).

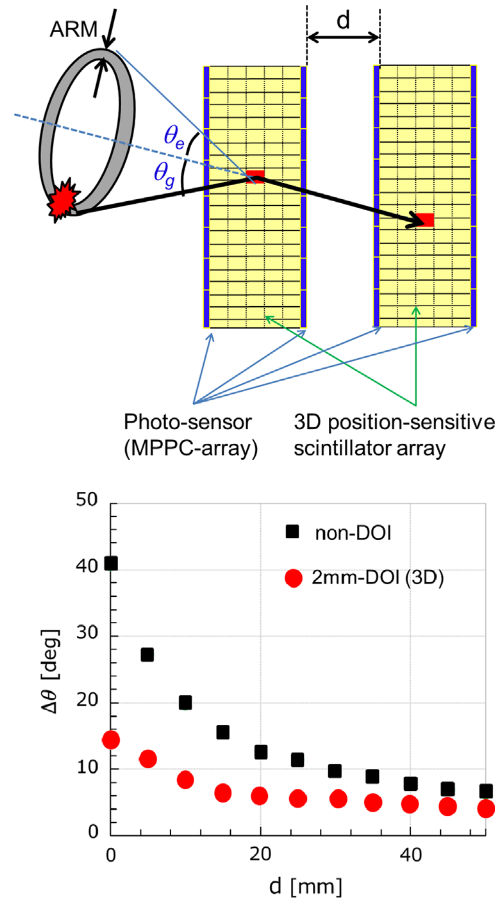

Fig. 2. Conceptual design of the DOI-Compton camera proposed in this paper (top), Geant-4 simulation of the angular resolution $\Delta\theta$ as a function of distance d for DOI and non-DOI configurations, assuming 50×50 mm^2 Ce:GAGG scintillator plates of 10 mm thickness for both the scatterer and the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

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.

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.

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2.2. 3D position-sensitive scintillators

Full details of the design and experimental setup for 3D position-sensitive scintillators are given in Ref. [7]. In short, we can measure the DOI of incident gamma rays by measuring the pulse-height ratio of double-sided MPPC arrays consisting of 4×4 channels coupled to both ends of a scintillator block (here we used Ce:GAGG). A $BaSO_4$ reflector (0.2 mm thick in the 2D direction) divides each pixel of the crystal block (2 mm cubic), whereas it is separated by a layer of air (about 10 μm−thick) that forms naturally by laying on top of each other. Fig. 3 (left) shows a photo of the DOI module specifically designed for this experiment.

To reduce the number of output signal channels, we applied a charge division technique based on the resistor network developed by Refs. [8,9]. By using this resistor network, we could reduce the number of readout channels down to eight. The sum of the eight output signals corresponds to the total energy deposition of the gamma rays, with the x, y and z (=DOI) interaction positions being calculated by using the centroid method. Fig. 3 (right) shows the position response of a performance test for a $5\times5\times5$ matrix of 2 mm cubic Ce:GAGG crystal pixels, as measured for 662 keV fully absorbed gamma rays at 20 °C. Note that each crystal block is clearly distinguished, working as a high-resolution 3D position-sensitive detector.

2.3. Demonstration as "DOI"-Compton camera

To verify our concept of a novel DOI-Compton camera, we made a simple test module consisting of two identical 1 cm cubic 3D position-sensitive scintillation detectors (see Fig. 4). The configuration of each Ce:GAGG cubic is completely the same as that shown in Fig. 3 (left), namely consisting of five layers of the 5×5 matrix of 2 mm Ce:GAGG cubic crystals. Each detector module works as the scatterer and the absorber, with the modules stacked together through a thin acrylic spacer. The distance between the modules is set to $d=4$ mm. The average energy resolution, as measured from E_{in} (see, Eq. (1)), was 10% for 662 keV gamma rays.

Fig. 5 (top) shows an example image taken with the prototype camera developed here. To reconstruct the image, maximum-likelihood expectation–maximization (ML-EM) was efficiently applied to the list-mode data, resulting in the list-mode MLEM reconstruction algorithm [10]. In the experiment, a 1-MBq ^{137}Cs isotope was placed 20 cm ahead of the detector module, corresponding to a radiation dose of ≃3 μSv/h. Note the significant improvement in the image taken in 3D mode, achieving $\Delta\theta\simeq10^\circ$. Fig. 5 (bottom) shows the same image but ignoring the DOI of incident gamma rays, that is, 2D (non-DOI) mode. Although the experiment used a rather simple setup, these results suggest that the DOI-Compton camera being proposed here is both versatile and offers capabilities which are interesting for various applications like nuclear medicine and high energy astrophysics.

3. Prototype camera by Hamamatsu photonics

Based on these successful experiments and various simulation studies for optimizing the detector, we are now developing a handy DOI-Compton camera for early operation and testing in Fukushima. Fig. 6 shows photos of the first prototype module, measuring $8.5\times14\times16\ cm^3$ in size and weighting only 1.5 kg. As a gamma-ray camera, we adopted a 50×50 array of $1\times1\times10$ mm thick Ce:GAGG scintillator arrays for both the scatterer and the absorber, and four 8×8 MPPC array boards which measure the scintillating light using a resistive charge division network. The distance between the scatterer and the absorber is set to $d=15$ mm. Digital outputs from the camera are sent to a laptop via the USB 3.0 interface board. The ML-EM image is updated every second by integrating data accumulated over the past 30 s.

The prototype also carries a visible light camera with a fisheye lens which provides a 180° field of vision in order to take an optical image to be superimposed on the gamma-ray image of the same

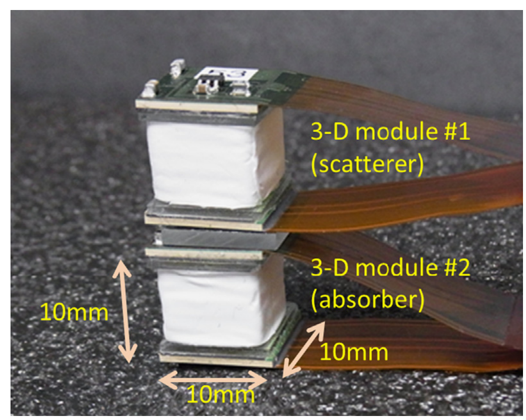

Fig. 4. Photo of the Compton camera test module, consisting of two identical 3D Ce:GAGG crystal blocks.

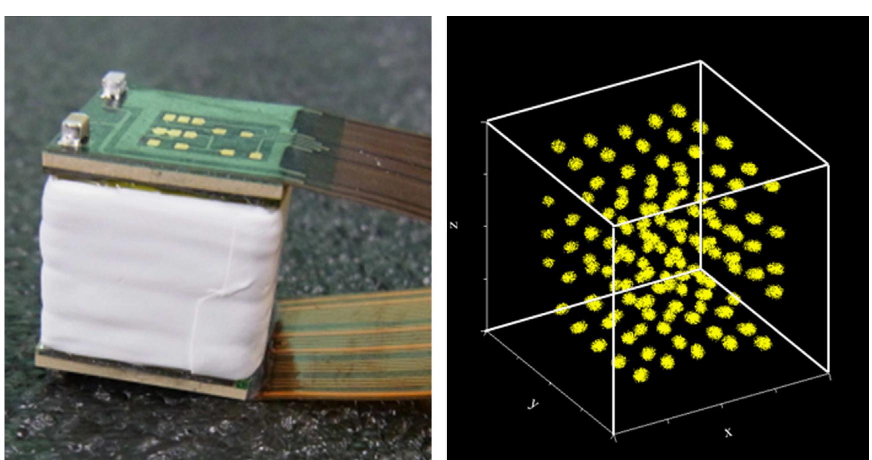

Fig. 3. Photo of 3D position-sensitive crystal arrays (left). Two MPPC arrays are optically coupled to the top and bottom sides of the crystal arrays. 3D position histogram of a crystal block, as measured for 662 keV gamma rays (right).

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FOV. This prototype still operates in 2D mode, that is, without measuring the DOI of incident gamma rays. Nevertheless, the camera works well as shown in the example image of Fig. 7, already achieving angular resolution of $\Delta\theta \simeq 14^\circ$ (FWHM) for 662 keV gamma rays. An integration time of 30 s is sufficient to reconstruct the image for a weak isotope, when the corresponding radiation dose is $\simeq 6$ μSv/h. Note that $\Delta\theta \simeq 14^\circ$ (FWHM) is precisely consistent with expectation raised from the Geant-4 simulation presented in Fig. 2 (bottom) of the non-DOI case. From the same simulation, we can expect to achieve $\Delta\theta \simeq 7$–8° by employing the DOI configuration in the near future. Finally, Fig. 8 presents an event map comparing

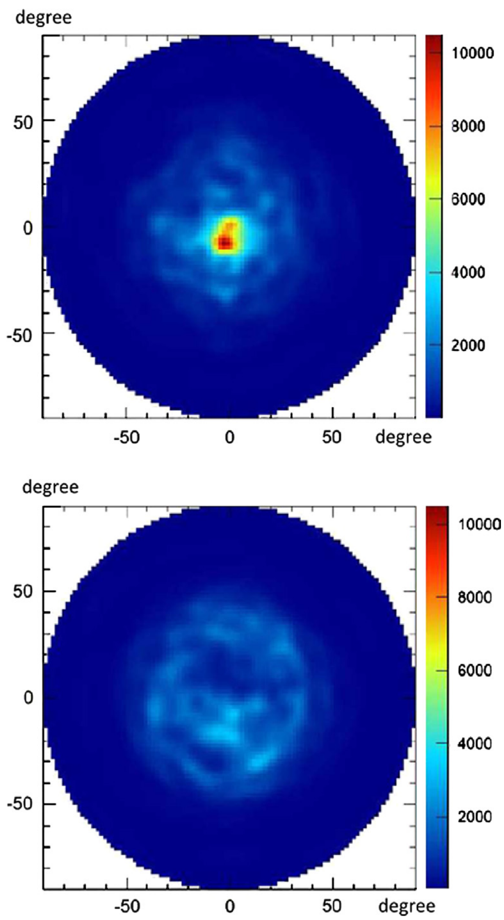

Fig. 5. Compton reconstructed ML-EM image of a 137Cs isotope, as described in the text. An image taken with a 3D prototype detector (top), same image but taken with the 2D configuration (bottom).

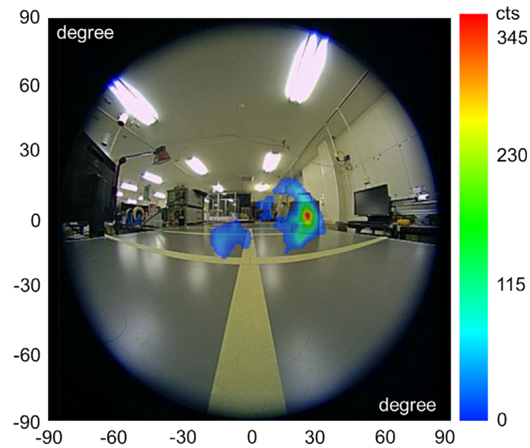

Fig. 7. Compton reconstructed image of a ^{137}Cs isotope, taken with a prototype Compton camera as shown in Fig. 5. An integration time of 30 s is needed to reconstruct the image for a weak source when the corresponding radiation dose is $\simeq 6$ μSv/h.

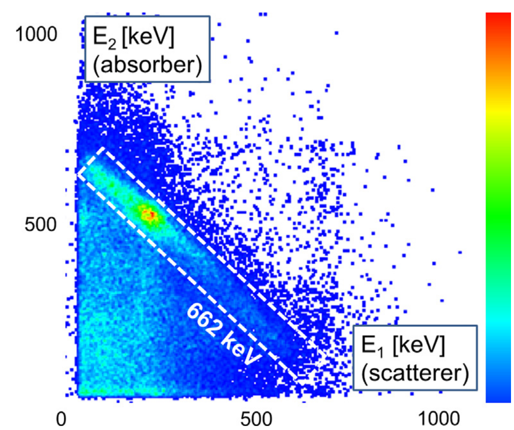

Fig. 8. An example event map taken with the prototype Compton camera comparing energy deposits in the scatterer (E_1) and the absorber (E_2). The area enclosed by a dashed line corresponds to events for 662 keV gamma rays.

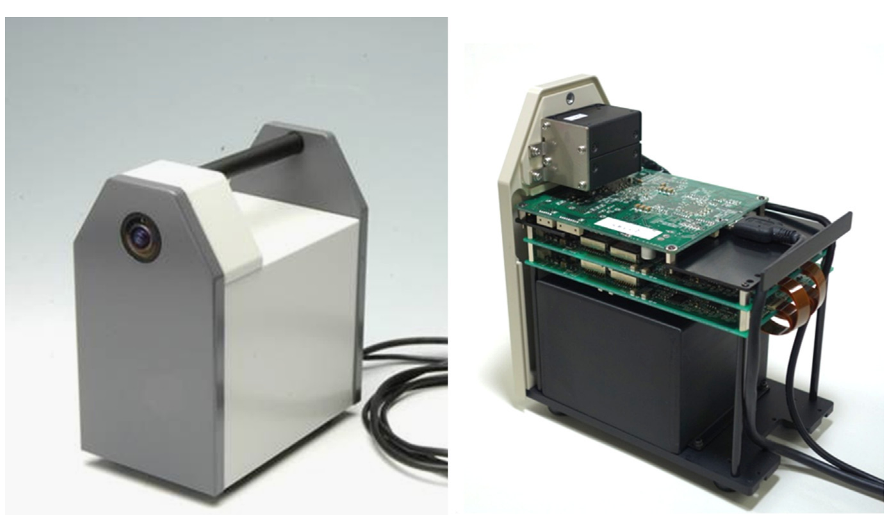

Fig. 6. Photos of the handy Compton camera prototype currently being fabricated by Hamamatsu Photonics K. K.

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the energy deposits on the scatterer (E_1) and the absorber (E_2). Again the energy resolution of 10% (FWHM) was obtained for 662 keV gamma-rays.

4. Conclusion

We proposed a novel and handy Compton camera that realizes a wide 180° field of vision, with its sensitivity about 50 times superior to other cameras being tested in Fukushima. We can thus expect almost "real-time" gamma-ray image with angular resolution better than 10° (FWHM), even for a weak radiation source. The 3D position-sensitive scintillators coupled with the large-area monolithic MPPC arrays are the key technologies developed here. We also presented the current status of the prototype camera 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 only 30 s.

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