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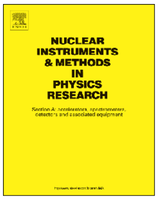

"Stereo Compton cameras" for the 3-D localization of radioisotopes

K. Takeuchi [a], J. Kataoka [a], T. Nishiyama [a], T. Fujita [a], A. Kishimoto [a], S. Ohsuka [b], S. Nakamura [b], S. Adachi [b], M. Hirayanagi [b], T. Uchiyama [b], Y. Ishikawa [b], T. Kato [b]

[a] *Research Institute for Science and Engineering, Waseda University, 3-4-1, Ohkubo, Shinjuku, Tokyo, Japan*
[b] *Solid State Division, Hamamatsu Photonics K. K., 1126-1, Ichino-cho, Hamamatsu, Shizuoka, Japan*

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ABSTRACT

The Compton camera is a viable and convenient tool used to visualize the distribution of radioactive isotopes that emit gamma rays. After the nuclear disaster in Fukushima in 2011, there is a particularly urgent need to develop "gamma cameras", which can visualize the distribution of such radioisotopes. In response, we propose a portable Compton camera, which comprises 3-D position-sensitive GAGG scintillators coupled with thin monolithic MPPC arrays. The pulse-height ratio of two MPPC-arrays allocated at both ends of the scintillator block determines the depth of interaction (DOI), which dramatically improves the position resolution of the scintillation detectors. We report on the detailed optimization of the detector design, based on Geant4 simulation. The results indicate that detection efficiency reaches up to 0.54%, or more than 10 times that of other cameras being tested in Fukushima, along with a moderate angular resolution of 8.1° (FWHM). By applying the triangular surveying method, we also propose a new concept for the stereo measurement of gamma rays by using two Compton cameras, thus enabling the 3-D positional measurement of radioactive isotopes for the first time. From one point source simulation data, we ensured that the source position and the distance to the same could be determined typically to within 2 meters' accuracy and we also confirmed that more than two sources are clearly separated by the event selection from two point sources of simulation data.

1. Introduction

Following the nuclear disaster in Fukushima in 2011, numerous radioactive isotopes (e.g. ^{134}Cs and ^{137}Cs) were released and spread widely and elimination thereof remains an urgent task. To help identify radiation "hotspots", various gamma cameras have been developed and field-tested [1,2].

The Compton camera – a type of gamma cameras – comprises two position-sensitive detectors: the "scatterer" and "absorber". The Compton camera can determine the arrival direction of incident gamma rays by calculating the energy deposits and the interaction positions in the scatterer and absorber based on the kinematics of Compton scattering. Fig. 1 shows its main working principle. Based on a single event, the Compton camera confines the direction of incident gamma rays to a conular area (the so-called "Compton cone"). To overlap the Compton cones many times, the arrival direction is determined statistically. Eq. (1) expresses θ_k in Fig. 1:

$$\cos\,\theta_k = \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2} \tag{1}$$

Angular resolution measurement (ARM) refers to the minimum elongation between the position on the Compton cone and the actual source position and is used to indicate the Compton camera performance. ARM is calculated from the following equation:

$$\mathrm{ARM} = \theta_k - \theta_g \tag{2}$$

θ_g is the geometrical angle that is calculated by the three points of interaction at the each detector and of the source position. ARM indicates an improved value by improving the energy and position resolution. Accordingly, we employed the Depth-Of-Interaction (DOI) measurement method to achieve significantly improved position resolution. Details of said measurement and the reading technique adopted for 3-D scintillator arrays are given in Ref. [3]. The Compton camera does not require any mechanical collimation and has a wide field of view, meaning it can be used in various fields. For example, the Soft Gamma-ray Detector [4] on ASTRO-H satellite, Japan's sixth X-ray astronomy mission [5], adopts the Si/CdTe Compton camera. Moreover the Compton camera is expected to be applied for Single Photon Emission Computed Tomography (SPECT) [6], targeting improved sensitivity as well as a potential application to decontaminate radiation hotspots.

Accordingly, we are proposing a novel Compton camera comprising 3-D Ce:GAGG scintillator arrays coupled with large-area MPPC arrays. Full details of the project are given in Ref. [7]. The Compton camera, however, can only give us the direction of the incident gamma rays, rather than the position of the hotspot.

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In the absence of any hindrance in the direction in which the Compton camera faces, the hotspot position can be determined by using a single Compton camera and an optical camera that are located at the same position. The hotspot is determined as the point in the optical image corresponding to the peak in the Compton camera image. However, we cannot determine whether the hotspot is in front of the obstacle or behind it. We therefore developed the stereo Compton camera by using two Compton cameras to know the position of the hotspots and then the distance to the same. By applying the triangulation surveying method to Compton cameras, we could successfully determine the source position for the first time.

In this paper, we show how to optimize the detector design relative to the new Compton camera; achieving far better angular resolution as well as improved detection efficiency for 662 keV gamma rays, by using Geant4 simulation (Section 2). Moreover, by applying a stereo configuration of two Compton cameras placed ~10 m apart, we can localize the 3-D positions, particularly the distance to radioactive isotopes, with typical accuracy of ~2 m. In addition, where more than two sources are in the field of view, we can separate them clearly by event selection (Section 3).

2. Optimization

2.1. Method

Compton camera performance is determined by two significant parameters: efficiency and ARM. To study how these are affected by the detector configuration, we developed a full simulation package for a Compton camera system, using Geant4. We assume that both the scatterer and absorber have surface areas of 50×50 mm^2, comprising 25×25 arrays of 2×2 mm pixel Ce:GAGG crystals. However, both the thickness of each crystal and the distance between the scatterer and absorber must be optimized for optimal Compton camera performance.

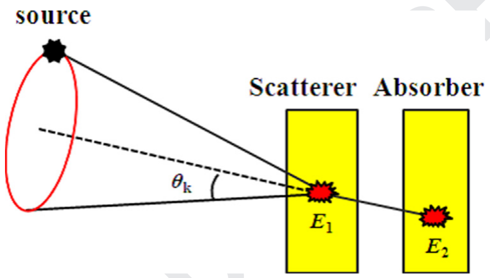

Fig. 1. The concept of the Compton camera (Note that E_1 denotes the energy of a recoil electron, E_2 the energy of a scattered photon, and θ_k the scattering angle. The red circle indicates the confined region where the source may exist). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

First, by keeping the distance between the scatterer and absorber at certain constants (i.e. 10, 25, and 40 mm), we tried to maximize detection efficiency by changing the thickness of the scatterer and absorber. To apply our 3-D position-sensitive detector technique [3], we kept the sum of detector thickness at 20 mm. We then tried to optimize ARM by changing the distance between the two detectors for the above configuration.

2.2. Results

The results given in Fig. 2 (left) show that increasing the scatterer thickness also increases the efficiency of the Compton camera, but efficiency declines when the thickness exceeds 9 mm. Efficiency stands for the “single-single event” (i.e. single Compton scattering in the scatterer, single site absorption in the absorber) as a percentage of incident gamma rays on the scatterer. Efficiency peaks with a scatterer thickness of 8 mm at a separation of 10 mm, beyond which any further increase in scatterer thickness is useless. A similar trend can be seen in each separation. Using the optimized 8 mm thickness of the scatterer, the effects of DOI on ARM are simulated at each distance. Fig. 2 (right) shows a related summary. In the DOI configuration, the scatterer comprises four layers of pixels 2 mm thick, while the absorber consists of six layers of pixels 2 mm thick. The ARM of the DOI configuration becomes lower than 10 (FWHM) at 15 mm separation. Under this condition, the Compton camera performs with 0.54% efficiency and 8.1 (FWHM) angular resolution.

3. Stereo Compton camera

3.1. Method

Stereo measurement (i.e. measuring the distance to target materials from triangulation calculated using two cameras) is often used in triangular surveying. To do the triangulation calculation, we need two points between which the distance is already known and two straight lines toward the target from these two points.

Compton cameras can provide the direction of the incident gamma-ray from the detectors. By preparing two Compton camera images of the same target, we can use the stereo measurement method, which was then applied to determine the source position.

Fig. 3 shows the concept of our 3-D measurement method. By picking up a bin in a distribution map, a line pointing to the source position can be drawn from the center of the scatterer. The two lines drawn by each Compton camera image have an intersection

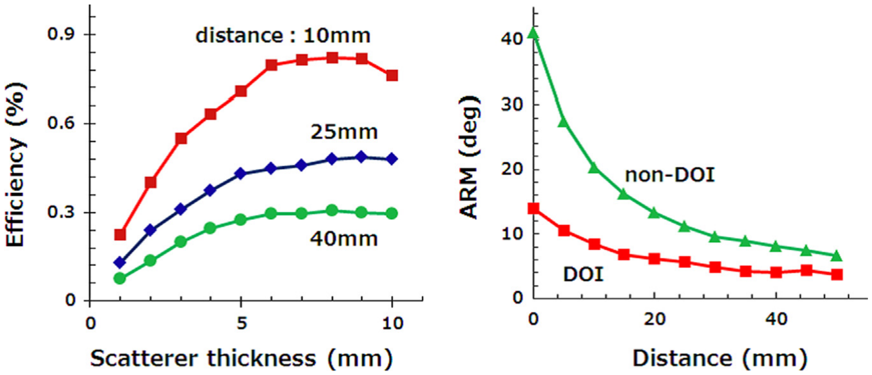

Fig. 2. (Left) Efficiency relative to various scatterer thicknesses at each distance. (Right) ARM (FWHM) for various distances between two detectors in DOI and non-DOI configurations.

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