

Segmented Compton Camera with Dual Perpendicular Silicon Photomultiplier Read-Out for 4π Gamma Ray Imaging

Ana Marija Kožuljević, Gabriela Jazvac, Luka Lotina, Luka Pavelić
Institute for Medical Research and Occupational Health, Division of Radiation Protection
Ksaverska cesta 2, 10000 Zagreb, Croatia
akozuljevic@imi.hr

ABSTRACT

Compton Cameras (CC) are gamma ray imaging systems exploiting the principles of the Compton scattering process for the reconstruction of the location of radioactive sources. They are used in a wide range of fields, including medical diagnostics, environmental monitoring, and homeland security applications such as mapping radiological and post-nuclear contamination. Conventional CC devices employ two layers of detectors-incident gamma rays undergo Compton scattering in the first layer and are subsequently photoelectrically absorbed in the second, giving information about interaction positions and energy deposits at the interaction sites. While these two-layer designs are capable of performing source imaging, they have a limited field of view and low detection efficiency, so they require manual or mechanical rotation systems for useful imaging, as well as long acquisition times to obtain images of sufficient quality. We propose a novel design of a CC for imaging in 4π with high detection efficiency, utilizing Gadolinium Aluminum Gallium Garnet crystals and silicon photomultipliers (SiPMs). The CC consists of 64 GAGG cubical voxels, arranged in four layers of 4x4 crystals. Their light output is detected from two sides, with 4x4 SiPMs positioned perpendicularly to each other. In between the layers are optical reflectors, which contain the optical photons in planes perpendicular to the SiPMs, ensuring the maximum signal is collected, while lowering the probability of inter-crystal leakage. This design offers a depth-of-interaction (DOI) capability and the possibility to use each voxel as a scatterer and an absorber, enabling the 4π imaging capacity. The system configuration considered is employing crystals of $3\times 3\times 3$ mm³ with a 3.2 mm pitch, using a one-to-one SiPM readout scheme. Monte Carlo simulations were performed in Geant4 to evaluate the performance of the proposed CC, and images of the Cs-137 gamma ray source in front of a face and a vertex of the detector were reconstructed using a simple back projection algorithm.

Keywords: *Compton Camera, gamma imaging, Monte Carlo simulations, dual perpendicular read-out, silicon photomultipliers*

1 INTRODUCTION

Radiation imaging, especially imaging of gamma-emitting sources, is a demanding challenge applicable to many problems, from medical imaging to post-nuclear disaster detection of released radionuclides, such as Cs-137 [1]. Directional information and knowledge of the spatial distribution of the gamma ray sources is crucial for the aforementioned tasks, and common methods of detection include not only energy-resolving detectors, but also heavy collimators or coded aperture approaches, limiting the size of the field of view (FOV). These designs need multiple detectors to cover the FOV or an additional equipment for rotation of the detector. A gamma ray imaging device that utilizes electronic collimation is called a Compton Camera (CC), based on the kinematics of Compton scattering of gamma rays. Typically, a CC has two layers: a layer in which the incoming

gamma ray scatters and transmits part of its energy to the recoil electron in the material, and a second layer in which the gamma ray is photoelectrically absorbed. Each layer in this configuration has its own read-out, but this usual design is still limited to small FOV and low detection efficiency, as the sensitive component of the CC is only one side of the detector susceptible to incoming gamma rays. In this work, we present a novel type of CC that has 4π imaging capability, thus covering the full FOV with depth of interaction (DOI) information, without additional appliances (Fig. 1). The CC design relies on detecting the scattered and absorbed gamma rays in one volume of a segmented scintillating detector, read-out from two sides by silicon photomultipliers (SiPMs). It consists of 64 voxels, each voxel a Gadolinium Aluminium Gallium Garnet (GAGG) cube. Each cube can act as a scatterer and an absorber, thus enhancing the detection efficiency and compactness of the detection system. The SiPMs are perpendicular to each other, sitting on two neighbouring faces of the cubical volume. Unlike the other proposed parallel dual read-out CCs [2, 3], this design does not require calculation of signal ratios for DOI determination. Other similar cubical designs have more complicated readout configurations, for example, the SiPMs coupled to the four lateral faces of the detector [4], or all six of the faces covered by SiPMs [5, 6].

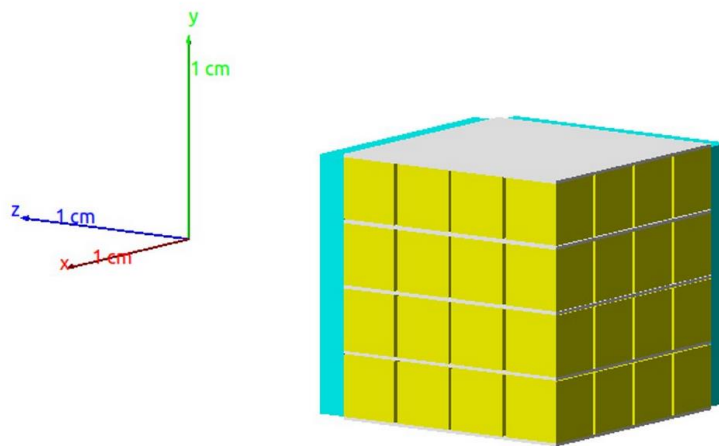


Figure 1. Visualisation of the proposed Compton camera design. The voxels are GAGG crystals (in yellow), with reflectors (in white) and SiPMs (in cyan).

2 METHODS

2.1 Detector design

We propose a novel type of gamma ray detector with depth of interaction (DOI) capability, comprised of 64 scintillating crystals, as depicted in Figure 1. The crystals are arranged in a $4 \times 4 \times 4$ voxels in a cubical formation, with crystal sizes of $3 \times 3 \times 3 \text{ mm}^3$ with 3.2 mm matrix pitch. The read-out are two silicon photomultipliers (SiPMs), positioned perpendicularly to each other on adjacent faces of the segmented detector cube, with 1-1 coupling to the crystals. The SiPMs are 4×4 matrices of pixels, with pixels' sizes of $3 \times 3 \text{ mm}^2$ with 3.2 matrix pitch, that correspond to the sizes of the respective voxels they are attached to. Reflectors, modelled as titanium dioxide (TiO_2), are placed in planes that are perpendicular to both SiPMs, in between the 4×4 layers of the crystals. The reflectors provide maximal light collection by the SiPMs, as well as lower the possibility of intercrystal light leakage from one plane to another. Additionally, reflectors encompass outer faces of the detectors that are not in contact with the SiPMs.

2.2 Data acquisition and analysis

Monte Carlo simulations of the proposed detector setups were developed in Geant4 programming package, v11.3.2 [7]. To simulate the physics processes, the QGSP_BIC_HP_EMZ physics list was used. This physics list includes the Doppler broadening phenomena, since it influences the spatial resolution of the CC, due to the momentum of electrons during a Compton scattering interaction. The GAGG crystals, i.e. the voxels, were selected as sensitive volumes in which the gamma rays deposit their energy. Point sources of relevant energies were placed in a spherical array with radius r around the detectors, with coinciding centers of the detector and the sphere, so that:

$$r = \text{Distance} + \frac{a\sqrt{3}}{2} \quad (1)$$

where a is the length of the side of the detector ($a = 12.6$ mm), and Distance is a parameter of separation between the face or the vertex and the source. The output of the simulation included the calculation of the efficiencies for events in which the total deposited energy in the module exceeds 10 keV, as well as other information, such as total energy per event per voxel, positions of the hits inside the voxels etc. saved for further analysis.

Both data collection and analysis were optimized for utilization of the bash *parallel* command to expedite the computing processes [8]. The analysis of the collected data was conducted in ROOT, a free, open-source data analysis programming package developed at CERN [9]. Plotting and image reconstruction was done in Python. The conducted analysis filters the collected data so that the events in which the energy deposit in the detector module is less than 100 keV were taken into consideration for further analysis, which reflects the experimental conditions of background reduction process. The total energy deposit in each voxel was smeared via Gaussian smearing on an event-by-event basis to achieve an energy spectrum expected in practical conditions.

2.3 Figures of merit

The proposed detector design has a non-uniform geometry that could influence its response, as it's sensitive volume is covered from two sides. To discern the detector's response to the gamma rays from various point sources, intrinsic, geometric and absolute efficiency was calculated for each face and vertex of the detectors. 5 million events were utilized for these calculations.

Intrinsic efficiency of a detector is defined as a ratio of the number of gamma rays that are detected and the number of gamma rays that enter the detector (Eq. 2):

$$\text{Intrinsic efficiency} = \frac{\text{Number of detected gamma rays}}{\text{Number of gamma rays that enter the detector}}, \quad (2)$$

with its error σ_{int} calculated as in Eq. 3:

$$\sigma_{\text{int}} = \sqrt{\frac{p(p-1)}{\text{Number of gamma rays that enter the detector}}}, \quad (3)$$

where p is the intrinsic efficiency defined as in Eq. 2. The intrinsic efficiency depends on the energy of the gamma rays that enter the detector, and the material and the thickness of the detector module.

Geometric efficiency of a detector is a measure on how well the detector intercepts radiation emitted from the source, and is defined as a number of gamma rays that enter the detector divided by the number of gamma rays emitted from the source (Eq. 4):

$$\text{Geometric efficiency} = \frac{\text{Number of gamma rays that enter the detector}}{\text{Number of emitted gamma rays}(4 \pi)}, \quad (4)$$

with the error σ_{geom} (Eq. 5) calculated assuming Poisson statistics:

$$\sigma_{\text{geom}} = \frac{\sqrt{\text{Number of gamma rays that enter the detector}}}{\text{Number of emitted gamma rays}(4 \pi)}. \quad (5)$$

The geometric efficiency of the detector is a function of the detector's size and source-to-detector distance, as it measures the detector's ability to intercept the gamma rays from a source.

Absolute efficiency of a detector is defined as a ratio of the number of photons that interacted with the detector and the number of photons emitted by the source (Eq. 6):

$$\text{Absolute efficiency} = \frac{\text{Number of detected gamma rays}}{\text{Number of emitted gamma rays}(4 \pi)} \quad (6)$$

and its error σ_{abs} calculated as in Eq. 7:

$$\sigma_{\text{abs}} = \frac{\sqrt{\text{Number of detected gamma rays}}}{\text{Number of emitted gamma rays}(4 \pi)}. \quad (7)$$

The absolute efficiency measures the overall performance of the detection system. It is also related to the intrinsic and geometric efficiencies, as it can be calculated from the relation:

$$\text{Absolute efficiency} = \text{Intrinsic efficiency} \times \text{Geometric efficiency}$$

2.4 Compton Camera modality and image reconstruction

In Compton camera modality, the detector can determine the path of an incoming gamma ray photon. To be able to do that, two interactions must take place in the detector: Compton scattering of the gamma ray in one voxel, and the photoelectric absorption of the scattered gamma ray in another. From the energies deposited in the voxels, it is possible to determine a Compton cone, defined by the angle θ_{recon} (Eq. 8):

$$\theta_{\text{recon}} = \arccos\left(\frac{m_e c^2}{E_1 + E_2} - \frac{m_e c^2}{E_2} - 1\right) \quad (8)$$

where E_1 and E_2 are the deposited energies in the first and second voxel, respectively, m_e is the resting mass of the electron, and c is the speed of light. The Compton cone represents the possible route that it took to reach the detector. As there are multiple combinations of the two voxels in the detector, the resulting cones intersect at the point in which the source lies.

The number of the possible combinations of the two voxels that can be utilized for image reconstruction is defined by the Compton sensitivity of the CC. The Compton sensitivity is characterized by the fraction of events in which the gamma rays interact with exactly two voxels in the detector, scattering in one voxel and is then photoelectrically absorbed in another (Eq. 9):

$$\text{Compton sensitivity} = \frac{\text{Number of Compton events}}{\text{Number of emitted gamma rays}(4 \pi)}. \quad (9)$$

The Compton sensitivity error σ_{CS} calculation is performed as in Eq. 10:

$$\sigma_{CS} = \frac{\sqrt{\text{Number of Compton events}}}{\text{Number of emitted gamma rays}(4\pi)} \quad (10)$$

Angular resolution measure (ARM) is defined by the Eq. 11, as the angle between the reconstructed Compton cone and the actual source direction:

$$\theta_{ARM} = \theta_{recon} - \theta_{true}, \quad (11)$$

where θ_{recon} is obtained from the energies deposited in the voxels (Eq. 8), and θ_{true} is obtained from the positions of the Compton scattering and photoelectric absorption of the gamma ray. The full width at half maximum (FWHM) of the obtained ARM distribution represents the angular resolution of the CC.

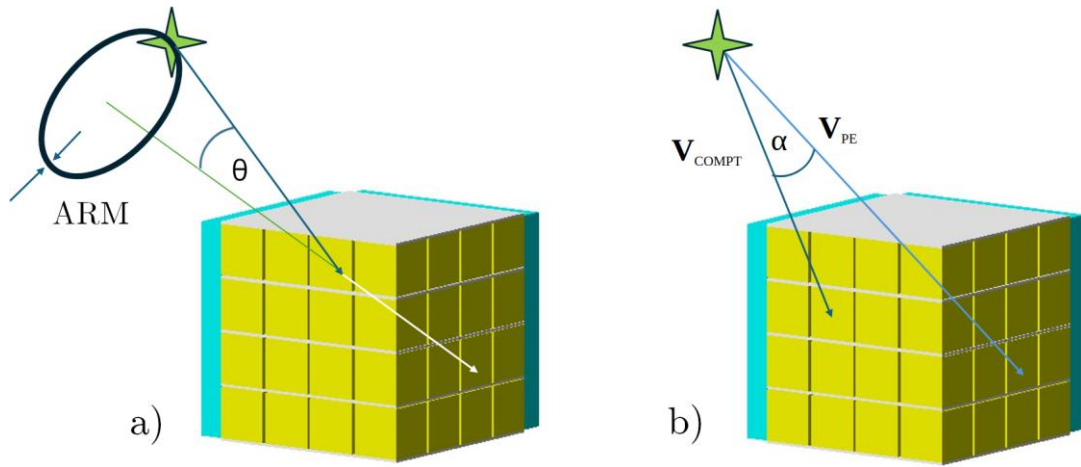


Figure 2. A gamma ray source (the green star) is placed around the Compton camera. A Compton cone (the black ellipse) and its opening angle θ in a) is defined by the energies deposited in the voxels, with Compton scattering (voxel at the end of the green vector) and photoelectric absorption (voxel at the end of the white vector) and their positions. The data selected for reconstruction of the source image is obtained from the cone defined by the vectors \mathbf{v}_{COMPT} (from the source to the voxel with Compton scattering event) and \mathbf{v}_{PE} (from the source to the voxel with photoabsorption event), and the angle α between them, depicted in b).

For the purpose of the image reconstruction, 100 million events were simulated. Simple back-projection reconstruction algorithm was developed in Python to test the CCs capability of reconstructing an image of a Cs-137 point source. This reconstruction method assumes the knowledge of the source-to-detector distance, and plots the Compton cones from different voxel combinations onto the plane in which the source is assumed to be. The combinations of the voxels with Compton scattering and photoelectric effect are selected in the following way:

- The deposited energy in each voxel is smeared by a Gaussian to correspond to 12% energy resolution at 662 keV, on event-by-event basis.
- The voxels with more than 100 keV of deposited energy are selected.
- The first voxel that fired in the Compton scattering is chosen to be the one with the deposited energy of 100 keV to 150 keV, and the sum of the energies deposited in both voxels is $E_{source} \pm 3\sigma$.
- The vectors \mathbf{v}_{COMPT} and \mathbf{v}_{PE} are defined as the vectors from the source to the centers of the respective voxels, and the angle α is the angle between these vectors.

- The distance between the voxels' centers is larger than 5.6 mm, and the difference in the magnitude of the vectors was set to be larger than 4 mm.
- The angle between the vectors was kept between 4 degrees and 5.5 degrees.

By selecting the events that occurred in the voxels with the properties described above, forward-scattering Compton events are kept for image reconstruction.

3 RESULTS

3.1 Influence of the geometrical non-uniformity on detector response

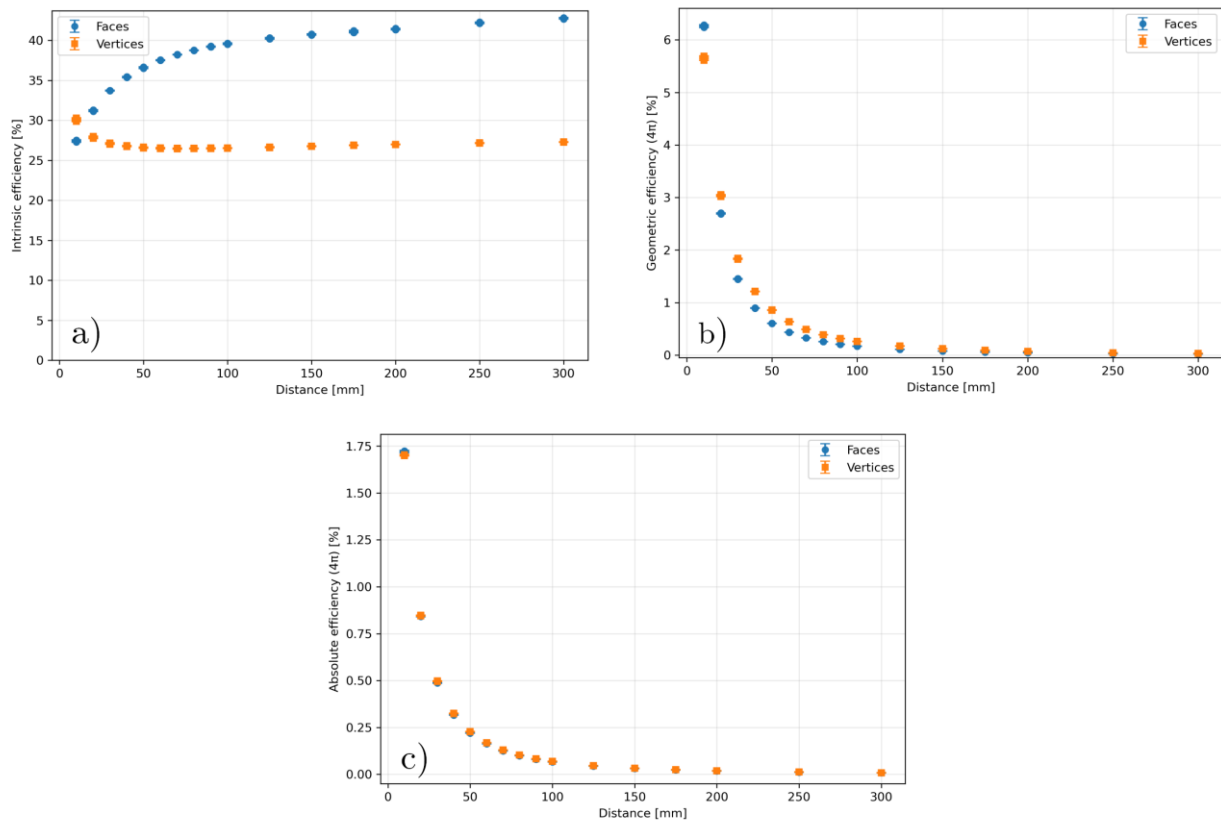


Figure 3. The a) intrinsic, b) geometric, and c) absolute efficiency of the detector for 662 keV gamma ray point source positioned at various distances in front of every face and vertex of the detector.

The proposed design of the CC relies on the SiPM read-out from two neighbouring faces of the detector cube. The effect of this geometrical non-uniformity of the proposed detector system was studied by efficiency calculations of the gamma ray photons that deposited more than 10 keV of their energies in one of the voxels in the detector module. The intrinsic, geometric and absolute efficiencies were measured and calculated for all of the detector's faces and vertices at source's energy of 662 keV, at source-to-detector Distances ranging from 10 mm to 300 mm. The results can be seen in Fig. 3, comparing the efficiencies for the faces and vertices of the CC.

3.2 Compton Camera images of a point Cs-137 source

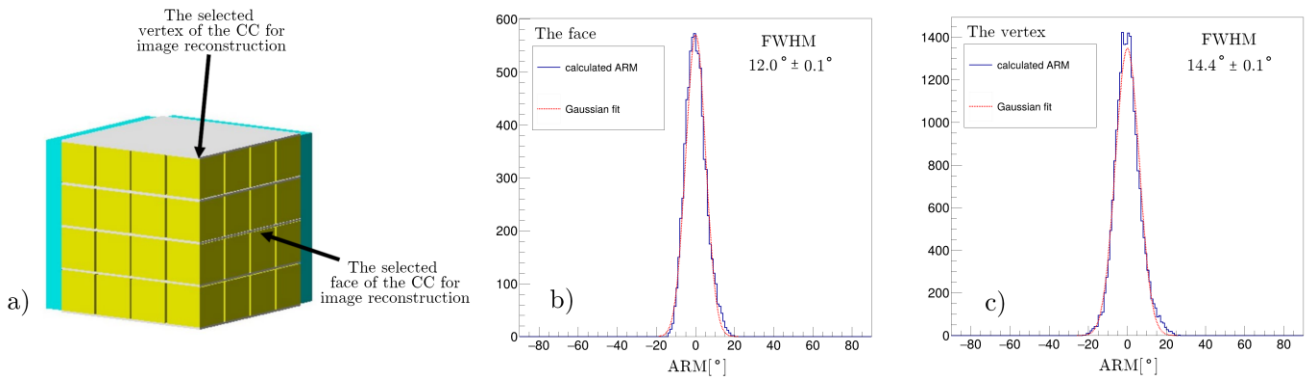


Figure 4. Depicted in a), the selected face and vertex of the CC for image reconstruction. In b) and c) are ARM distributions obtained for the selected face and vertex, respectively, for the point source with 662 keV gamma ray energy and source-to-detector distance of 50 mm. FWHM of ARM represents the angular resolution of the CC, obtained with the Gaussian fit.

The events selected as described in Subsection 2.4 were utilized for image reconstruction. The calculated ARM distribution for the selected face and vertex, when the source is positioned at the Distance of 50 mm, can be seen in Fig. 4a. The calculated ARM distributions are presented in Figs. 4b and 4c, along with the Gaussian fits for FWHM calculations. The FWHM value of the ARM distribution, i.e. the angular resolution, for the source positioned in front of the face of the CC is $12.0^\circ \pm 0.1^\circ$, and for the source position above the vertex is $14.4^\circ \pm 0.1^\circ$. The Compton sensitivity calculated from the events chosen for image reconstruction, for the source at the Distance of 50 mm is $(4.7 \pm 0.1) \times 10^{-5}$ for the face, and $(9.3 \pm 0.1) \times 10^{-5}$ for the vertex. The images of the 662 keV point source are reconstructed by simple back projection and presented in the Figure 5. The FOV of the images is 10 cm x 10 cm, and the image pixels are 1 mm x 1 mm in size.

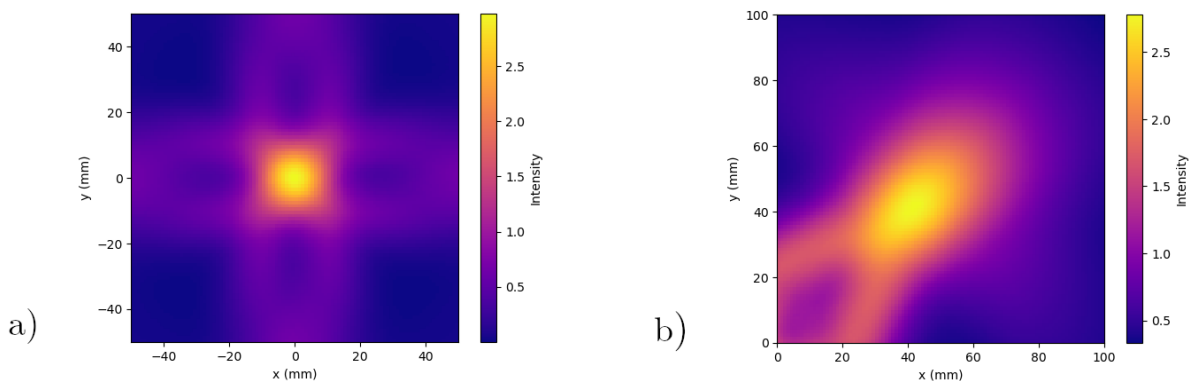


Figure 5. The reconstructed images of the 662 keV source positioned in front of the face of the CC in a), and above the vertex in b).

4 DISCUSSION

Intrinsic efficiency of the CC's faces improve with greater source-to-detector distances, since the gamma rays' angle of incidence becomes perpendicular to the face's surface, and the edge effects subside. This is evident in a approx. 60% increase visible in Fig. 3A, for point source of 662 keV energy. Similarly, the vertices exhibit the highest intrinsic efficiency when the source is closest to the vertex, where for 10 mm Distance the efficiency of the vertices exceed the efficiency of the faces, but falls off 10% with increasing source-to-vertex distance. The difference in geometric efficiencies between the faces and vertices is greatest when the source is the closest to the detector. The reason for this is the size of the cross section of the detector with which the gamma rays emitted isotropically from a point source can interact, which is effectively greater for the vertices due to the edge effects, prominent if the source is very near the face of the detector cube, except in the case of the source-to-detector distance of 10 mm, which is higher for the faces than the vertices of the CC. The absolute efficiency of detection shows no significant difference between the faces and the vertices, and falls off exponentially with increasing source-to-detector distance. With data selection as described in Subsection 2.4, the Compton sensitivity is lower for the face than for the vertex, because of the higher number of combinations available for photoelectric absorption inside the defined cone if the source is above the vertex. This can be improved by selecting a wider cone for the reconstruction of images of gamma rays that interacted with the face and improve the number of events available for reconstruction, but could also have diminishing returns regarding the angular resolution of the image. The images of the 662 keV point source at 50 mm Distance from the face and the vertex are reconstructed, which suggests the detector can act as a directionally sensitive CC. The image of the source above the vertex displays artefacts in the lower left area of the image, as well as deviation in the shape of the source, which are the result of utilizing the simple back projection algorithm for image reconstruction. This algorithm has reduced angular coverage, and the edge effects influence the reconstruction, leading to uneven sensitivity near the edges of the FOV, especially close to the origin of the plane (0, 0). This could be improved by utilizing other image reconstruction algorithms that do not suffer from such shortcomings, for example, forward back projection or Maximum Likelihood Expectation Maximization (MLEM) algorithm.

5 CONCLUSION

We propose a novel detector design with potential CC modality, employing cubical voxels made of GAGG scintillator crystals, read-out with two perpendicular SiPMs positioned on neighbouring faces of the detector. The characteristics of the detector response were studied with Monte Carlo simulations made in Geant 4 programming package, and the feasibility of the CC modality was tested by image reconstruction via simple back projection algorithm. The non-uniformity in the detector's sensitive volume does not impose a restraint in the operation of the detector, since the differences between the different faces, as well as vertices, are negligible. As expected, the absolute efficiency of the detector falls off with increasing source-to-detector distance, with no significant differences when the source is positioned in front of the faces of the detector or above the vertices. The angular resolution of the CC is comparable to similar detector designs. The CC modality is tested and images of a point source with 662 keV energy at the Distance of 50 mm from the face and the vertex of the detector is obtained. It is possible to ascertain the direction from which the gamma ray source is seen by the CC, but more advanced image reconstruction algorithms are required for more accurate representation of the point source above the vertex of the CC.

ACKNOWLEDGEMENTS

This research was funded by the European Union – Next Generation EU and is part of the project Voxel Matrix Detector for Full Solid Angle Radiological Imaging – VMDSan - NPOO.C3.2.R2-I1.06.0084.

REFERENCES

- [1] Sato, Y., Tanifuji, Y., Terasaka, Y., Usami, H., Kaburagi, M., Kawabata, K., Utsugi W., Kikuchi H., Takahira S., Torii, T. . Radiation imaging using a compact Compton camera inside the Fukushima Daiichi Nuclear Power Station building. *Journal of Nuclear Science and Technology*, Vol. 55 no. 9, pp. 965–970, 2018, <https://doi.org/10.1080/00223131.2018.1473171>
- [2] A. Kishimoto, J. Kataoka, T. Kato, T. Miura, T. Nakamori, K. Kamada, S. Nakamura, K. Sato, Y. Ishikawa, K. Yamamura, N. Kawabata, S. Yamamoto, Development of a Dual-Sided Readout DOI-PET Module Using Large-Area Monolithic MPPC-Arrays, *IEEE Trans. Nucl. Sci.*, Vol. 60, no. 1, pp. 38-43, Feb. 2013, 10.1109/TNS.2012.2233215.
- [3] H. Lee, T. Lee, W. Lee, Development of a position-sensitive 4π Compton camera based on a single segmented scintillator, *IEEE Trans. Nucl. Sci.*, vol. 67, no. 12, pp. 2511-2522, Dec. 2020, 10.1109/TNS.2020.3037896.
- [4] P. Peng, M. S. Judenhofer, S. R. Cherry, Compton PET: a layered structure PET detector with high performance, *Phys. Med. Biol.*, Vol. 64, no. 10, pp. 10LT01, May 2019, 10.1088/1361-6560/ab1ba0.
- [5] T. Yamaya, T. Mitsuhashi, T. Matsumoto, N. Inadama, F. Nishikido, E. Yoshida, H. Murayama, H. Kawai, M. Suga, M. Watanabe, A SiPM-based isotropic-3D PET detector X'tal cube with a three-dimensional array of 1 mm³ crystals, *Phys. Med. Biol.*, Vol. 56, no. 21, pp. 6793-6807, Oct 2011, 10.1088/0031-9155/56/21/003.
- [6] M. Ghelman, N. Kopeika, S. Rotman, N. Ben David, E. Vax and A. Osovizky, Wide Energetic Response of 4π Directional Gamma Detector Based on Combination of Compton Scattering and Photoelectric Effect, *IEEE Transactions on Nuclear Science*, vol. 71, no. 5, pp. 1072-1083, May 2024, doi: 10.1109/TNS.2024.3351682.
- [7] Agostinelli, S., Allison, J., Amako, K.A., Apostolakis, J., Araujo, H., Arce, P., Asai, M., Axen, D., Banerjee, S., Behner, F. et al. Geant4—A simulation toolkit. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* 2003, Vol. 506, pp. 250–303, 2003.
- [8] O. Tang. GNU Parallel 20210822 ('Kabul'). Zenodo, 2022
- [9] Brun R and Rademakers F. ROOT - An Object Oriented Data Analysis Framework. *Nucl. Instrum. Methods Phys. Res. A*, 389:81–86, 1997.