Modeling and Simulation of a Ring Geometry CdZnTe Detector for Medical Imaging Applications

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ABSTRACT

High-fidelity radiation transport simulations complimented with high-sensitivity detector data can be used for image reconstruction in medical physics applications. Cadmium zinc telluride (CdZnTe or CZT) is an attractive compound material as a radiation detector particularly for gamma-ray imaging. This paper describes modeling of CZT detectors arranged in a ring using the Geant4 simulation tool kit for thyroid imaging with ^{123}I. Geant4 has been used extensively for high-energy charged particle transport, photon transport, and detector response characterization. This paper discusses results of Geant4 simulations using the ring-geometry CZT detector setup, forming the basic framework for further work in image reconstruction using simulated datasets.

INTRODUCTION

Cadmium zinc telluride (CdZnTe or CZT) has been extensively studied for a broad range of gamma-ray spectroscopic and imaging applications [1]. CZT provides an alternative to high purity germanium (HPGe) detectors that typically require a cryogenic operating condition. CZT can be operated at room temperature to produce high energy-resolution spectra comparable to HPGe. Furthermore, finely-pixelated CZT detectors provide high spatial resolution that is of great interest in the medical imaging applications.

Parathyroid glands are located in the neck region of a human body. They secret parathyroid hormone which enhances the release of calcium into the blood when it does not function normally. Hyperactive parathyroid glands can lead to complex health issues which include kidney and skeletal problems amongst others [2].

To study these glands, a radioisotope of iodine, ^{123}I (half-life: ~13.22 hours) is often used along with ^{99m}Tc-pertechnetate. Iodine-123 decays by electron capture to ^{123}Te, and in the process, emits gamma rays predominantly with energy of 159 keV. A gamma camera is used to capture these gamma rays and generates images of the glands that reveal condition of thyroid function and identify potential anomalies [3].

Geant4 is a free software package written in C++ that exploits software engineering techniques and object-oriented programming to achieve efficiency and ease of modern programming language. The package is composed of tools (written in form of objects) that can be used to accurately simulate the passage of particle through matter. Geant4 is capable of simulating both high- and low-energy physic processes using a wide variety of sources and data drawn from expertise across the global research community [4].

DESCRIPTION OF WORK

Background

Geant4 has been used in a broad range of applications by nuclear engineering and nuclear physics communities. At Brookhaven National Laboratory (BNL), it has been used to simulate response of CZT detectors to nuclear materials and medical radionuclides. The last updated model of a CZT (Figure 1) in Geant4 upon which the current research was built was a version generated in 2012. Since then, Geant4 has undergone a number of significant alterations with improved efficiency and new functionalities. The work described in this paper is the effort of extending this model to include the modern capabilities in Geant4.

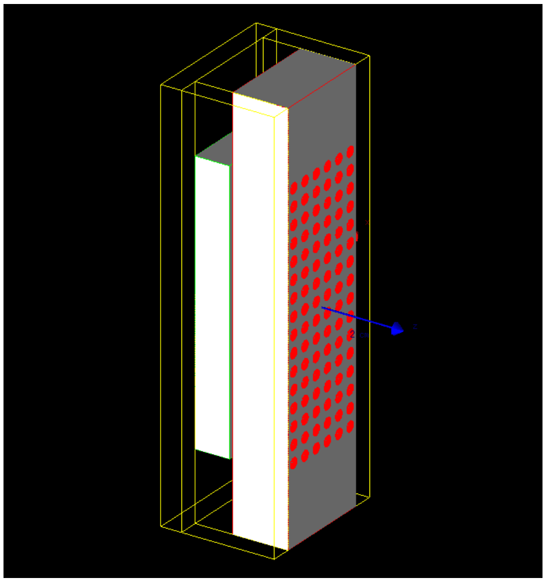


Fig. 1: 16 x 6 2-D CZT Camera Model

Geant4 Model

Geant4 was used to model a physical CZT detector. Similar to most radiation physics modeling tool kits, three aspects must be defined in the model to achieve a successful simulation environment: (1) geometry definition, (2) physics/primary particle generation definition, and (3) event/run action [5].

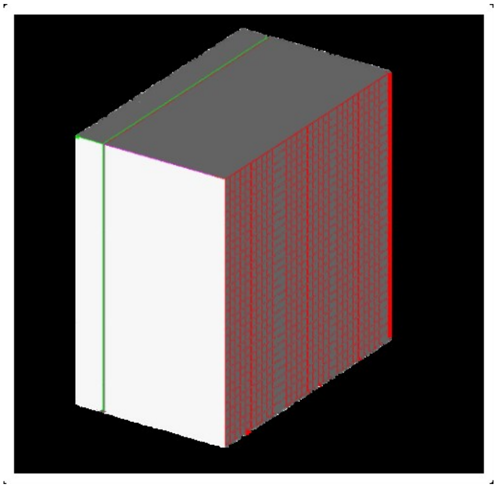


Fig. 2: Modeled CZT detector with 32x32 pixels coupled to a parallel-hole collimator

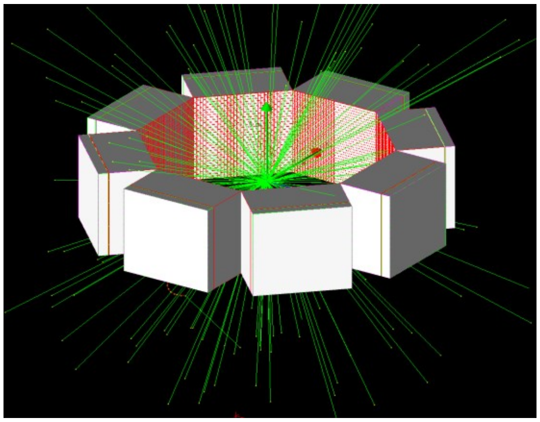


Fig. 3: Particle trajectory in the Ring CZT Camera

A total of eight CZT pixelated detectors (Figure 2) are placed in a ring configuration (Figures 3). Preliminary modeling effort involved using a point source placed at the center to represent a simplified ingested source. The material composition data are obtained from the National Institute of Standard and Technology (NIST). A set of detailed descriptions of the CZT detector model was developed using a number of header files structured in the form of objects.

For each simulation run, one million events (initial particles) were generated to obtain the histograms and eventually spectra presented in this paper. Figure 3 shows the particle trajectory emanating from the source at its center, generated using 200 source events.

RESULTS AND ANALYSIS

To characterize the CZT detector's response to gamma-ray photons, two sources were analyzed (i.e. low and high energy photons). The ^{123}I is typically used for thyroid imaging with the photon energy 159 keV, used as low energy source. A relatively high energy emitting radionuclide commonly available in medical and research facilities is ^{137}Cs with the photon energy at 622 keV. The spectrum of the high energy photons from ^{137}Cs are used to verify the next to absent Compton region of the low energy spectrum derived from ^{123}I. At low energies, the effect of Compton scatter is negligible, Figure 5. The observed behavior is due to the low Compton scattering cross section for low- z isotopes at lower photon energies.

For each simulation, 8 separate histograms are generated, one for each detector in the ring. The spectrums are generated from collapsing the output histogram for the two sources.

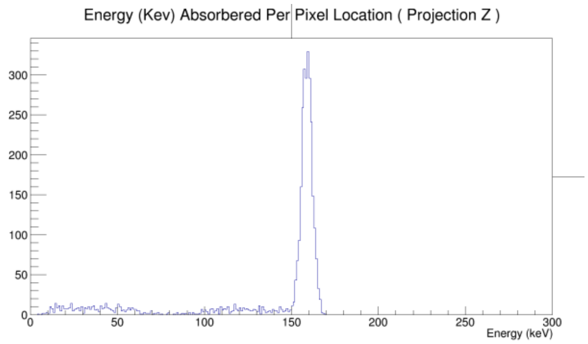


Fig. 5: Cumulative detector spectrum to I-123

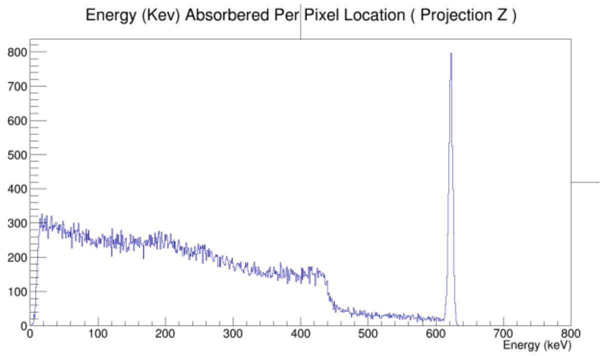


Fig. 6: Cumulative detector spectrum to Cs-137

To simulate a more complex source, representative of an organ source, multiple point sources are positioned inside the ring detectors, Figure 6. Figure 7-9 show the detector response of crystal D1, D2 and D3 respectively. It is important to note that each of crystals D1, D2 and D3 have been chosen to represent three source-detector geometry configuration. The orientation of the 6 point sources have been chosen to simulate both symmetric and asymmetric scenarios between each source and crystal location.

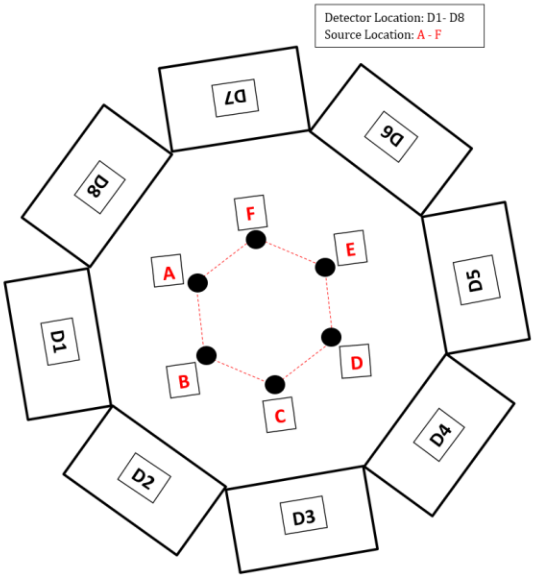
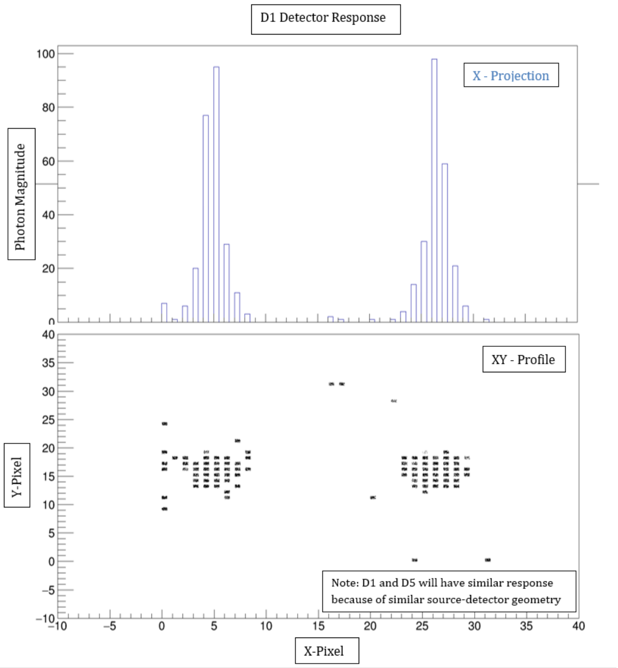


Fig. 7: Positions of radioactive sources inside the detector ring



Note: D1 and D5 will have similar response because of similar source-detector geometry

Fig. 8: Photon response of detector crystal D1

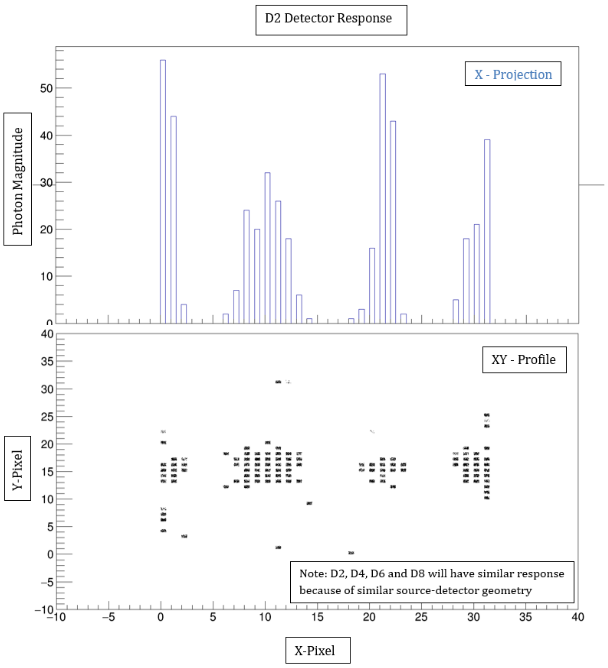


Fig. 9: Photon response of detector crystal D2

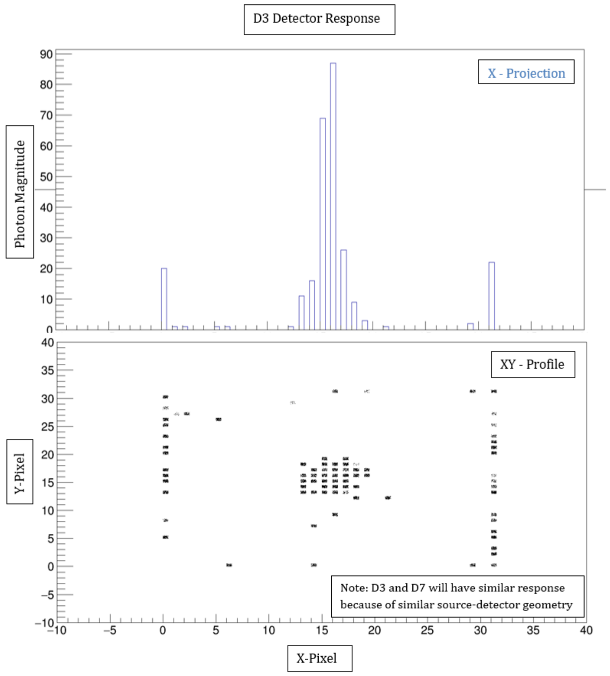


Fig. 10: Photon response of detector crystal D3

CONCLUSIONS

Detectors' response to each of the sources varies according to the source-detector geometry. GEANT4 model was able to characterize the detector behavior as expected in 2D source distribution. For example, the detector response for detector position D3 is dominated by point source at C but it still records response from sources positions B and D. This results form the basis of image reconstruction. The next step is to place sources in x-y-z coordinates to convolute a detector response to multiple point-sources placed in 3 dimensions. Finally, the simulation include a model of an asymmetrical, complex source, organ (i.e. Thyroid). The results will be compared to the experimental data.

Based on the results, it is possible to model a CZT detector configuration like the ring-geometry we modeled in Geant4 for medical applications. Future work may constitute modeling thyroid gland and surrounding tissue to characterize the self-shielding effect, the distributed source and asymmetry effects in all three directions. Further experimental data from the pixels in the 8 ring detectors with appropriate radionuclide collimator [6] will be collected and reconstructed to produce images of the sources. The benchmarked model will be used to model other physical process of interest once the geometry and the physical process is properly understood and implemented in Geant4.

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