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A Simulation Study of a Pixelated CZT Detector Combined Energy-Independent Collimator Using Finite Element and Monte Carlo Methods for SPECT Applications

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A Simulation Study of a Pixelated CZT Detector Combined Energy-Independent Collimator Using Finite Element and Monte Carlo Methods for SPECT Applications

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Introduction

Compared to other semiconductor materials, **Cadmium Zinc Telluride (CZT)** is currently considered a leading material for use in clinical SPECT applications [1]. Over the last few decades, simulation and experimental studies related to the charge sharing effect of pixelated CZT detectors have been performed in order to estimate the charge sharing effect between two neighboring pixels and to determine the optimum pixel size of CZT detectors.

The goal of this work is to investigate the **charge-transport effect** in our pixelated CZT detector design using various radionuclides covering a broad range of gamma emission energies **from Tl-201 to I-131** that are used for **clinical SPECT applications** and to estimate physical effects in the detectors combined with our **energy-optimized high-sensitivity pixel-matching parallel-hole collimator** [2].

Materials and Methods

Specification of CZT Detector

- CZT detector size
  - 1.6 mm × 1.6 mm × 5.0 mm with 0.1 mm pixel gap
  - 9 pixels in 3 × 3 square pixel

Material Properties	
Average atomic number	49.1
Density (g/cm^3)	5.78
Electron mobility (cm^2/Vs)	1000
Electron lifetime (s)	3×10^{-6}
Hole mobility (cm^2/Vs)	50 ~ 80
Hole lifetime (s)	10^{-6}
Dielectric constant	10.9
Resistivity (cm)	3×10^{10}
Nominal operating bias voltage, range (V)	-500, -200 to -1000
Plating (Anode & Cathode)	Au

Detector Model Properties	
Pixel size (mm^3)	1.6 × 1.6 × 5
Pixel gap (mm)	0.1
Hole length (mm)	23
Septa thickness (mm)	0.32
Hole diameter (mm)	1.28
Hole shape	Rectangular
Material	Tungsten-Alloy

Detector Model

- investigated center, corner and edge pixels of CZT detector module
- simulated **weighting potential, CIE 3D-map, and diverse energy spectrum**

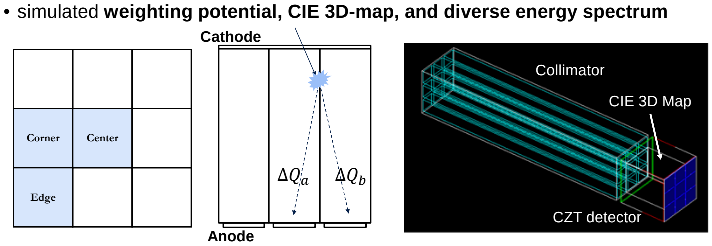

Figure 1. 3 × 3 pixelated CZT detector model corresponding to Center, Corner and Edge pixel and simulation model including collimator and CIE 3D map

Simulation

- Monte Carlo (MC) Simulation
  - **GEANT4** (version 10.4 supporting multi-threading) [3]
  - to investigate a motion of incident photon inside the modeled CZT detector
  - Physics Lists (Standard Electromagnetic Physics option 4) for ; Photoelectric effect, Compton, Rayleigh scattering and x-ray fluorescence
  - with diverse point sources; Tl-201 (71 keV), Co-57 (122 keV), Tc-99m (140 keV), Lu-177 (113, 208 keV) In-111 (177, 245 keV), I-123 (159 keV), and I-131 (364 keV)
- Finite Element Method (FEM)
  - **COMSOL MULTIPHYSICS** (version 5.4) software with AC/DC module [4]
  - to calculate the charge transport in the CZT detector
  - provided graphical user interface to fine geometry of our model
  - with environment, specify material properties, physical constants, and necessary equations

Equation for Charge Sharing Model

- calculation of the induced charge signal based on the Shockley-Ramo theorem[5]
- with electric field and weighting potential
- a map of **Charge Induction Efficiency (CIE)** of the k electrode for a specific position suggested by Prettyman [6] using adjoint electron n* could be solved by following equation;

$$\underbrace{\frac{\partial n^*}{\partial t} = \mu_e \nabla\varphi\nabla\phi_w}_{\text{carrier generation term}} \underbrace{- \frac{n^*}{\tau_e}}_{\text{trapping rate}} \underbrace{+ \mu_e \nabla\varphi\nabla n^*}_{\text{current density of drifting carriers}} \underbrace{+ D_n \nabla^2 n^*}_{\text{current density of electron diffusion}}$$

τ_e average lifetime of electrons,
μ_e mobility for electron,
D_n diffusion constant for electron,
$\nabla\varphi$ electric potential,
$\nabla\phi_w$ weighting potential

Results

Weighting Potential

- The weighting potential has a steep rising at the anode
- at the red arrow, induced charge would be less than that induced from other parts of the pixel volume because the difference between the weighting potentials in the electron generation location and the collecting anode would be much less than 1

$$induced\ charge = -q(\underbrace{\phi_w(x_n)}_{\text{Weighting Potential in the collecting anode}} - \underbrace{\phi_w(x_0)}_{\text{Weighting Potential at the electron generation location}})$$

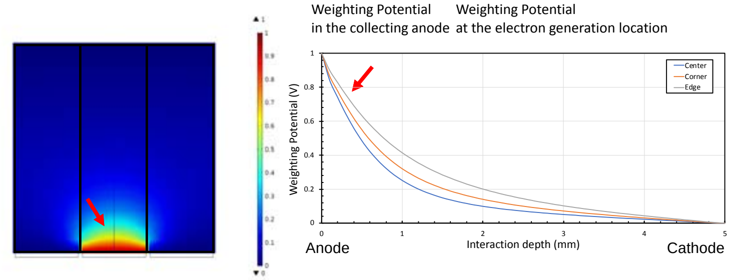

Figure 2. Weighting potential in 3 × 3 pixelated CZT detector. An example 2D distribution of the weighting potential at center pixel (left) and the weighting potential along a line crossing at center corresponding to center, corner and edge pixel

Charge Induction Efficiency 3D Map

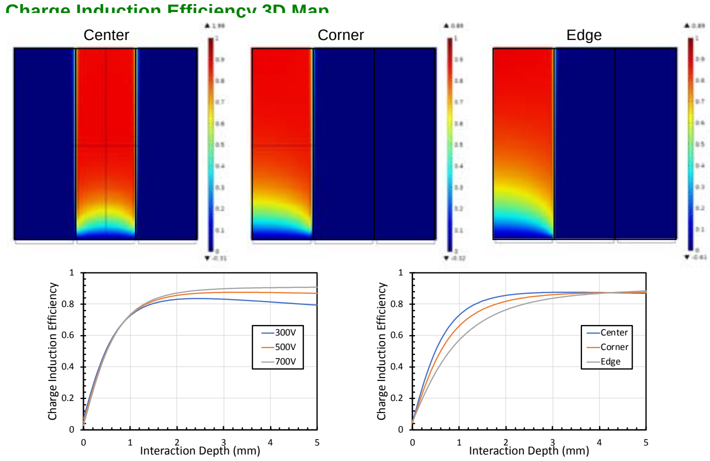

Figure 3. CIE 3D map and profiles corresponding to center, corner and edge pixel with different operating bias voltages applied

MC Simulation

- simulated energy spectra with diverse energy ranges (w/o FEM)

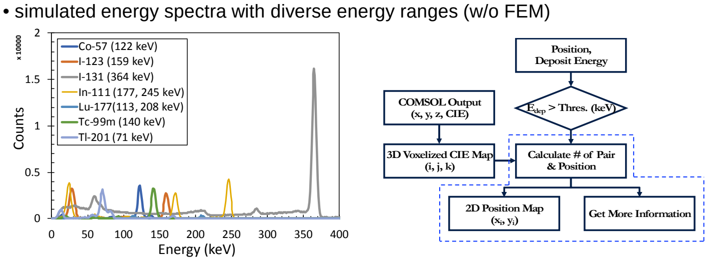

Figure 4. Initial simulated energy spectra (left) and a simple diagram for further study (blue dotted-box) combining FEM and MC method

Further Study

We will import the CIE 3D map to the modeled pixelated CZT detector module combining parallel hole collimator. Also, we plan to correctly predict the effects that take place in the detector module and to optimize the data recording algorithm using this model for our energy-independent and high-sensitivity general-purpose CZT SPECT system.

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