Semiconductor detectors for Compton imaging in nuclear medicine

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Semiconductor detectors for Compton imaging in nuclear medicine

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ABSTRACT: An investigation is underway at the University of Liverpool to assess the suitability of two position sensitive semiconductor detectors as components of a Compton camera for nuclear medical imaging. The ProSPECTus project aims to improve image quality, provide shorter data acquisition times and lower patient doses by replacing conventional Single Photon Emission Computed Tomography (SPECT) systems. These mechanically collimated systems are employed to locate a radioactive tracer that has been administered to a patient to study specifically targeted physiological processes. The ProSPECTus system will be composed of a Si(Li) detector and a High Purity Germanium (HPGe) detector, a configuration deemed optimum using a validated Geant4 simulation package. Characterising the response of the detectors to gamma irradiation is essential in maximising the sensitivity and image resolution of the system. To this end, the performance of the HPGe ProSPECTus detector and a suitable Si(Li) detector has been assessed at the University of Liverpool. The energy resolution of the detectors has been measured and a surface scan of the Si(Li) detector has been performed using a finely collimated $^{241}$Am gamma ray source. Results from the investigation will be presented.

KEYWORDS: Gamma detectors (scintillators, CZT, HPG, HgI etc); Compton imaging

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1 Introduction

Single Photon Emission Computed Tomography (SPECT) systems employ a gamma camera to locate a radioactive tracer which has been administered to a patient to study a specifically targeted physiological process. A typical system is composed of scintillation detectors coupled to a mechanical collimator which allows the radiation distribution to be inferred. However, use of the collimator results in only a small fraction of the patient dose being used to generate a SPECT image. The ProSPECTus project [1] aims to improve image quality, shorten data acquisition times and lower patient doses by replacing the gamma camera with a semiconductor detector Compton camera [2]. The ProSPECTus system will be composed of a Si(Li) scatter detector and HPGe absorber detector, a configuration deemed optimum [3] using an experimentally validated Geant4 [4, 5] simulation.

Utilising position and energy sensitive detectors in the system is essential as Compton kinematics are employed to reconstruct the paths of incident gamma rays using the interaction positions and energy depositions within the scatter and absorber detectors. Images are typically generated using cone beam reconstruction techniques [6], where the maximum overlap in cone surfaces reveals the location of the radiation source. However, more advanced iterative reconstruction techniques can be employed to significantly improve image quality [7]. The principle sources of image degradation are the energy resolution and position resolution of the detectors, Doppler broadening in the scatter detector, the geometrical configuration and detector non-uniformity [1]. Therefore, characterising the response of the detectors to gamma irradiation is essential in optimising the performance of the system.

2 The ProSPECTus HPGe detector

The absorber detector that will be used for the ProSPECTus Compton camera is an ORTEC manufactured HPGe strip detector. It has a (60×60×20) mm active volume that is electronically segmented through orthogonal contacts to give 12 AC (p-type) and 12 DC (n-type) contact strips with a strip pitch of 5 mm which provide position of interaction information, as shown in figure 1. The
Figure 1. A schematic illustration of the ProSPECTus HPGe detector.

AC coupled contacts are 0.3 $\mu$m thick and are separated by 180 $\mu$m and the DC coupled strips are 50 $\mu$m thick and have a larger gap separation of 300 $\mu$m. The detector is currently housed inside a temporary test cryostat. This contains two ORTEC fast charge-sensitive preamplifiers that can be connected to one AC and one DC channel. To investigate the output of all channels, the preamplifiers therefore have to be moved between measurements. The crystal is fully depleted at +900 V and has an operating voltage of +1200 V supplied to the AC contacts, whilst the DC contacts remain grounded.

2.1 Energy resolution

To accurately assess if an incident gamma ray has deposited all of its energy within a Compton imaging system, it is essential for the detectors to have excellent energy resolution. This is of particular importance if the system is intended for use in multiple-isotope imaging, where discrimination of gamma rays with similar emission energies may be required. In medicine, two common radioisotopes for nuclear medical imaging are $^{99m}$Tc and $^{123}$I, which emit gamma rays with energies of 141 keV and 159 keV, respectively. It is an aim of the ProSPECTus project to build a Compton imaging device which will be capable of discriminating these two radioisotopes. The acceptance criteria of the ProSPECTus absorber detector are such that the energy resolution of the ProSPECTus detector must have an average Full Width at Half Maximum (FWHM) of less than 1.7 keV at 122 keV and all channels must have a FWHM of less than 2.3 keV at 122 keV. The criteria were determined in previous work using Geant4 simulations to model the influence of energy resolution on the image quality and the ability to discriminate multiple radioisotopes of similar energy [1].

Following delivery of the ProSPECTus absorber detector to the University of Liverpool, the FWHM at 122 keV was measured for every AC and DC channel of the detector mounted in the
The maximum acceptable FWHM is illustrated by the dashed green line. When the source was positioned at either side of the detector, the FWHM of the DC channels was measured with a uniform response, in agreement with the manufacturer’s quoted results, as shown in figure 2. When the source was incident from the AC face and DC face, the average FWHM of the DC channels was calculated to be 1.48 keV and 1.50 keV within a 1.44 to 1.67 keV and 1.40 to 1.71 keV range, respectively. The DC channels therefore meet the identified performance criteria. For the AC channels, when the source was incident on the AC face of the detector, a uniform response was observed, with an average FWHM of 1.50 keV and a range of 1.38 to 1.82 keV, meeting the specified requirements. However, when the source was incident on the DC face of the detector, the average FWHM at 122 keV was measured to be 1.99 keV and the range was 1.62 to 2.62 keV. This degradation of performance is due to a slight low energy tail in the photopeak. These findings are consistent with measurements made by ORTEC before shipping and are possibly due to electron trapping in the detector. In this case, the performance is expected to be worse for the AC channels when the gamma rays deposit their energy far from the AC face, which will occur when a low energy source such as $^{57}$Co is incident on the DC face. When the detector is fully furnished with 24 preamplifiers, it will be possible to further investigate this degradation.

The energy resolution is suitable for the absorber component of the ProSPECTus Compton camera. A measurement of energy is required from only one detector face and therefore the DC channels can be used, avoiding potentially compromised performance through use of the AC channels. It is expected from previous investigations using Geant4 simulations that the contribution to image FWHM from the energy resolution of this absorber detector will be negligible relative to the scatter detector.

### 3 A Si(Li) detector

The scatter detector under investigation in this work is a Canberra Si(Li) strip planar detector with 13 channels on each circular face, as shown in figure 3. Unlike the ProSPECTus HPGe detector, every channel is currently furnished with a Canberra preamplifier. The detector has an active area...
Figure 3. Photographs showing the (a) Si(Li) detector in its cryostat with the Cryo-Pulse 5 cooler and controller device and (b) preamplifiers.

of 3500 mm$^2$ and a thickness of 8 mm. It is operated at +430 V and cryogenically cooled using a CryoPulse CP5 cooler.

3.1 Energy resolution

The FWHM of the Si(Li) detector has been measured using a $^{241}$Am source. Channel 01 on the DC face of the detector (an edge strip) was excluded from the results as it produced no signal. Other than this defective channel, the detector was shown to have excellent energy resolution, as the FWHM was measured to be within the range 1.4 to 1.6 keV at 59.4 keV, for all channels. An accurate measurement of energy in the scatter detector is required to reconstruct cones with minimum uncertainty in the cone apex angle. The influence of energy resolution in degradation of image quality has been determined in previous work using Geant4 simulations [1]. For this scatter detector with $\sim$1.5 keV FWHM, it is expected from previous simulations that an image generated for a point source of 141 keV gamma rays, will have an image FWHM of $\sim$12 mm. Therefore, the excellent energy resolution of this detector makes it an ideal scatter component of a Compton camera.

3.2 Noise levels

The sensitivity of a Compton camera for nuclear medical imaging will be significantly affected by the low energy threshold set experimentally to discriminate true energy deposition from electronic noise. Gamma rays with 141 keV incident energy which Compton scatter once in the scatter detector will transfer less than 40 keV and the distribution of energy deposits is heavily weighted towards low energies, as shown in figure 4 for data simulated using Geant4.
Due to the distribution of energy deposited by events which Compton scatter once in the scatter
detector, it is expected that removing such events via a low energy threshold will considerably
reduce the sensitivity of the system. For the absorber detector, the energy deposited by a gamma
ray after a single Compton scatter in the scatter detector will be greater than 100 keV, as shown in
figure 4, therefore application of a low energy threshold on the absorber detector is not expected to
degrade the performance.

The influence of setting a low energy threshold on the scatter detector has been investigated
for the ProSPECTus Compton camera using Geant4 simulations and the results are presented in
figure 5, for various gamma ray energies within a range suitable for medical imaging. It can
be seen that the application of a low energy threshold is more influential to the loss of data as
the threshold increases. For gamma rays with 141 keV incident energy, a 50% loss for a 10 keV
threshold is recorded in comparison with a 10% loss for a 2 keV threshold. As the incident gamma
ray energy is increased, the effect is shown to be significantly reduced, as for gamma rays with
364 keV incident energy, only a 5% loss for a 10 keV threshold and 1% for a 2 keV threshold
is observed.

Although it is essential to minimise the loss of data, there are practical limitations to setting
low energy thresholds experimentally, restricted by the noise in the system and inherently in the
detector. For the ProSPECTus system, it was decided that the maximum acceptable energy thresh-
old of the scatter detector should be 5 keV, where a loss of 25% is expected to occur for 141 keV
gamma rays, informed by the Geant4 simulations. However, reducing the noise to less than 5 keV
in the detector would be extremely beneficial in maximising sensitivity of the device. The noise
levels for this Si(Li) detector have therefore been measured, to investigate its suitability for med-
cial Compton imaging. The main source of noise in this measurement is electronic noise from
the detector components, such as the FET (Field Effect Transistor) which is not cooled. The re-
results showed that for the DC channels, the noise was approximately 2 keV, whilst the AC channels
have a slightly enhanced noise ranging from 2.5 to 4.5 keV. Therefore, the experimental low energy
threshold can be set on the DC face of this detector, where the noise levels and thus sensitivity
losses are lowest. As the maximum noise measured for the DC channels was 2 keV, it is expected
that the 5 keV threshold can be achieved.
Figure 5. A graph showing the percentage of Compton imaging events removed due to the application of a low energy threshold, from a data set containing gamma rays which Compton scatter once in the scatter detector and once in the absorber detector.

3.3 $^{241}$Am surface scan

The uniformity of response to gamma irradiation for the Si(Li) has been assessed by precisely scanning a 1 mm collimated $^{241}$Am source across the AC and DC faces of the detector. An automated Parker x-y positioning table was used to scan the surface of the detector in 1 mm steps across a (76 × 76) mm grid. Over 65 hours of data were acquired for the DC surface scan, with a step duration of 40 s and count rate of 200 s$^{-1}$. The step duration for the AC surface scan was 45 s, the count rate was 290 s$^{-1}$ and the total acquisition time was approximately 80 hours.

Pulse shape and energy data were recorded from the detector using the GRETINA Digitizer cards [8]. Events were only recorded when the energy deposited in at least one DC channel was more than the energy threshold (10 keV). The events were categorised according to their fold, which is defined as the number of channels which record a net charge, if at least one channel has recorded over the energy threshold (10 keV for DC channels, 0 keV for AC channels). Approximately 85% and 83% of energy gated events were categorised as single pixel events (fold [1,1]) for the DC and AC irradiated face, respectively.

Intensity plots as a function of scanning table position have been produced for the DC and AC surface scans, as shown in figure 4. The top panel shows intensity plots which include events for all folds and the bottom panel shows the plots gated on events with single pixel interactions (fold [1,1]). The DC channels are oriented vertically from left to right and the AC channels are oriented horizontally from top to bottom. An energy gate of 8 keV has been applied to the 59.4 keV $^{241}$Am photopeak. The intensity plots in the top panel show a relatively uniform response to irradiation across both surfaces of the detector, with the edges recording slightly less data due to increased probability of gamma rays scattering beyond the active volume. The low intensity region on the left hand side of these plots represents the position of channel DC01 which was not instrumented. In addition, a reduction in intensity of approximately 30% in the inter-strip gap is evident between DC12 and DC13, illustrated by the region enclosed by the dotted line in figure 6a. This could be indicative of a charge collection or cross-talk problem between these strips, relative to the rest of the detector. Within the region of channels AC01 to AC04, an 8% reduction in the intensity is also observed in both scans, shown for illustrative purposes in the region enclosed by the dashed line in figure 6a. The cause of this slight reduction is currently under investigation.
Figure 6. Energy gated intensity plots as a function of scanning table position for the source incident on (a) the DC face and (b) the AC face for all folds and on (c) the DC face and (d) the AC face for single pixel events. The dashed line indicates a region of reduced counts across strips AC01-AC04 and the dotted line highlights the 30% reduction in counts in the interstrip gap between DC12 and DC13.

The intensity plots for single pixel events (bottom panel of figure 6) show a reduction in the number of counts recorded in the inter-strip gap between the DC channels (and to a much lesser extent the AC channels). This can be translated as an increase in the number of counts in these regions of the intensity plot for multiple pixel events, shown in figure 7.

Such behaviour has been reported in germanium strip detectors [9] and it was suggested that when a single interaction occurs in the inter-strip gap, the charge carriers produced in the detector are collected by the two strips adjacent to the gap, registering as a fold 2 type event. This effect is more evident between the DC channels, which could be as a result of a smaller inter-strip gap, leading to an increased probability of charge sharing between the strips. It is essential to understand this phenomenon so that the true interaction position can be identified and used in Compton image reconstruction. To this end, an investigation into this cause of this effect is ongoing.

4 Conclusions and discussion

The performance of the ProSPECTus HPGe absorber detector and a Si(Li) detector have been investigated. The energy resolution was measured for the HPGe detector and results showed that the average FWHM at 122 keV was \( \sim 1.5 \) keV, unless the source was incident on the DC face of the
detector which resulted in an average FWHM for the AC channels of $\sim 1.99$ keV. As it is required that the energy is readout by only the AC or only the DC channels, it is recommended that the DC channels are used, to ensure optimum performance. The ProSPECTus HPGe detector performance is deemed acceptable for its use as an absorber detector in Compton imaging.

The average FWHM of the Si(Li) detector was measured to be $\sim 1.5$ keV at 59.4 keV and the noise levels ranged from 2.0 to 4.5 keV, which are excellent performance characteristics for its intended use as a scatter detector. The uniformity of the Si(Li) detector in response to irradiation from a 1 mm collimated beam has been discussed. The detector shows relatively good uniformity, with some interesting charge collection features which are currently under investigation. These features are not expected to significantly degrade the performance of the system as a Compton camera, and it is recommended that the detector is utilised in the imminent acquisition of preliminary Compton imaging data for gamma ray point sources of varying energy, to assess system efficiency and image quality. Future work with the system will include the acquisition of Compton imaging data for medical phantoms.

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