

Position sensitivity of the first SmartPET HPGe detector

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Abstract

In this paper we discuss the Smart Positron Emission Tomography (PET) imaging system being developed by the University of Liverpool in conjunction with CCLRC Daresbury Laboratory. We describe the motivation for the development of a semiconductor-based PET system and the advantages it will offer over current tomographs. Details of the detectors and associated electronics are discussed and results of high precision scans are presented. Analysis of this scan data has facilitated full characterization of the detector response function and calibration of the three-dimensional position sensitivity. This work presents the analysis of the depth sensitivity of the detector.

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1. Introduction

The SmartPET project aims to exploit advances in the sensitivity, energy and position resolution of High Purity Germanium (HPGe) detectors to construct a small animal Positron Emission Tomography (PET) demonstrator system. The development of sophisticated digital electronics and the use of Pulse Shape Analysis (PSA) [1] and γ -ray tracking (GRT) algorithms [2] will allow accurate position and energy information to be extracted, enabling scattered interactions to be identified and used for image reconstruction.

2. The SmartPET system

In clinical PET systems over 60% of γ -rays emerging from a patient undergo Compton scattering before reaching the detectors [3]. Conventionally, these events are

rejected on the basis of energy, resulting in a highly inefficient system.

The SmartPET project aims to tackle the deficiencies in current PET systems by utilizing the excellent energy resolution and position sensitivity offered by HPGe detectors to include a greater proportion of events in the reconstruction data set. This increased efficiency aims to reduce patient dose and increase patient throughput, while precise knowledge of γ -ray energy and interaction position will improve the spatial resolution achievable in diagnostic images.

In addition, the system has the ability to function in a magnetic field and as a result holds the potential for dual modality PET/MRI imaging.

2.1. The SmartPET detectors

SmartPET utilizes a dual head configuration comprising two planar HPGe detectors mounted in a rotating gantry to allow data acquisition over 180°. These detectors, manufactured to our specifications by ORTEC (Fig. 1),

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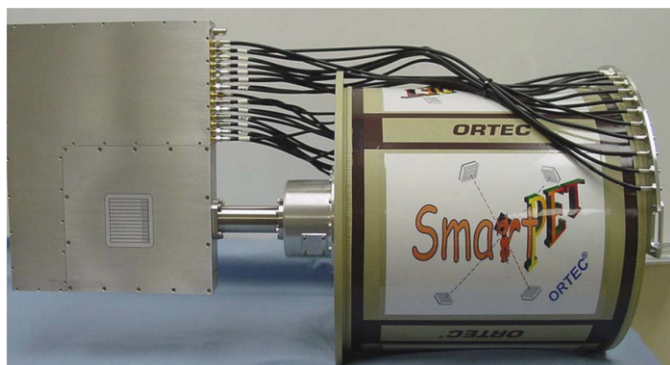


Fig. 1. The first SmartPET HPGe detector at Liverpool.

have dimensions of $60 \times 60 \times 20$ mm and 12×12 orthogonally segmented contacts. The strip pitch is 5 mm on both sides. The active region is surrounded by a guard ring of 7 mm width and 20 mm depth. The crystal housing includes a 1 mm aluminium entrance window for increased low-energy efficiency.

The detectors have implanted contacts where the AC strips are $\sim 0.3 \mu\text{m}$ thick separated by $180 \mu\text{m}$ while the DC contact is segmented into $50 \mu\text{m}$ thick strips with $300 \mu\text{m}$ separation.

Each of the 24 strips is coupled to an ORTEC designed fast charge sensitive preamplifier with warm FET configuration and gain of 300 mV/MeV . The detectors are depleted at -1300 V and operated at -1800 V .

The use of PSA aims to improve upon the raw position resolution of $5 \times 5 \times 20$ mm provided by the segmentation of the detector. A spatial resolution of $1 \times 1 \times 1$ mm is potentially achievable [1] by analysing the preamplifier response following a γ -ray interaction. Analysis of the resulting charge pulse [4] provides depth of interaction information while calibration of transient charges induced in neighbouring strips [5] allows the lateral position to be determined.

3. Experimental measurements

The first SmartPET detector has been characterised by performing precision scans using collimated sources at a range of γ -ray energies. The scanning setup (Fig. 2) makes use of a Parker Automation positioning table [6] which moves the collimator and source at a precision of $100 \mu\text{m}$. The source is positioned on top of the scanning table surrounded by 17 cm of lead. This lead is essential if adequate shielding of the $70 \text{ MBq } ^{137}\text{Cs}$ source is to be provided. Embedded in the lead is a 1 mm diameter tungsten collimator. The first stage of the characterisation, and the focus of this work, is to calibrate the depth sensitivity of the detector. This is performed by moving the collimator over the side face of the crystal, probing the response of the detector as a function of depth. The scan has been performed over an area of 64×25 mm in 1 mm steps. The system was counting at each position for 2 min

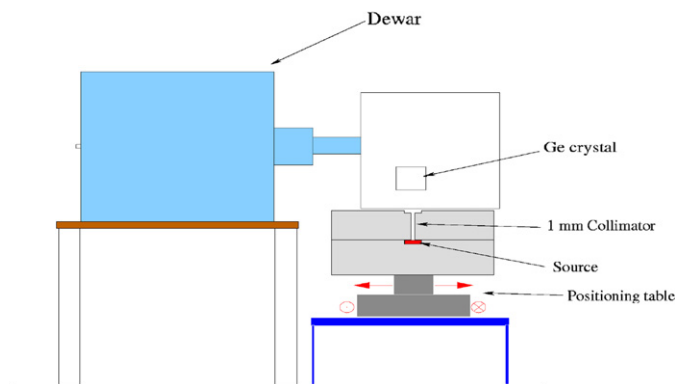


Fig. 2. The scanning table set up.

at a count rate of 70 cps. About 29% of events deposited their full energy inside a single strip.

From the side scan, risetime analysis of the charge pulse allows the position sensitivity as a function of depth to be calibrated while parameterisation of the transient charge response allows the x - y position resolution to be quantified.

3.1. The digital acquisition system

The digital DAQ system allows simultaneous readout of all 24 SmartPET preamplifiers into six, four-channel GRT4 VME cards [7]. These signals are digitised over a dynamic range of $\pm 1 \text{ V}$ using 14-bit, 80 MHz FADCs allowing pulse shapes to be stored for offline analysis. Each trace is stored as 250 samples at 12.5 ns per sample.

Each GRT4 card contains two Xilinx Spartan 2 FPGAs which derive the energy of the incident γ -ray using a Moving Window Deconvolution (MWD) algorithm [8], the energy being calculated by performing a trapezoidal fit to the decay of the preamplifier pulse. In addition, each trace is tagged with a 16-bit header and 48-bit timestamp to facilitate event correlation and the data are stored for offline analysis on an event-by-event basis.

The trigger was provided by a logical OR of the 12 DC channels. The CFD threshold for all the channels was set to 60 keV .

4. Measurements and results

The SmartPET detector has a typical energy resolution of around 1.5 keV FWHM at 122 keV and time resolution approximately 10 ns . In planar germanium detectors, the electric field is nonuniform towards the edges of the crystal and hence the charge collection and pulse shape generation processes are more complicated in these regions. As a result the response of the edge strips is not included in this analysis. A narrow energy gate is placed around the 662 keV photopeak and interactions with a multiplicity 1 on both the AC and DC side of the detector are considered. Here, we define multiplicity as being the number of strips to contain real charge. In Fig. 3 the number of events

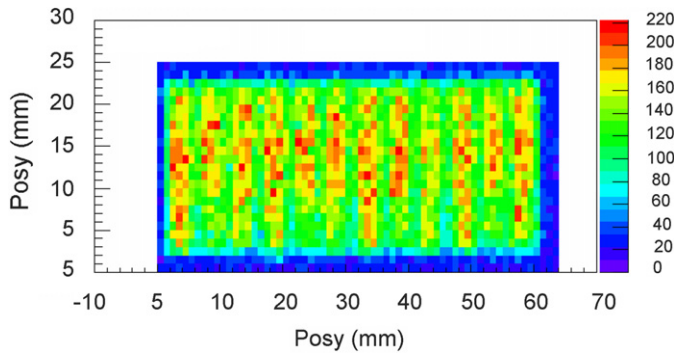


Fig. 3. The intensity (number of counts) map of the side scan. There are typically around 150 counts in each pixel.

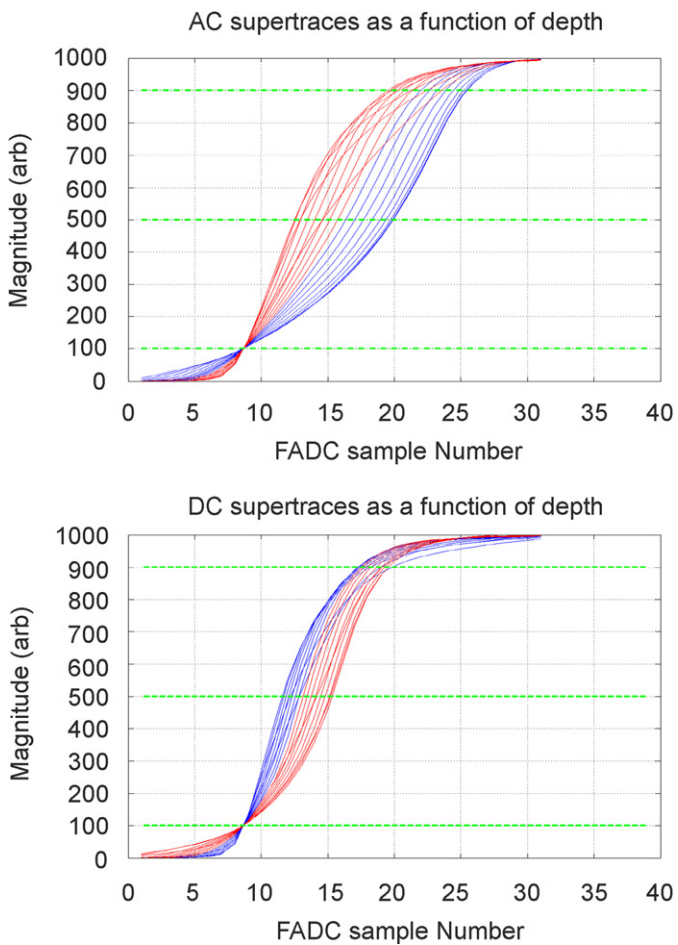


Fig. 4. AC (top) and DC (bottom) contact Superpulses as a function of depth (1 mm steps).

meeting the energy and multiplicity requirements is shown as a function of position where the *y*-axis shows the depth through the crystal.

By selecting events from this intensity matrix the pulse shapes resulting from the corresponding events can be output and analysed. These charge pulses are characterised by defining a number of parameters related to the timing properties of the trace (and therefore the charge collection within the detector). This technique, known as risetime

analysis, will typically define parameters such as T10, T50 and T90 where T10 is the time taken for the pulse shape to reach 10% of its maximum value.

It is found that the charge collection time (risetime) for typical single interaction events is similar across all strips, with the exception of edge strips, where a longer profile is observed. As a result, these regions of the detector must be considered separately and are not included in this analysis. Using all events for all strips (excluding edge strips), a pulse shape database containing all traces for a given depth was created. This database was produced every 1 mm through the depth of the detector. For every depth, each trace was then T10 time aligned, summed together and averaged producing an individual pulse shape for each depth, known as a “Supertrace” or “Superpulse”.

Fig. 4 (top) shows the average AC pulse shape as a function of depth (from DC face to AC face) and a similar response for the DC side (bottom).

The point at which the pulse shapes reach 10%, 50%, and 90% of their maximum value is marked on each plot.

Analysis of these superpulses shows that the T50 parameter exhibits the largest variation with depth. As a result this parameter is chosen for the purpose of interaction depth determination. The T50 values as a function of depth have been plotted and are shown in Fig. 5. The uncertainties in time were calculated from an analysis of the standard deviation of the baseline noise associated with each Supertrace. The uncertainty in

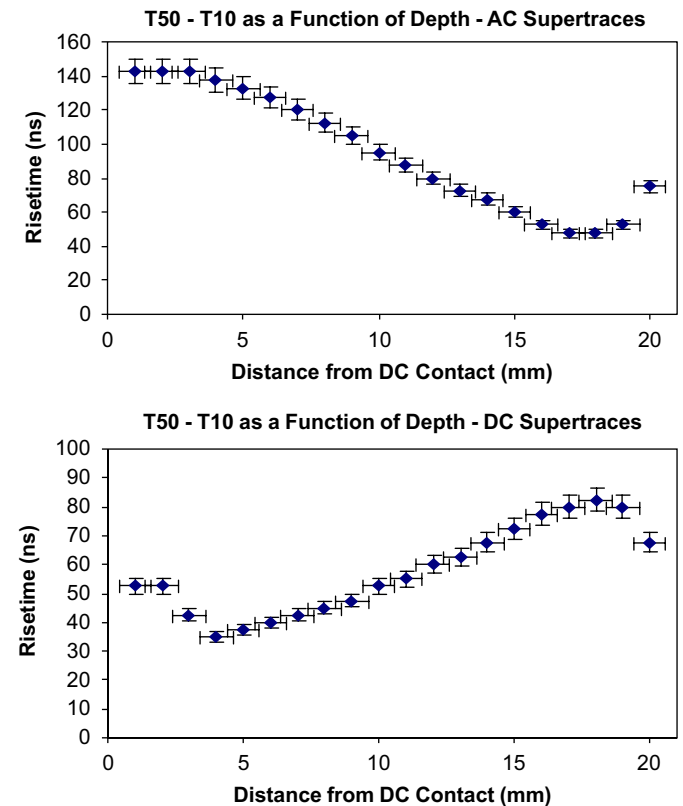


Fig. 5. T50–T10 distributions as a function of depth for AC and DC Superpulses.

Table 1
Fit parameters resulting from a linear fit to the T50 vs depth data set

	a (ns)	Δa (ns)	b (ns/mm)	Δb (ns/mm)
AC	-8.12	0.8	177.18	9.2
DC	-3.72	0.6	21.33	5.8

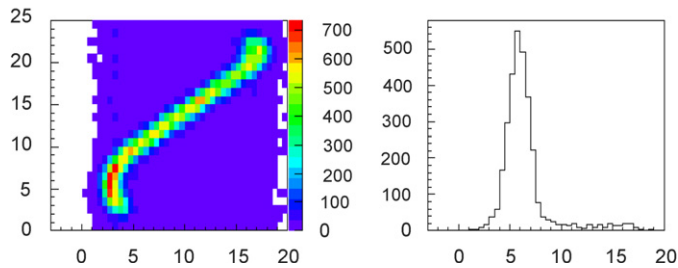


Fig. 6. Calculated position vs collimator position (left) and a slice through position 10 showing a Gaussian spread (right).

position is due to divergence of the collimated beam during scanning of the crystal.

These plots show a linear relationship between T50 risetime and depth through the majority of the detector. The regions where this linear relationship does not hold are around 3 cm from either contact. These are the regions where the weighting field [9] is large and require further investigation. In simple terms, the weighting field is a nonphysical entity which provides a framework for calculating the ability of a charge carrier to induce a signal on a contact, assuming that contact has unit bias and all other contacts are grounded. It is proposed that in regions of the detector where the weighting potential [9] is large, the charge collection response differs from the rest of the detector.

For the majority of the depth profile however, the linear relationship shown above holds. As a result a linear fit of the form $y = ax + b$ has been performed on the data and Table 1 summarises the fit parameters for both the AC and DC contacts.

By using these fit parameters it is possible to calculate the interaction position of a γ -ray. In order to test the ability of

this technique to accurately identify the position, the calculated interaction depth is compared to the collimator position. Results of this comparison are shown in Fig. 6.

By applying a Gaussian fit to the comparison data, a standard deviation of $\sigma = 1.23 \pm 0.2$ mm is calculated. This σ value provides an indication of the ability of this technique to accurately reconstruct the interaction position of single-hit full-energy γ -ray events.

5. Conclusion and discussion

A series of measurements have been made in order to investigate the position sensitivity of the planar germanium SmartPET detector. Super traces have been produced for different positions through the depth profile of the detector. Analysis of these pulse shapes show that the T50 parameter has the largest range with a good signal-to-noise ratio. By using this parameter the depth of interaction may be reconstructed. There is good agreement between this reconstructed position and the position of the scanning table. Preliminary results show that by using this method the interaction depth sensitivity through the majority of the detector is found to be less than 1 mm for single hit events.

Acknowledgements

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