TIMING PERFORMANCE OF THE SILICON PET INSERT PROBE

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Simulation indicates that PET image could be improved by upgrading a conventional ring with a probe placed close to the imaged object. In this paper, timing issues related to a PET probe using high-resistivity silicon as a detector material are addressed. The final probe will consist of several (four to eight) 1-mm thick layers of silicon detectors, segmented into $1 \times 1 \text{ mm}^2$ pads, each pad equivalent to an independent p + nn+ diode. A proper matching of events in silicon with events of the external ring can be achieved with a good timing resolution. To estimate the timing performance, measurements were performed on a simplified model probe, consisting of a single 1-mm thick detector with 256 square pads (1.4 mm side), coupled with two VATAGP7s, application-specific integrated circuits. The detector material and electronics are the same that will be used for the final probe. The model was exposed to 511 keV annihilation photons from an ^{22}Na source, and a scintillator (LYSO)–PMT assembly was used as a timing reference. Results were compared with the simulation, consisting of four parts: (i) GEANT4 implemented realistic tracking of electrons excited by annihilation photon interactions in silicon, (ii) calculation of propagation of secondary ionisation (electron–hole pairs) in the sensor, (iii) estimation of the shape of the current pulse induced on surface electrodes and (iv) simulation of the first electronics stage. A very good agreement between the simulation and the measurements were found. Both indicate reliable performance of the final probe at timing windows down to 20 ns.

INTRODUCTION

The MADEIRA project is aiming at minimising the patient dose during nuclear medicine imaging procedures. The project consists of five work packages, the second of them focusing on research of a new instrumentation technique, a PET probe, illustrated in Figure 1. The probe is designed to function in combination with a standard PET unit and to be placed close to the imaged object where it can have a large field of view of the object. Events collected in the probe will have high spatial resolution information. High-resolution events will be combined with data collected by the external (conventional) PET ring, the data from external ring serving to remove artefacts due to limited angle tomography⁽¹⁾. Adding data with high spatial resolution improves the quality of image for a given dose or, conversely, reduces patient dose for a given image quality.

High-resistivity silicon was chosen for probe material for several reasons: (i) excellent spatial resolution of segmented detectors, providing means for proximity focus exploitation, (ii) compactness and sturdiness, simplifying mechanical design, (iii) developed design and processing technology, (iv) good energy resolution, enabling event classification/Compton scatter recognition and (v) possibility of operation in magnetic field. The most serious drawback is its low efficiency; only 2 % of incident

annihilation photons interact in 1 mm of silicon with Compton scattering being the most common interaction. Although commonly used sensitive materials (for example, scintillators coupled with light detectors) exhibit higher efficiency, they have serious limitations when aiming for compact systems with high spatial resolution⁽²⁾. To improve the detection efficiency, thicker silicon detectors are used, causing extension of signal collection times. This paper will present a study of timing of the silicon detectors and associated electronics intended for MADEIRA PET probe. The following sections will describe the tested module, the timing setup, the results, comparison with simulation, performance impact and estimate of the final probe performance.

SETUP DESCRIPTION

Silicon module

Timing performance of the final probe prototype was tested on a model assembly. The model consisted of a 1-mm thick silicon sensor called SINTEF256, manufactured by SINTEF (<http://www.sintef.no>) segmented into 256 square pads with a side of 1.4 mm. The sensor is operated as a p–i–n diode in reverse bias mode. The generated signals are processed by an off-the-shelf application-specific integrated circuit (ASIC) called VATAGP7, produced

by IDEAS (GammaMedica–IDEAS, <http://www.gm-ideas.com>). Each ASIC hosts 128 identical channels with a charge-sensitive preamplifier whose output is split into a pair of CR-RC² shapers. The output of the fast shaper (shaping time of 150 ns) is passed to a leading edge discriminator for a trigger pulse. The slow shaper (shaping time of 500 ns) provides the interaction energy. A pair of VATAGP7 required for 256 pad detector readout is placed on a custom-made PCB hybrid (called B770G/H), as shown in Figure 2. Downstream electronics is based

Figure 1. Schematic drawing illustrating the PET probe principle.

Figure 2. Photograph of the test setup: SINTEF256, $4.4 \times 1.1 \text{ cm}^2$ segmented silicon sensor coupled with a pair of VATAGP7 ASICs on a custom made D770G/H PCB board.

on standard components including a VME crate and PC operating as a control and storage device. The final probe will aim at high spatial resolution with a reduced pad side of 1 mm; however, the same electronic platform and ASICs will be used.

Coincidence setup

The timing properties were tested with the coincidence setup sketched in Figure 3. A positron source (^{22}Na) emits a pair of oppositely directed photons, where one interacts in a lutetium/yttrium orthosilicate (LYSO) scintillator–photomultiplier tube (PMT) assembly and the other in the silicon module. The output of LYSO/PMT fed to a constant fraction discriminator gave a timing reference. The expected time resolution is around 1 ns FWHM⁽³⁾. For each event, the delay of trigger coming from combined output of all ASIC channels was stored and the ASIC was operated in sparse mode where energy and address of the hit pad was recorded for each interaction.

Figure 3. Schematic drawing of the coincidence setup.

Figure 4. Distribution of events vs. delay of the silicon trigger (x-axis) and the energy of the interaction (y-axis) in a 2D histogram. The reverse sensor bias was set to 175 V.

RESULTS AND OBSERVATIONS

Figure 4 shows distribution of the measured events with respect to energy of the Compton electron and

Figure 5. Distribution of events with respect to the delay for events where Compton electron energy was within 2 keV of 220 keV. The shaded histogram shows distribution for a direct charge injection (sensor omitted) corresponding to 220 keV interaction.

delay of the trigger of the silicon module. The dominant feature of the distribution is the time walk; Figure 5 shows a slice for a fixed interaction energy. Width of the slice was set to 2 keV, matching energy resolution of the silicon sensor⁽⁴⁾. For clarification, the shaded histogram in Figure 5 shows timing distribution of direct charge injection into a single ASIC channel—the width of the distribution corresponds to jitter only. The width of the measured slice (white histogram in Figure 5) is governed by additional broadening related to variation of interaction position in the sensor^(5, 6).

Simulation

The process of photon detection and signal processing was simulated to verify the source of the broadening. The simulation⁽⁷⁾ consists of four parts: (i) GEANT4⁽⁸⁾ for realistic tracking of Compton electrons excited during the interaction of the annihilation photons, (ii) propagation of secondary ionisation (electron–hole pairs) in the electric field for the given bias voltage, (iii) induction of signal on electrodes for a realistic weighting field calculated by

Figure 6. Comparison of measurement and simulation. Top row: Distribution of events with respect to delay (x-axis) and Compton electron energy (y-axis). Left: Measurement. Right: Simulation with parameters corresponding to measurements. Bottom row: Distribution with respect to delay for events with a fixed energy (left: 300 keV, right: 50 keV) for a 2 keV energy window, measurement (black) and simulation (red histogram).

TCAD (Synopsys, Inc., <http://www.synopsys.com>) and (iv) application of virtual ASIC electronics (including trigger generation).

The distribution of simulated trigger generation instances can directly be compared with the measured distribution of delays between the silicon and the PMT/LYSO trigger. Figure 6 shows both distributions face to face. The bottom row of Figure 6 shows a pair of 2 keV-wide slices of the top 2D histograms: for 300 keV (left) and 50 keV Compton electrons (right). The agreement between simulation and measurements is excellent.

Improving the performance

One of the simple corrective steps for timing resolution is to increase the bias voltage, thereby increasing the electric field and accelerating the sweeping of electrons and holes to the electrodes. Figure 7 shows the effect using a set of measurements where the bias voltage was varied between 175 and 430 V. Note that in the simulation the shaping time τ had to be set to 150 ns to match the measured data.

Estimation of the impact of imperfect timing

Impact of imperfect timing is best observed by looking for data collection efficiency for time windows typically used in PET imaging (6–12 ns for LSO/LYSO and BGO detectors, respectively)⁽⁹⁾. Taking 10, 20 and 30 ns time windows as a benchmark, the efficiency plots shown in Figure 8 were made. The delay of the time window was chosen to maximise the efficiency for each energy (1 keV bins), removing time-walk effects from the efficiency plot. Efficiency of 50 % for 10 ns time window indicates a preferred usage of thinner detectors where extreme rates are to be handled. Over-biasing the detector allows for significantly shorter time windows, for example, increasing voltage from 175 to 430 V reduces it from 20 to 10 ns. For an adequate operation with non-negligible dead time, the efficiency of the true events should exceed 50 %, using time windows in the 20 ns range.

Actual probe performance

To predict the final probe performance, the simulation was performed for a reduced pad size. The

Figure 7. Voltage scan. Each graph shows the distribution of events with respect to the energy of the interaction (y-axis) and the trigger delay (x-axis). The bias voltages were 175 V (top left), 260 V (top right), 345 V (bottom left) and 430 V (bottom right). Distributions are scaled to equal event counts.

Figure 8. Efficiency as a function of Compton electron energy for listed time windows and detector voltages. The delay of the window was chosen to maximise number of accepted events.

Table 1. Comparison of overall efficiency (given in %) for a given time window.

Time window (ns)	Model measured 175 V	Model measured 430 V	Model simulated 430 V	Final simulated 430 V
10	38	51	58	50
20	61	75	82	77
30	74	86	95	92

Measurements at 175 and 430 V, simulation of model and final probe.

estimated efficiencies for listed time windows are given in Table 1, showing only a small change. Table 1 also shows the comparison between efficiencies for measured and simulated data, clearly showing an overestimate in the later due to neglected effects of jitter and LYSO/PMT resolution.

CONCLUSIONS

Timing resolution of thick silicon detectors was studied using annihilation photons from an ^{22}Na positron source. Comparison of measured data with

simulated values leads to the conclusion that variation in photon interaction position significantly contributes to broadening of timing distribution. This effect can be reduced by over-biasing the sensor. On the basis of the presented results, it is estimated that the MADEIRA PET probe with 1-mm square pads and 1-mm thick sensors will be capable of reliable performance at timing windows down to 20 ns.

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