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Evaluation of a high resolution silicon PET insert module

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ABSTRACT

Conventional PET systems can be augmented with additional detectors placed in close proximity of the region of interest. We developed a high resolution PET insert module to evaluate the added benefit of such a combination. The insert module consists of two back-to-back 1 mm thick silicon sensors, each segmented into 1040 1 mm^2 pads arranged in a 40 by 26 array. A set of 16 VATAGP7.1 ASICs and a custom assembled data acquisition board were used to read out the signal from the insert module.

Data were acquired in slice (2D) geometry with a Jaszczak phantom (rod diameters of 1.2–4.8 mm) filled with ^{18}F-FDG and the images were reconstructed with ML-EM method. Both data with full and limited angular coverage from the insert module were considered and three types of coincidence events were combined.

The ratio of high-resolution data that substantially improves quality of the reconstructed image for the region near the surface of the insert module was estimated to be about 4%. Results from our previous studies suggest that such ratio could be achieved at a moderate technological expense by using an equivalent of two insert modules (an effective sensor thickness of 4 mm).

1. Introduction

Whole-body PET scanners have evolved considerably in the recent decade, but still offer relatively poor volumetric resolution, compromising their ability of quantifying radiotracer uptake [1,2]. Improvements in spatial resolution of PET detectors can be attained through finer segmentation of detector elements [3]. However, the achievable spatial resolution will be limited by positron range and acollinearity of annihilation photons, the latter being dependent on the distance between the annihilation point and detector elements [3].

The performance of a whole-body PET scanner may be augmented by using an additional high resolution insert. Such configuration would enhance photon sensitivity by increasing the system's geometric detection efficiency [4], and improve its spatial resolution. A number of multi-resolution PET concepts have been investigated by several groups, utilizing either semiconductor materials such as silicon [5–9] and cadmium zinc telluride (CdZnTe) [10,11] or scintillators such as cerium-doped lutetium (-yttrium) oxyorthosilicate (L(Y)SO) [12–16], usually read out by silicon photomultipliers (SiPMs).

The proposed approach implies placement of additional detectors (*inserts*) within the existing scanner ring. As a result, a mixture of events of different modes is collected simultaneously: standard ring–ring interactions, events where one of the annihilation photons interacts in the insert and the remaining one in the ring (insert–ring) and possibly, should the geometry of the insert allow, insert–insert interactions. Such strategy is feasible only if spatial resolution of the insert sufficiently surpasses the resolution of the baseline scanner.

In the approach investigated by our group [17–19], high resistivity silicon sensors segmented to individual pads were chosen as the detector material for the insert, offering excellent spatial [20] and energy resolution [21]. Silicon-based detectors should be insensitive to operation in a magnetic field [22], enabling the employment of PET inserts for MRI [23] and, due to their segmentation, are not expected to be susceptible to mis-localization of annihilation photons (depth-of-interaction (DOI) effect).

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We developed a high resolution silicon PET insert module, building block for the insert concept. The aim of the present study was to characterize image quality of each coincidence type and determine portions of additional events (insert–ring, insert–insert) required for improved image quality. As PET inserts can cover only a portion of the object, geometries where image quality is maintained despite limited angular coverage was investigated. While silicon might not be the definitive material for PET insert application, it satisfies the crucial requirement for the insert, the high spatial resolution. In that sense the results are indicative for other semiconductor materials or scintillator-SiPM assemblies able to achieve such spatial resolution. We were also guided by availability, robustness and knowledge of operation. Some drawbacks, including limited efficiency, timing and event classification difficulties, are addressed in the discussion.

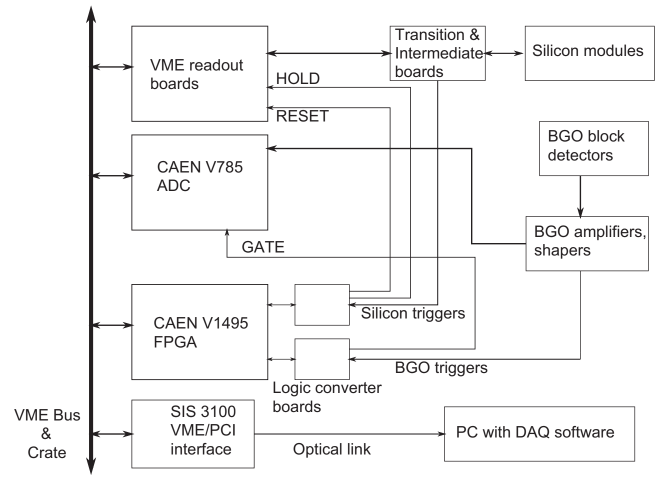

Fig. 2. Schematic drawing of the data acquisition system for the evaluation setup. During the measurements, insert modules were used in parallel with the outer ring.

2. Materials and methods

2.1. PET insert module

The PET insert module (or 'module', shown in Fig. 1) consists of a single pair of 1 mm thick silicon sensors manufactured by SINTEF (SINTEF Group, Norway), each segmented into 1040 1 mm^2 pads. Each pad is a diode with a p^+nn^+ doping profile, and the pads are arranged in a two-dimensional mesh (40 by 26). The two sensors are placed 0.8 mm apart in a back-to-back configuration and are glued to two double-sided hybrids. Silicon sensors were operated at 136 V bias (full depletion occurs at ~100 V). The insert can be composed of several modules.

The VATAGP7.1, 128 readout channel low noise application-specific integrated circuit (ASIC), designed and fabricated by IDEAS (Integrated Detector and Electronics (IDE) AS, Norway), was employed as the front-end electronics for the module. Individual readout channels consist of a common charge sensitive preamplifier with its output split to an analog (VA) and a digital (TA) branch. The VA branch consists of a noise filtering slow semi-Gaussian CR-RC shaper with adjustable a shaping time of 500 ns. The shaper is followed by a Sample & Hold circuit, triggered by external electronics. The ASIC provides a sparse-adjacent readout mode where only the hit channel along with a number of adjacent channels is read out. In our case, 15 adjacent channels were used to estimate common mode noise of the ASIC. The TA branch consists of a fast CR-RC shaper (150 ns shaping time) followed by leading edge discriminator and a monostable that produces a trigger if the signal exceeds the externally set threshold voltage. A single module is read out by 16 chips embedded on two double-sided hybrids also providing mechanical support for the sensors.

From hybrid, the signals are relayed through transition board to the intermediate board (IB) which serves as an additional amplification and analog control unit for every hybrid. The final unit of the silicon readout is a VME (Versa Module Eurocard)-compatible board providing analog to digital conversion and digital processing of the event. The packaged events are then sent through VME back-end and VME-PC optical link to the personal computer serving as slow control, storage and processing unit (Fig. 2).

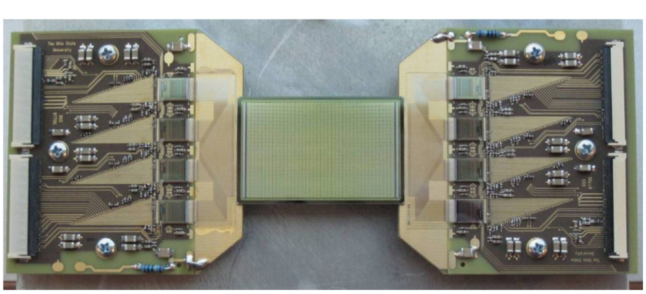

Fig. 1. Silicon insert module. Two sensors are placed in a back-to-back configuration (second sensor not visible) and glued to two double-sided hybrids, where ASICs are hosted.

By default, readout chain is started by trigger from the ASIC. For coincidence operation this chain is broken via on-board switch, and the IB provides buffered trigger signal available for coincidence logic, which should either provide a confirmation through a readout trigger or a reset indicator otherwise. The IB serves as the reception port for both signals and relays the reset to the hybrid and ASICs.

The modules were characterized prior to tests in PET geometry [24]. In terms of timing, time-walk similar to TA branch shaping time of ~150 ns was found to be the dominant contribution. Additional contribution comes from variation in pulse shape with interaction location, adding up to ~50 ns timing uncertainty at moderate biases used in the setup.

The measured energy resolution was 2.5 keV full width at half maximum (FWHM) at 60 keV ^{241}Am photo-peak [25]. Nevertheless, sensors are normally operated in open mode for 511 keV photons, that is accepting any interaction type, because of the low probability of the photo-electric absorption. Stable operation was achieved for thresholds above ~20 keV. Both timing and energy spectra of silicon detectors measured in the coincidence setup are shown in Fig. 3.

Either a partial or a full ring can be constructed using multiple modules. A full inner ring can be assembled by combining several modules in a circular arrangement, providing near-complete angular coverage. Both concepts are illustrated in Fig. 4. The naming convention of the interaction types refers to the detectors used in our evaluation setup (i.e., 'Si' for silicon and 'BGO' for bismuth germanate scintillator detectors used in outer ring). Two additional types of coincidence events are available when using a full inner ring: high resolution Si–BGO events (where one of the annihilation photons interacts in the module and the other is detected in the outer scintillator ring) and very high resolution Si–Si events (where both annihilation photons interact in modules).

2.2. Evaluation setup

Schematic drawing of the evaluation setup used to acquire the data is shown in Fig. 5. The setup consists of a partial BGO ring mimicking standard PET detectors, rotating table for imaging