Evaluation of Monolithic Detector Blocks for High-Sensitivity PET Imaging of the Human Brain

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Abstract—We propose and evaluate an improved design at the level of PET detector blocks based on monolithic crystals that will eventually be used on a research prototype for human brain PET/MRI imaging – the BrainPET scanner. These new detector blocks, when compared with pixilated designs, feature simpler mechanics, lower cost, larger sensitive volume, better energy and spatial resolutions, all of which contribute to improvements in PET detector technology. Moreover, the magnetic compatibility of all the materials composing the block makes it suitable for operation inside an MRI scanner. Results from both experimental data and Monte Carlo simulations allow an evaluation of the performance of the detector blocks, illustrating their potential for high-sensitivity PET imaging of the human brain.

I. INTRODUCTION

MULTIMODALITY imaging profiting from both functional and anatomical data is becoming each day more and more important in providing clinicians with detailed information for diagnosis and treatment planning, as can clearly be seen worldwide in the choice of PET/CT scanners over PET-only systems. New developments in multimodality imaging are now addressing the possibility of simultaneous PET and MRI acquisitions [1], based on the arguments that MRI offers better contrast for soft tissue than CT with no ionizing radiation exposure to the patient; also, some improvement in spatial resolution may be obtained by confining the positron range within a strong magnetic field [2]. The first examples of PET/MRI hybrid systems have been implemented in recent years by inserting magnetically-compatible PET detector modules on already existing small animal MRI scanners [3], each module being formed by pixilated LSO blocks readout by APD matrices [1,3]. In this work we propose and evaluate an improved design at the level of PET detector blocks based on monolithic crystals that will eventually be used on a research prototype for human brain PET/MRI imaging. These new detector blocks, when compared with pixilated ones, feature a simpler design, lower cost, larger sensitive volume, better energy resolution and comparable or better spatial resolution [4], thus contributing to overall improvements in PET detector technology.

II. PET IMAGING WITH MONOLITHIC BLOCKS

A. Scanner and block geometry

We consider a modular PET detector ring design capable of being inserted in existing clinical MRI scanners. In order to maximize the sensitive volume, detector blocks are based on trapezoidal LYSO:Ce scintillator crystals readout by Hamamatsu S8550-02 APD matrices. A detector block is formed by two independent sub-detectors, each one coupled to a pair of APD matrices, with overall external dimensions determined by considering a 40 cm diameter bore for the PET scanner. The crystals are encapsulated in BaSO₄ which acts both as an optical reflector and a mechanical stabilizer of the whole block. The axial length of the scanner is defined by the number of adjacent rings of detector blocks considered, keeping in mind that a minimum of 8 such rings is necessary to fully image the human brain in a single acquisition. Fig. 1 shows a Raytracer image of the proposed trapezoidal detector with two independent blocks, together with a view of a full scanner configuration formed by 4 rings of detector blocks.

B. Operation of monolithic blocks on a PET scanner

The monolithic blocks operate based on the shape of the light distribution collected by all pixels. For each incoming photon that deposits ionizing energy on a LYSO:Ce crystal, scintillation light is produced and a large number of optical photons eventually reach the APD pixels. It has been shown that, using the data from the light distributions on pixels over a large number of events, both statistical and neural network (NN) methods may be used in order to estimate the coordinates of entrance of incoming photons on monolithic blocks, achieving intrinsic spatial resolutions better than 2 mm

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full-width at half-maximum (FWHM) [5]. Our design will use a NN for each detector block so that, whenever two blocks are in coincidence, a line-of-response (LoR) on the full PET ring is defined by the points of entrance of the incoming photons on each block [6]. Since the coordinates are calculated at the surface of the block, there is no need to consider the exact point(s) of interaction of the incoming photons as they are intrinsically accounted for by the NN position determining algorithm.

III. MATERIALS AND METHODS

The evaluation of the detector block performance started with Monte Carlo simulations, where several geometries were considered, from simple parallelepipeds with single APD readout to more complex trapezoidal blocks with double readout. First results from simulation led to the definition of a prototype block that was then assembled and characterized on a laboratory setup. The following paragraphs describe the materials used and the methods followed in the Monte Carlo simulations and laboratory measurements.

A. Monte Carlo simulations

Detailed simulations of detectors and physics were carried out using a framework based on the Geant4 toolkit [7]. All the materials, including the APDs and the BaSO₄ or Teflon reflectors were taken into account in the geometrical description of the blocks. Generation of scintillation photons in LYSO:Ce crystals has been parameterized according to the manufacturers datasheet. Optical tracking of photons was implemented using the UNIFIED model [8] included in Geant4. Pencil-like beams of 511 keV with normal incidence to the bottom face of the module were simulated, mapping the whole surface and generating optical photon data for training and testing of the NN algorithms.

B. Experimental setup

We have implemented an experimental setup at CIEMAT (Madrid) dedicated to the characterization of monolithic detector blocks, featuring an electronically-collimated beam of 511 keV photons from a $^{22}$Na radioactive source and a discrete electronics readout system. The setup is based on a detector box which mounts the block under study on a dedicated printed circuit board providing front-end readout, as well as high- and low-voltage distribution. The position of the box is controlled by DC motors allowing translations in horizontal and vertical axis with 0.01 mm precision, and rotations around the vertical; moving the box in front of the collimated beam allows the mapping of the whole detector block at different incidence angles. The detector box also features a water cooling system controlled by an external mini-chiller in order to dissipate the heat generated by the preamplifiers and ensure a stable temperature throughout the measurement procedures.

Each of the 64 APD pixels is directly connected to a Cremat CR-110 charge preamplifier which provides a nominal gain of 1.4 mV per fC of collected charge. The outputs of the Cremat preamplifiers are fed into four CAEN N568B 16-channel Spectroscopy Amplifiers, which provide further amplification (a factor of about 200) and shaping (at 1 μs shaping time). The amplified signals are then sent into a pair of CAEN V785 Peak Sensing ADCs which digitize the information from the 64 APD pixels and send it to a master PC running Windows XP, which controls the whole data acquisition system. A schematic representation of the experimental setup is shown on Fig. 2.

A beam of 511 keV photons is obtained by placing two axially-aligned lead cylinder collimators, featuring 4.0 mm diameter drilled holes, between a point-like source of $^{22}$Na with 0.25 mm diameter and a 1” diameter 2” thick BaF₂ fast scintillator readout by a Bicron photomultiplier tube (PMT). The output of the PMT is amplified by an Ortec 855 Dual Amplifier module and sent to a Canberra 2037A Single Channel Analyzer which triggers the data acquisition system every time an energy corresponding to the 511 keV peak is detected on the PMT; whenever that happens, positron annihilation kinematics ensures that a 511 keV photon has been emitted back-to-back in the opposite direction. The width of the beam is determined by geometry based on the relative placements of detector, radioactive source and PMT; a ratio of 1:4 is used for detector-source and source-PMT distances in order to obtain a 1.0 mm diameter beam at the surface of the detector.

C. The prototype monolithic block

For the purpose of validating the monolithic detector block concept, we have assembled a laboratory prototype based on a single 10 mm thick LYSO:Ce scintillator from Saint-Gobain Crystals (PreLuDe 420) with dimensions 18.5 mm x 21.4 mm, corresponding to the lower sub-detector of the geometry proposed at the beginning of this work (presented on Fig. 1). The crystal was glued to a pair of Hamamatsu S8550-02 APD matrices using Saint-Gobain BC-600 optical cement and wrapped in several layers of Teflon tape to improve overall light collection on the APD pixels. A photograph of the block before Teflon tape wrapping is shown in Fig. 3 together with an image of the corresponding model used in Monte Carlo simulations.
IV. RESULTS

We have evaluated the energy resolution of the prototype block and the accuracy of the neural network (NN) position determining algorithm for perpendicular photon incidence.

A. Energy resolution

The energy of each event was calculated by summing the amplitudes of the signals from all the 64 pixels in the block. We measured an energy resolution of 32.5% FWHM for the 511 keV photopeak (spectrum shown on Fig. 4), a factor 2.5 larger than the corresponding simulated result. The observed discrepancy is probably due to noise and gain non-uniformity across the 64 electronics channels of the real detector block, not accounted for in the simulations.

Fig. 4. Example of a measured energy spectrum obtained with the prototype monolithic detector. Energy resolution at 511 keV is 32.5% FWHM.

B. Spatial resolution

The detector block was scanned at 1.0 mm steps with perpendicularly incident 511 keV photons from a 0.25 mm electronically collimated point source of 1 MBq of $^{22}$Na. The data were used to train and evaluate a neural network (NN) algorithm in determining the coordinate of entrance of the incident photon on the monolithic block. We measured a spatial resolution of 2.1 mm FWHM (4.9 mm FWTM) for a 1.0 mm wide collimated beam (Fig. 5), a result in good agreement with Monte Carlo simulations.

Fig. 5. Results of the accuracy of the neural network (NN) position determining algorithm using real data from the prototype monolithic detector block: 2.1 mm FWHM and 4.9 mm FWTM.

V. CONCLUSIONS

We have evaluated a novel detector block design for high-sensitivity, high-resolution functional imaging of the human brain, compatible with intense magnetic fields. Neural network position determining algorithms provide spatial resolutions down to 2.1 mm FWHM (4.9 FWTM) for real data. Future work will focus on improving energy resolution, evaluating results for different angles of incidence and defining the final design of the detector blocks for the BrainPET scanner.

REFERENCES