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 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.

The Monolithic Detector Block

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 APD matrices (32 pixels in a 4x8 array of 1.6 x 1.6 mm^2 pixels at 2.3 mm pitch). The crystals are enclosed in a thin layer of $BaSO_4$ reflector. A block is formed by two sub-detectors, each coupled to two APD matrices, with overall external dimensions determined by considering a 40 cm diameter bore for the BrainPET scanner.

Principle of operation

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 or neural network (NN) methods may be used in order to estimate the coordinates of entrance of incoming photons on monolithic detector blocks, achieving intrinsic spatial resolutions of the order of 2 mm. Our design will use a NN for each detector block, so that lines-of-response on the full PET ring will be defined by the points of entrance of the incoming photons on each detector.

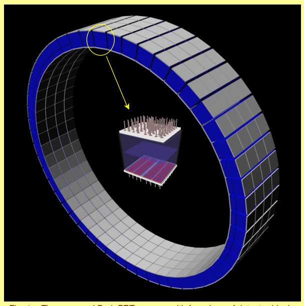

Fig. 1 – The proposed BrainPET scanner with four rings of detector blocks.

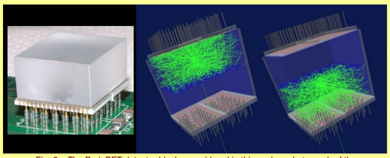

Fig. 2 – The BrainPET detector blocks considered in this work: a photograph of the laboratory prototype used in the measurements (left) and results from Monte Carlo simulation of interactions in the Monolithic Detector Block (center and right).

Fig. 3 – The experimental setup at CIEMAT used in the evaluation of the prototype detector block.

Materials and methods

We have simulated, assembled and tested a prototype detector module using collimated beams of 511 keV photons from ^{22}Na. The prototype consists of a single 18.5 x 21.4 x 10.0 mm^3 LYSO:Ce monolithic scintillator from Saint-Gobain Crystals glued to a pair of Hamamatsu S8550 APD matrices using BC-600 Optical Cement also from Saint-Gobain Crystals, the whole wrapped in Teflon tape. This configuration is similar to a sub-detector of the Detector Module concept under evaluation in this work.

Monte-Carlo simulations

Detailed simulations of detectors and physics were carried out using a framework based on the Geant4 toolkit. All the materials, including the APDs and the $BaSO_4$ reflector were taken into account in the geometrical description of the block. Generation of scintillation photons in LYSO:Ce blocks has been simulated according to the manufacturers datasheet. Optical tracking of photons was made using the UNIFIED model implemented in Geant4. Pencil-like beams of 511 keV with normal incidence to the bottom face of the module were simulated mapping the whole surface generating optical photon data for training and testing the NN algorithms. An electronics noise of 600 electrons ENC rms has been included in the simulation.

Experimental characterization

We have implemented a laboratory benchmark for monolithic detector blocks at CIEMAT (Madrid, Spain) consisting of 64 discrete electronics channels based on Cremat CR-110 charge sensitive preamplifiers, CAEN N568B spectroscopy amplifier modules and CAEN V785 ADCs. Experimental data at different photon entrance points and angles of incidence is generated using an electronically collimated ^{22}Na source. The results have been used to validate the monolithic detector block concept for operation in a PET ring and also to fine tune the input parameters for Monte Carlo simulation.

Results

Energy resolution

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

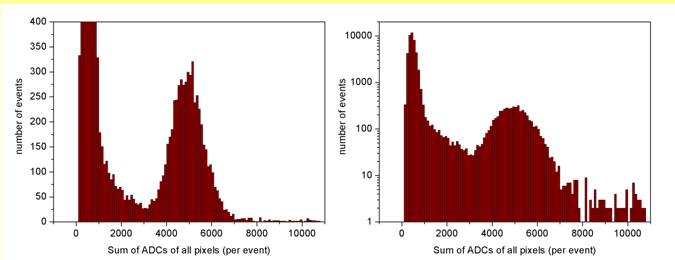

Fig. 4 – Measured energy spectra from the prototype monolithic detector in both linear (left) and logarithmic (right) scale. Energy resolution at 511 keV photopeak is 32.5% (FWHM).

Spatial resolution

The detector block was scanned at 1.0 mm steps with perpendicularly incident 511 keV photons from a 0.25 mm 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 events of photon incidence far from the borders of the crystal. These results are in agreement with Monte Carlo simulations.

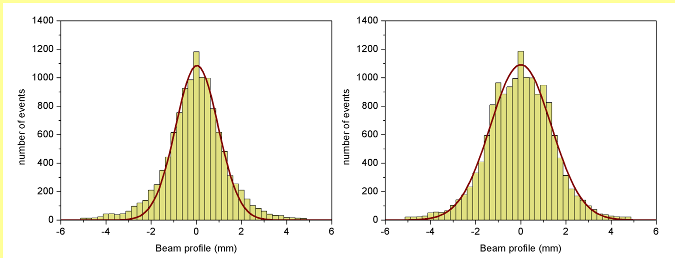

Fig. 5 – Results of the accuracy of the neural network (NN) position determination algorithm using real data from the prototype detector block: 2.1 mm FWHM (4.9 mm FWTM) for beam incidence far from the borders of the block (left) and 3.0 mm FWHM (5.8 mm FWTM) for the whole data set (right).

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

Results from experimental characterization of prototypes and Monte Carlo simulations are in good agreement with design target specifications

Neural network position determining algorithms provide spatial resolutions down to 2.1 mm FWHM (4.9 mm FWTM) for real laboratory data

Future work will focus on improving energy resolution, evaluating results for different angles of incidence and defining the final design of the BrainPET detector blocks