Performance Evaluation of a PET Demonstrator for PET-MR Imaging Based on Monolithic LYSO:Ce Scintillators

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Abstract

We are developing a positron emission tomography (PET) insert based on avalanche photodiode (APD) arrays and monolithic LYSO:Ce scintillators for human brain functional studies inside a clinical 3T magnetic resonance imaging (MRI) equipment. In a previous work [1], we demonstrated the performance of our detectors by implementing an experimental setup consisting of two monolithic blocks working in coincidence, which were read out by the first version of an application specific integrated circuit (ASIC), VATA240, followed by external coincidence and digitalization modules. This preliminary demonstrator showed good spatial resolutions at detector level and good imaging qualities, which achieved reconstructed images of ^{22}Na point sources with spatial resolutions of 2.1 mm FWHM. Nevertheless, we detected image distortions and compressions due to the non-linearities close to the edge of the crystals and the absence of neighbor blocks. In this work we report on the performance evaluation of a larger scale PET demonstrator, which is based on the new updated ASIC (VATA241) [2] and is formed by two sectors of four monolithic detector blocks placed face-to-face, with the aim of obtaining a better evaluation of the imaging capabilities of our BrainPET scanner. Moreover, the new prototype demonstrator has been built for validating the data readout architecture, the coincidence processing implemented in a Virtex 5 field programmable gate array (FPGA), as well as the continuous neural networks (NN) training method required to determine the points of entrance over the surface of our monolithic detector blocks.

The BrainPET scanner

- PET/MRI scanner with **APDs** which allow operation inside **strong magnetic fields**. MRI has the advantage of an important reduction in patient dose and the additional information provided by functional MRI (fMRI), diffusion tensor imaging (DTI) or magnetic resonance spectroscopy (MRS).
- **Artificial neural network (NN) algorithms** are used to determine the point-of-entrance of 511 keV gammas over the surface of each monolithic detector block, providing spatial resolutions in the order of 2 mm FWHM for the **LYSO:Ce monolithic blocks.**

BrainPET detector design

- Trapezoidal monolithic LYSO:Ce crystals are painted white and optically coupled to a pair of Hamamatsu S-8550-02 APD arrays (8x8 pixels in total per detector block).
- An ASIC (VATA241) sums the charge collected at the 8 pixels of each row and column of the APD array, generates a trigger and provides data for digitization.
- The final scanner comprises two individual crystals stacked along the radial direction. In this demonstrator we have used a single layer of detector blocks.
- Monte Carlo simulations were made for the double layer full-ring design [3].

The Experimental Setup

- PET demonstrator based on four crystals face-to-face at nominal BrainPET distance (40 cm).
- Air-cooled boxes for stabilizing the temperature of the APDs.
- 8 rows and 8 columns from the VATA241 ASIC are digitized by 12-bit ADCs.
- Trigger signals provided by the ASIC are processed by a Virtex5 FPGA.
- Three-axis manual positioning stages for moving the source along the PET field of view (FoV).
- A precision rotating source holder allows acquisition of tomographic data at different angles.

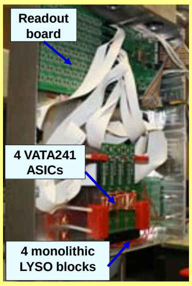

Fig. 1 – Photograph of one of the two boxes, showing the 4 front-end boards as well as the readout board.

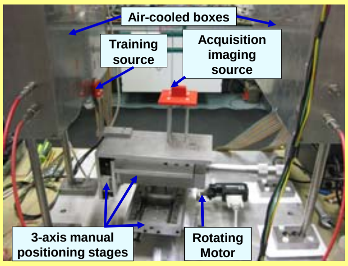

Fig. 2 – Photograph of the laboratory setup used for training the NN algorithms and acquiring the PET tomographic data. Both detector boxes are air-cooled for stabilizing the temperature of the APDs.

Artificial Neural Network (NN) Training Method

- Light distribution profiles processed by NN algorithms.
- Training data set at known incidence positions prior to imaging data acquisition:
  - Rotating 0.25 mm diameter ^{22}Na source at 0.3º steps.
  - Known incidence position: center of the face-to-face detector + source → Projection over the trained block.
  - Beam width (~1 mm) = Acceptance cone with each face-to-face crystal.
  - About 60 training points per incidence position.

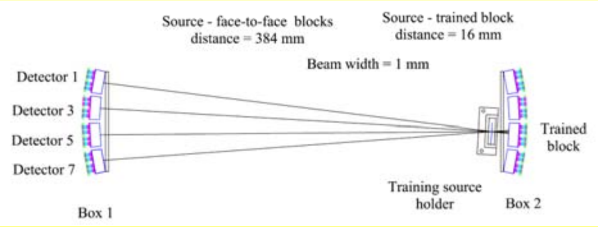

Fig. 3 – Schematic of the four detector blocks placed face-to-face at the BrainPET nominal distance

Results

VATA241 ASIC Front End

• Noise performance

- ASIC is very sensitive to the Common Mode (CM), since it sums the charge from all 64 inputs.
- Noise slope (APD capacitance = 11pF): **40 e⁻/pF and 70 e⁻/pF** (with and without CM subtraction)
- **Fast shaper rms noise** measured at baseline **= ~ 1200 e⁻**
- **Slow shaper rms noise** measured at baseline **without APDs connected = ~ 1300 e⁻**
- **Slow shaper rms noise** measured at baseline with **APDs connected and biased = ~ 2000 e⁻**

• Timing Resolution

- **Good time-walk results (below 0.7 ns)** for the dynamic charge range observed.
- **Jitter is a limiting factor: 1.5 ns rms** and **2.9 ns rms**, for fast square and exponential input pulses (resp.) when the APDs are biased at inputs.
- Better jitter results with high τ of the CFD HP filter and high attenuation factors of the CFD.

Readout Board

• PET Coincidence Operation

- We have determined the center position and detector profile of each detector block by measuring the coincidence count rate over the detector block.
- The readout board works as expected, sending the digitalization of the 8 rows and 8 columns provided by the ASIC to a PC, together with the detector block identifier and its time stamp.

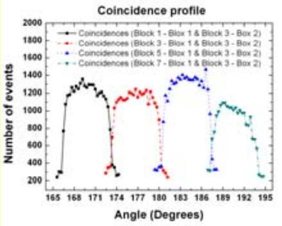

Fig. 4 – Detector block identifier and number of coincidences observed when the radioactive source rotates along the sector.

PET demonstrator

• Energy resolution (FWHM)

- Photopeak widths:
  - **^{22}Na (511 keV) = 22.0%**
  - **^{137}Cs (662 keV) = 18.0%**
  - **^{22}Na (1274 keV) = 11.1%**
- Very good linearity (R = 0.99999)
- An important degradation (from 12.0% FWHM to 22.0% FWHM) is observed with long APD-ASIC routing, which increases the input capacitive loads.

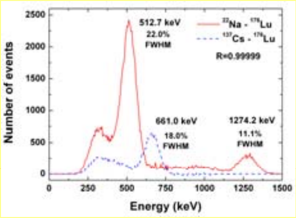

Fig. 5 – Measured energy spectra obtained with the VATA241.

• Spatial resolution from NN Algorithms

- Measured spatial resolutions: between 2.20 mm and 2.32 mm FWHM.
- Similar spatial resolutions obtained using a collimated beam width of 1 mm for NN training [1].

Spatial resolution in coincidence with	FWHM (mm)	Center at (mm)
Block 1	2.20	0.13
Block 3	2.21	-0.01
Block 5	2.26	-0.12
Block 7	2.32	-0.17

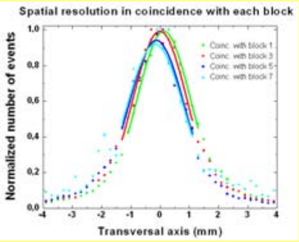

Fig. 6 – Measured FWHM spatial resolution before test beam correction obtained with each of the four face-to-face detectors, which form the coincidence PET sector.

Conclusions

- **We are developing a PET insert based on APD arrays and monolithic LYSO:Ce scintillators for human brain functional studies inside a clinical 3T MRI equipment.**
- **We have tested the linearity (R=0.99999), the energy resolution (22% at 511 keV) and time walk (0.7 ns) of the detector block design, obtaining satisfactory results. Nevertheless, an improvement of the VATA241 ASIC in the jitter timing is necessary for its use in a PET scanner.**
- **We have validated the NN training method, which will be used for the BrainPET scanner, obtaining spatial resolutions at detector level between 2.2 mm FWHM and 2.32 mm FWHM, which are compatible with the results achieved in our first demonstrator when using a collimated beam width of 1 mm during the training process.**
- **We have validated the data readout architecture of our demonstrator and the coincidence processing implemented in a Virtex 5 FPGA.**
- **We will shortly report on the overall imaging performance of this PET demonstrator with the aim of showing the capabilities of our BrainPET scanner.**

[1] I. Sarasola, et al., "PET Demonstrator for a Human Brain Scanner Based on Monolithic Detector Blocks," *IEEE Trans. Nucl. Sci.*, [in press]
[2] I. Sarasola, et al., "A novel front-end chip for a human PET scanner based on monolithic detector blocks," *12th International Workshop on Radiation Imaging Detectors IWORID2010*, Jan. 2011, JINST 6 C01034 2011.
[3] P. Rato Mendes et al., "Optimization of a monolithic detector block design for a prototype human brain PET scanner," 2008 IEEE Nuclear Science Symposium Conf. Rec., 2008, pp. 4927-4930.