Nuclear Instruments and Methods in Physics Research A 753 (2014) 84–90

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Development of a prototype of time-over-threshold based small animal PET scanner

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ARTICLE INFO

Article history:
Received 21 October 2013
Received in revised form
1 April 2014
Accepted 5 April 2014
Available online 15 April 2014

Keywords:
Time over threshold
Avalanche photodiode
Positron emission tomography

ABSTRACT

A time-over-threshold (ToT)-based positron emission tomography (TODPET) scanner was designed and fabricated. The PET scanner consisted of eight block detectors, each of which is composed of a 12×12 array of $2 \times 2 \times 10\ mm^3$ Pr:LuAG crystals individually coupled with a 12×12 UV-enhanced avalanche photodiode (APD) array. The APDs were individually read out using a custom-designed time-over-threshold application-specific integrated circuit (ASIC) and field-programmable gate array (FPGA) readout system. The PET scanner has an energy resolution of 10% and a time resolution of 4.2 ns. A spatial resolution of 1.17 mm (FWHM) was demonstrated in the initial results.

1. Introduction and background

Positron emission tomography (PET) is a very effective tool for analyzing the distribution of target molecules and plays an important role in small animal molecular imaging. In biological research, precise imaging of radio-labeled tracers is necessary in revealing the functions of biological systems. Therefore, many types of PET scanners have been designed and developed. It is possible that the theoretical limits of spatial resolution for such scanners may soon be reached [1–11]. On the basis of studies that have indicated that their use may enhance spatial resolution, scanners have been designed to use individual readouts [12–14]. However, introduction of an individual readout system will necessitate the use of power-consuming hardware such as analog-to-digital converters (ADCs) as well as a time-to-digital converter (TDC) for each channel. To overcome this problem, several time-based methods and modules have been designed and investigated [15–19]. In this paper, the design and implementation of a time-over-threshold (ToT)-based PET system are summarized. This process involved building a compact digital animal PET

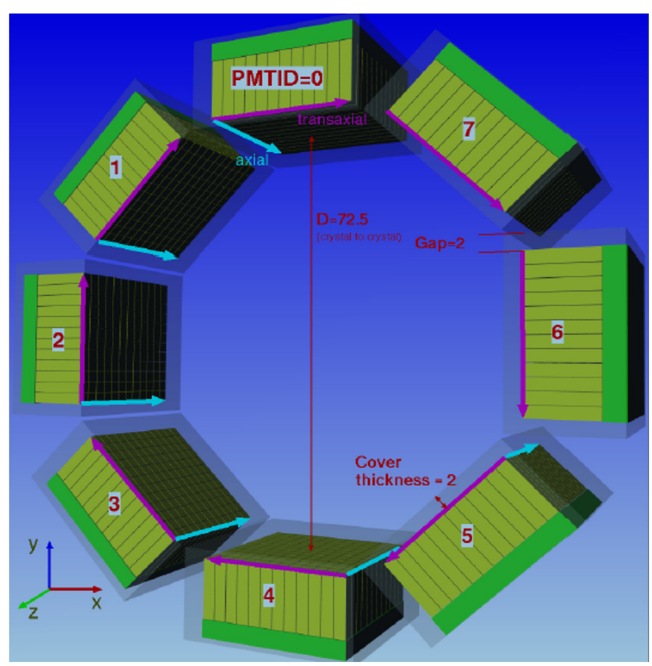

Fig. 1. Geometry of the designed TODPET ring.

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http://dx.doi.org/10.1016/j.nima.2014.04.008
0168-9002/

scanner consisting of an avalanche photodiode PET (APDPET) with a ToT-based application-specific integrated circuit (ASIC) and digital signal processing scheme at the front-end that utilizes leading edge timing and ToT-based energy measurement. Eight 144-channel detector modules—each having 12 × 12 Pr:LuAG–APD arrays individually coupled with ToT-based mixed signal ASICs—were constructed and configured together into a ring-shaped architecture. In Section 2, the scanner used in this fabricated PET system is explained. Details about the materials, electronics, and detectors used are provided in Section 3. A summary is given in Section 4 in which measurements and image reconstructions based on basic characteristics such as energy, time, and spatial resolution are evaluated.

2. Scanner architecture

The PET designed for this study consists of eight detector modules with 144 (12 × 12) channels each (Fig. 1). PMTID in the figure indicates the detector number in the PET system. D, Gap, Cover thickness indicate the distance (mm) between coincidence pair, the gap (mm) between two neighboring detector modules and the distance (mm) between the surface of Aluminum cover and that of Pr:LuAG crystal. In each module, one channel is composed of a Pr:LuAG crystal coupled with one APD pixel that is individually coupled with one ToT ASIC channel. Each ToT ASIC output is connected to an integrating FPGA board for multiplexing in order to reduce the number of transmission lines needed. The wired-OR multiplexing readout implemented in the FPGA reduces the number of lines from 144 to 24 (i.e., 12 lines demarking the *X* and *Y* axes, respectively) in each module (Fig. 2). The overall PET ring has 192 (24 × 8) ToT digital outputs that are processed by an ADC-based data acquisition (DAQ) system that uses a coincidence function to sum the ADC outputs for the initial evaluation. The count rate is therefore limited by the dead time (4 μs) of the DAQ system. Outputs (i.e., coincidence events) acquired by the DAQ system are sent via four Ethernet cables to a DAQ PC and a data reconstruction PC (Fig. 3). Fig. 4 shows the schematic of our DAQ. DAQ includes the summing amplifiers and the sampling ADC with 80 MHz frequency. The energy is measured by summing the ADC values for the duration of ToT, which corresponds to the pulse width of ToT signal. The dynamic range of ToT signal acceptable for the sampling ADC is up to 500 ns.

The TODPET system is designed for use as a small animal PET scanner with an aimed time resolution of ~10 ns [20].

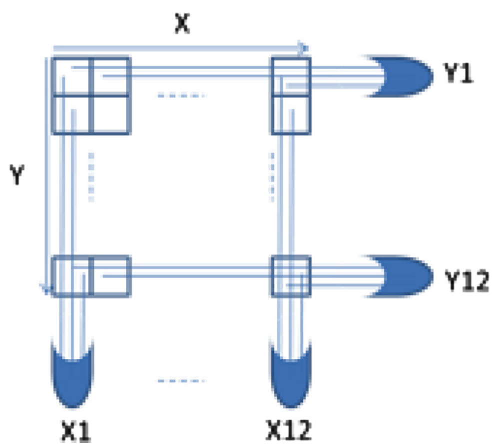

Fig. 2. *X*–*Y* wired-OR multiplexing readout.

3. Materials and methods

3.1. Pr:LuAG crystal arrays

Fig. 5 shows a picture of the 12 × 12 Pr:LuAG matrix developed for this system. The pixels are divided from each other by a reflective, 0.2-mm-thick $BaSO_4$ layer, and each pixel is 2 × 2 × 10 mm^3 in size.

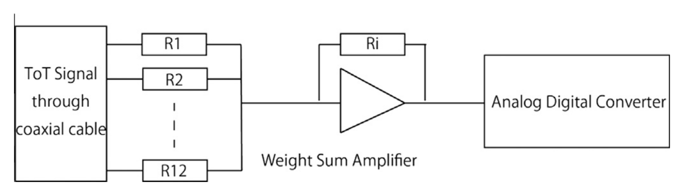

Fig. 4. DAQ system for one module.

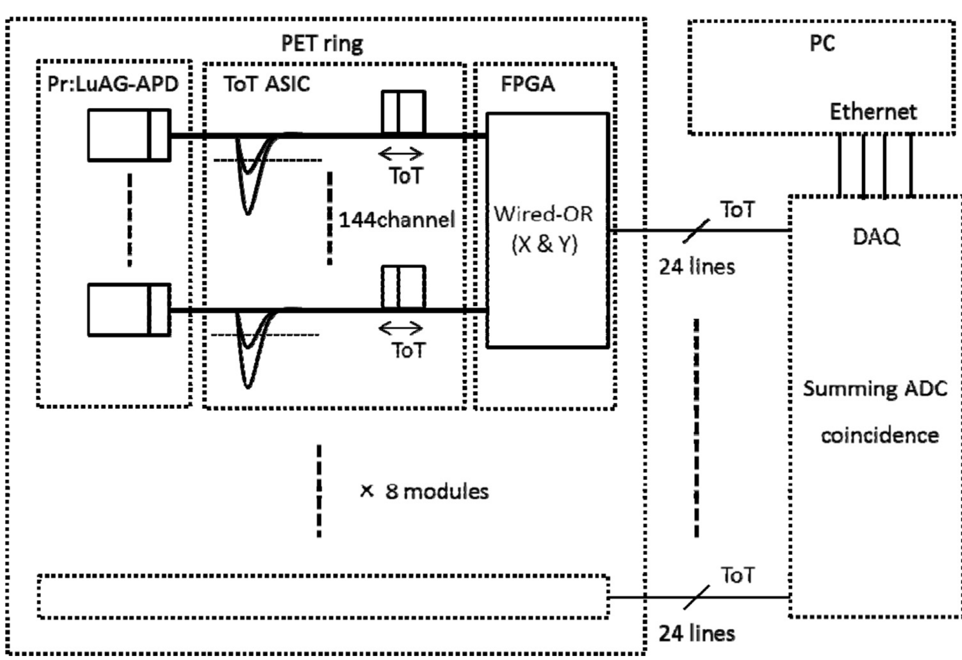

Fig. 3. Whole system of the PET system.