ARTICLE IN PRESS

Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Study of silicon photomultipliers for the medical imaging systems

N. D'Ascenzo *, V. Saveliev

National Research Nuclear University, Moscow, Russia

ARTICLE INFO

Keywords:
Silicon photomultipliers
PET systems

ABSTRACT

Novel photodetectors Silicon Photomultipliers (SiPMs) in combination with scintillation materials as LySO give an impressive progress in the development of the new generation Medical Imaging Systems. The experimental study of the detection system based on highly granular LySO crystals and SiPM is presented in the geometrical configuration of Positron Emission Tomography (PET) systems. An energy resolution of $(7.68 \pm 0.15)\%$ and a time resolution of (806 ± 26) ps are measured. The experimental results are implemented in the GATE mathematical model of PET system equipped with LySO/SiPM detection block.

1. Introduction

The new development of photodetectors and novel scintillation materials gives the possibility to substantially improve the performances and the principles of detection for the development of new generation medical imaging systems. A novel type of photodetector was developed on the basis of the semiconductor technology—Silicon Photomultipliers [5]. SiPM shows an excellent performance including the single photon response at room temperature (10^6 intrinsic gain of multiplication), high detection efficiency $\sim 25-60\%$ for the visible range of light, fast timing response ~ 30 ps. The operational conditions are suitable for many applications: operation bias 20–60 V, no sensitivity to strong electromagnetic fields. The SiPM is rapidly being used or proposed in many nuclear medicine applications. Many projects are active on the design of PET and Gamma camera using SiPM/crystal detectors [3]. To achieve a high space resolution without adversely affecting the sensitivity, crystals need to remain about 30 mm in length, but with a small cross-section in the range of few mm and with individual read-out by photodetectors. The use of new type of fast scintillation crystals and the fast timing response of SiPMs open the possibility of time of flight methods. In addition the measurement of the depth of interaction is realized quite simply with SiPMs bringing a significant improvement to imaging quality. In this paper the results are presented of the experimental study of the PET detection system prototype based on LySO scintillation crystals and SiPMs. Discussion attempts also on the modern mathematical simulation of the detection system of PET on the basis of the GATE simulation framework [8].

2. Mathematical model of PET based on LySO/SiPM detection system

The mathematical model allows to include the detailed geometry, the physics processes and the reconstruction by standard methods for the performance study. A detailed geometrical configuration of a detector ring for a PET scanner based on the LySO/SiPM detection system is shown in Fig. 1. The geometry of the system is typical of the state of the art high resolution brain PET scanners, with a diameter of 53.5 cm [4]. Each detector module consists of a 6×6 array of LySO crystals read-out individually by a SiPM. The realistic description of the detection elements consists of the LySO crystals covered by reflecting layer of Teflon. The optic coupling of the crystals with the SiPM is included according to experimental estimations. The considered physics processes are gamma ray propagation, interactions and scintillation processes in the crystals and scintillation light propagation taking into account the surfaces properties. The photo-luminescence and radio-luminescence emission spectra of LySO are taken according to the reported experimental measurements, the light yield is 27 000 photons/MeV. The variance σ_{LySO} is equivalent to the expected Poisson statistic variance multiplied by a 4.41 resolution scale factor, which takes into account the nonuniformity of the LySO response. The LySO refractive index (1.82) and the LySO density (7.4 g/cm^3) are considered. The surface between the LySO and the Teflon is simulated as consisting of small micro-facets [8]. Light propagation and collection of photons on the face of SiPMs are also included. The photon detection efficiency of the SiPMs used in the simulation is reported from experimental measurements [7]. The timing performance is included in the simulation as the time dependence of the scintillation process and

* Corresponding author.
E-mail addresses: ndasc@mail.desy.de, nicola.dascenzo@desy.de (N. D'Ascenzo).

0168-9002/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2011.11.091

Please cite this article as: N. D'Ascenzo, V. Saveliev, Nuclear Instruments & Methods In Physics Research Section A (2011), doi:10.1016/j.nima.2011.11.091

of the light propagation. The time distribution of the LySO scintillation photon emission has two exponential components with decay time respectively 12 ns and 42 ns and relative intensities respectively 35% and 65%. The 27.54 ps intrinsic time resolution of the SiPM [7] is implemented in the simulation as a Gaussian smearing of the photon detection time. The coincidence condition is defined for events with signals in the two opposite crystals with deposited energy within $\pm 3\sigma$ around the photo-peak and within a coincidence time window of 80 ns.

According to the NEMA NU2-2001 performance protocol, the source configuration used for the estimation of the space resolution is the β^+ emitter ^{18}F, arranged in a glass spherical capillary with radius respectively of 0.2 mm and 0.3 mm with initial activity is 10^4 Bq. The reconstruction of the Lines of Response (LOR) is performed by using the centre of the two crystals found in coincidence. A standard filtered backprojection algorithm FBP2 with Hammer filtering is applied to the sinogram for the reconstruction of the original image and study of the spatial resolution. The sinogram and the corresponding reconstructed image are shown in Fig. 2 as a result of the simulation of the response of the PET system based on $3\times3\times25$ mm^3 LySO crystals. The transverse spatial resolution is estimated as $\sigma_x = (0.94\pm0.62)$ mm and $\sigma_y = (0.87\pm0.46)$ mm. The estimated average transverse resolution (FWHM) is (2.13 ± 1.26) mm. Axial resolution is defined by the geometry of the ring and the corresponding axial resolution is estimated as about 18.6/3.0 = 6.2 mm.

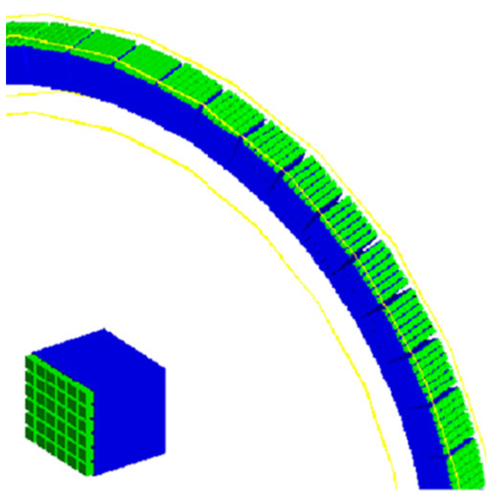

Fig. 1. Detailed geometry of the PET detection system on the basis of LySO scintillator crystal read-out individually by SiPM. One ring quadrant and a zoomed view of the detector head.

3. Experimental study of the prototype of the PET detection system

The experimental study of the new detection system was performed on a prototype of PET detection system. In order to simplify many aspects of the study, it was chosen to use just two LySO crystals coupled to a SiPM. The scintillator crystals used in this study are two $2.5\times2.5\times15$ mm^3 LySO crystals, wrapped in two layers of 0.25 mm thick Teflon films. The distance between the LySO crystals is 1 cm. Each crystal is read out on one side with a SiPM. They are directly coupled to the surface of the LySO crystals without any optics coupling material. The SiPMs are produced by SensL, Ireland with a total area of 1 mm^2 [6]. The Photon Detection Efficiency (PDE) of the SiPM has a maximum of 20% at about 470 nm. The dark rate is about 2 MHz and the background is significantly lower than the photon flux corresponding to the detection of a 511 keV photon. The SiPM signals are read out directly by 4 GHz oscilloscope (Textronix TDS7404B) without any front end electronics. The signals are digitized with a sampling rate of 20 Gs/s, which corresponds to 100 ps time stamp for two channels and to a 50 ps shift between the two signals. A positron source ^{22}Na is placed in the middle and aligned with the line of centres crystals connection.

The analysis of the experimental data is performed over a total statistics of about 10^4 triggered signals. The fully digitized signals have typical maximum amplitude of about 100 mV, the rise time is 28 ns and the decay of the signal follows an exponential form with time constant of about 60 ns. A mathematical model of the PET detection system prototype was also created on the basis of the general mathematical model described in Section 2.

Energy Resolution of the detection system with LySO/SiPM. The best possible performance obtainable with an LySO crystal is estimated with the Monte Carlo mathematical model as $R = \sigma/E_{phot} = (4.73\pm0.06)\%$ [2]. This estimation is also in good agreement with reported experimental results, where an energy resolution of $(4.24\pm0.01)\%$ is obtained with a $3\times3\times15$ mm^3 crystal read-out over the whole 3×3 mm^2 area by a SiPM [1]. The energy spectrum measured in the test setup is shown in Fig. 3. The SiPM used in the experimental set-up has an 1×1 mm^2 active area which is smaller than the crystal surface. Although their average photon detection efficiency in the LySO emission spectral region is around 20%, the small active area limits the overall photon collection efficiency of the LySO/SiPM system.

Time resolution of the detection system with LySO/SiPM. The coincidence time resolution of the LySO/SiPM detection system is defined as the time at which the output signal from the SiPM crosses a defined threshold N_{th}, expressed in number of photons. The key intrinsic properties determining the timing resolution of

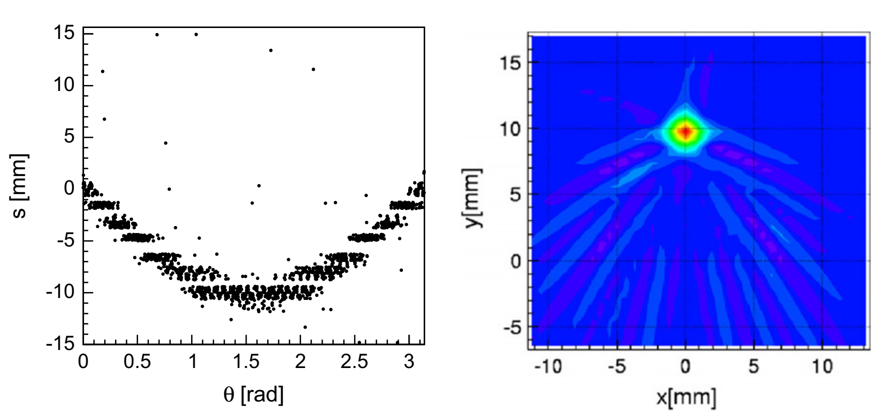

Fig. 2. Sinogram (left) and reconstructed image (right) resulting from the simulation of the response of the PET system based on LySO/SiPM detectors to a ^{18}F source of 0.2 mm radius placed at a vertical distance of 1 cm from the centre of the tomograph.

Please cite this article as: N. D'Ascenzo, V. Saveliev, Nuclear Instruments & Methods In Physics Research Section A (2011), doi:10.1016/j.nima.2011.11.091

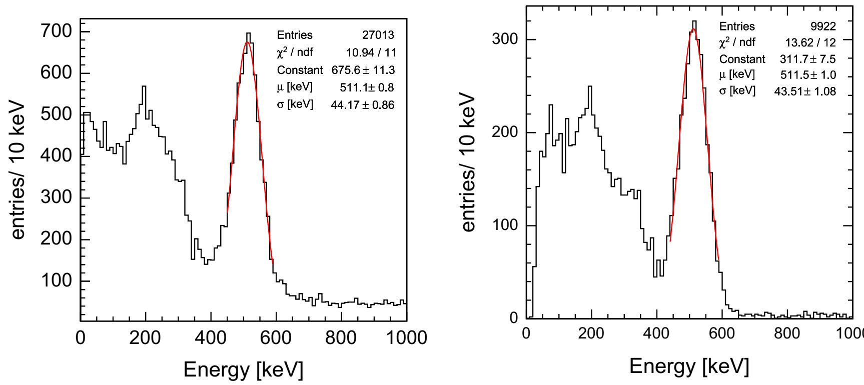

Fig. 3. Energy resolution of the experimental setup in Monte Carlo (left) and experimental data (right).

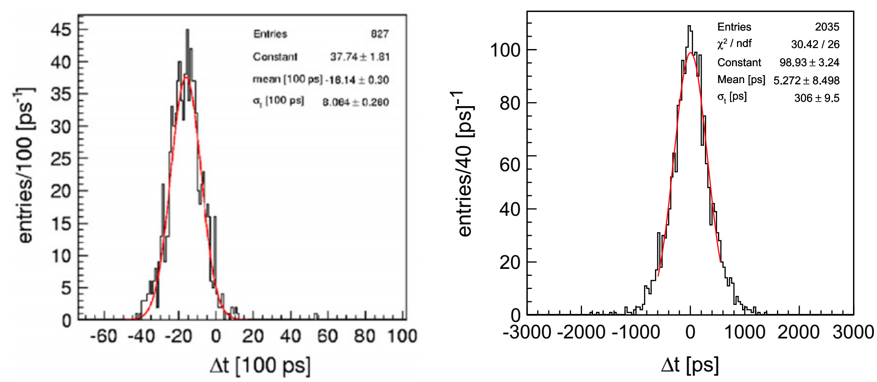

Fig. 4. Measured (left) and simulated (right) time difference distribution of two LySO/SiPM detection elements in coincidence of 511 keV signal from the β^+ emitter ^{22}Na.

the LySO/SiPM system are the rise time of the single photon SiPM signal and the rise time of the LySO scintillation photons emission. The best possible coincidence time resolution of a LySO/SiPM detection system can be estimated as $\sqrt{2}\sigma_{LySO} \oplus \sqrt{2}\sigma_{SiPM} = \sqrt{2} \cdot \sqrt{29^2+29^2} \sim 60$ ps [2]. The fast time response of the SiPM and of the LySO are promising for the design of new generation TOF PET, in which a time resolution of less than 500 ps would improve considerably the S/N ratio. The time difference spectrum of the SiPM/LySO detection system estimated with the Monte Carlo mathematical model of the test setup is shown in Fig. 4. The estimated time resolution is calculated with a Gaussian fit as 306 ± 9 ps at a timing threshold $N_{ph} = 1$ photon. The measured time difference spectrum of the SiPM/LySO detection system in response of a Na^{22} source is shown in Fig. 4.

The time at which the signal crosses the threshold N_{th} is estimated with a linear fit to the detected signal. The time resolution $\sigma_t = 806 \pm 26$ ps is measured from a Gaussian fit to the coincidence time spectrum. The measurement is in fact very sensitive to the chosen timing threshold. From a comparison between the dependence of the coincidence time on the timing threshold in data and the Monte Carlo, the timing threshold applied to the experimental data can be estimated as about two detected photons. This is the main limit of the set-up and dominates the resolution obtained in the experimental result. Additionally the measured coincidence time resolution is limited by the 100 ps intrinsic time resolution of the digital oscilloscope.

4. Conclusions

The application of the single read-out of LySO crystals by SiPM would introduce an important contribution to the design of modern PET systems. A transverse space resolution of about 2 mm is estimated with a Monte Carlo study of a PET system based on arrays of $3 \times 3 \times 25$ mm^3 LySO crystals with individual SiPM read-out. The axial resolution of the system depends on the thickness of the detector ring and the detector design can be optimized according to the clinical needs, due to the modular structure of the LySO/SiPM detection system. The experimental study of the LySO/SiPM detection system found also the technology mature to fulfil the needs of the design. The energy resolution of about 8% is measured in response of a SiPM/LySO detection system to the 511 keV photons from the β^+ source ^{22}Na, showing good agreement with the Monte Carlo estimation. The measured time resolution of two LySO/SiPM detection systems in coincidence is 800 ps against the 306 ps expected by the Monte Carlo estimation.

References

[1] N. D'Ascenzo, A. Eggemann, E. Garutti, A. Tadday, Il Nuovo Cimento C 30 (5) (2007).
[2] N. D'Ascenzo, V. Saveliev, in: Jin-Wei Shi (Ed.). The New Photo-Detectors for High Energy Physics and Nuclear Medicine, Photodiodes-Communications, Bio-Sensings, Measurements and High-Energy Physics, InTech, 2011, ISBN: 978-953-307-277-7.
[3] D.J. Herbert, V. Saveliev, N. Belcari, N. D'Ascenzo, A. Del Guerra, A. Golovin, IEEE Transactions on Nuclear Science NS-53 (1) (2006) 389.
[4] J. Karp, S. Suleman, M. Daube-Witherspoon, R. Freifelder, C.A. Cardi, L. Adam, M. Bilger, G. Muehllehner, Journal of Nuclear Medicine 44 (2003) 1340.
[5] V. Saveliev, V. Golovin, Nuclear Instruments and Methods in Physics Research Section A 442 (2000) 223.
[6] SensL, 〈http://www.sensl.com〉, 2010.
[7] A.G. Stewart, V. Saveliev, S.J. Bellis, D.J. Herbert, P.J. Hughes, J.C. Jackson, The Journal of Quantum Electronics 44 (2) (2008) 157.
[8] D. Strul, G. Santin, V. Breton, C. Morel, Nuclear Physics B 125 (2003) 75.

Please cite this article as: N. D'Ascenzo, V. Saveliev, Nuclear Instruments & Methods In Physics Research Section A (2011), doi:10.1016/j.nima.2011.11.091