IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10491-7

Colloquia: IFAE 2009

Detectors for the next-generation PET scanners

S. Marcatili(1)(2)(*), G. Collazuol(3)(2), M. G. Bisogni(2), G. Llosà(1)(**), G. Magazzú(2), G. Ambrosi(4), F. Corsi(5), G. Dalla Betta(4)(7), C. Piemonte(8) and A. Del Guerra(1)

(1) *Dipartimento di Fisica, Università di Pisa - Pisa, Italy*
(2) *INFN, Sezione di Pisa - Pisa, Italy*
(3) *Scuola Normale Superiore - Pisa, Italy*
(4) *INFN, Sezione di Perugia - Perugia, Italy*
(5) *DEE-Politecnico di Bari - Bari, Italy*
(6) *INFN, Sezione di Padova - Padova, Italy*
(7) *Università di Trento, DISI - Povo di Trento, Italy*
(8) *FBK-irst Divisione Microsistemi - Povo di Trento, Italy*

(ricevuto il 19 Settembre 2009; pubblicato online il 2 Dicembre 2009)

Summary. — Next-generation PET scanners are expected to fulfill very high requirements in terms of spatial, energy and timing resolution. Modern scanner performances are inherently limited by the use of standard photomultiplier tubes. The use of Silicon Photomultiplier (SiPM) matrices is proposed for the construction of a small animal PET system with depth of interaction capabilities. Measurements showing that SiPM matrices are highly ideal for PET applications, have been reported.

PACS 29.40.-n – Radiation detectors.

1. – Requirements for the next generation PET scanners

Positron Emission Thomography is a powerful imaging technique in which positron emitting radionuclides bound to biologically significant molecules are used to investigate many metabolic processes *in vivo*. The two antiparallel photons resulting from each single positron annihilation in tissue, are detected in time coincidence and used to determine their "line of flight". Thomographic acquisition of these Line Of Responses (LOR) allows for the 3-dimensional reconstruction of the map of activity inside the organism under investigation.

(*) E-mail: sara.marcatili@pi.infn.it
(**) Now at Instituto de Fisica Corpuscolàr, Valencia, Spain.

Standard PET detectors are currently based on the well-established technology of Photo Multipliers Tube (PMT). PMTs of different types coupled to crystal scintillators of various geometries, provide PET modules with different performances. However, in the last years, the constraints that next-generation PET scanners are expected to fulfill, have posed the basis for a radical renewal of PET technology.

Current PET scanners performances are definitely limited by intrinsic features of the detector employed. Their spatial resolution is strongly influenced by detector's pitch and parallax errors, and these ultimately depend upon detector layout. A small-pitch or a continuous detector, in fact, can result in a more accurate position determination and would make it feasible the sub-millimetric resolution required in small animal imaging. At the same time, a small and compact detector could be assembled in a multi-layer module capable of measuring the radiation Depth Of Interaction (DOI). In the process of image reconstruction, the assumption that gammas interact at detector surface is generally made, resulting in a bad determination of LORs. In addition, Signal to Noise Ratio (SNR) can be improved by using the Time Of Flight (TOF) technique.

An intrinsic limitation of Positron Emission Thomography is its poor capability to reveal detailed morfological strucutures. The need for a better identification of anatomical contours has lead to the development of hybrid imaging systems composed by a PET scanner associate to a X-ray Computed Tomography (CT) apparatuses. Their use is nowadays widely diffuse in day-to-day clinical practice, even if they present the disadvantage of significantly contribute to the total dose delivered to the patient. On the other hand, MRI would provide exceptionally high-resolution images and functional information complemental to those obtained from PET without resulting in an additional dose delivering. However the use of PMT is not straightforward in a magnetic field environment. All these requirements lead to the necessity of an innovative solution. The use of a high-granularity, compact, solid-state detector seems to be the right choice, as many studies are currently indicating [1-3].

The Silicon PhotoMultiplier (SiPM) [4] has been demonstrated to be the optimum candidate [5]. A SiPM consists of Geiger Mode Avalanche PhotoDiodes (GM-APD) arrays connected in parallel through a polysilicon resistor. Each of the microcells permits the conversion of light in one photoelectron, thus, by summing up all the contribute from the microcells composing the SiPM, a signal proportional to the deposited energy can be obtained for a low light flux. Current SiPMs are composed of a variable number of microcells (from few hundreds to thousands) of different sizes (linear dimensions from 25 to 100 μm) and they are now available in detectors of relatively large size. SiPM matrices [5] consist of SiPM arrays grown on a common substrate and they have been produced in 4×4 or 8×8 pixels versions at FBK-irst [6]. Thanks to its typical pitch, ranging from 1 to 1.5 mm with a negligible dead area due to the signal routing, the SiPM matrix can provide high spatial resolution maps when used for imaging applications. Moreover, its compactness makes it possible the realization of multi-layers detector modules capable to provide DOI information, while the very limited time jitter (about 70 ps FWHM at single photoelectron level in the case of single SiPM [7]) makes viable the realization of human TOF-PET scanners if a very fast scintillator is adopted. Furthermore, the high intrinsic gain (up to 10^6) attainable at low bias voltage (~ 50 V), and the consequent high signal-to-noise ratio makes the use of sophisticate electronics redundant. Being a solid-state detector, SiPM is intrinsically magnetic field insensitive, and hence can be used in the assessment of PET/MRI apparatuses.

2. – A SiPM based small animal PET prototype

One of the goals of the DASiPM (Development and Application of SiPM) Collaboration is the construction of a small animal PET scanner prototype based on SiPM matrices and LYSO scintillator crystals. The complete detector will be composed of two high spatial resolution heads with DOI capabilities. Three modules consisting on SiPM matrices of 1.5 mm pitch, coupled to continuous LYSO crystals 0.5 mm thick are assembled in a pile, in $1.2\,\text{cm}^2$ area detector heads. Simulation of the prototype, performed via Geant4 toolkit, predicts a sub-millimetric spatial resolution at the center of the Field Of View (FOV), for a ^{18}F point source [8].

However the use of SiPMs makes it necessary to develop a read-out system capable to manage signals from many channels. This system should also exhibit excellent timing properties (time jitter below few hundreds of ps) and good spectroscopy capabilities not to degrade SiPM intrinsic performances. The data acquisition should sustain a $10\,\text{kHz/cm}^2$ rate, which is the maximum expected in a pre-clinical scenario for a small animal PET scanner. The front-end should be based on Application Specific Integrated Circuit (ASIC), so as to manage many channels and keep the system compact at the same time. Standard ASIC chips are not ideal for SiPM applications because they have been mainly conceived for PMTs, and, when connected to a SiPM, they generally saturate because of its huge intrinsic gain.

The read-out system which is currently being developed, is based on an ASIC chip that handles both the signals pre-amplification and the fast-or trigger generation. The read-out board, which at the moment mounts a commercial chip of the VA-TA family by IDEAS, can also house a dedicated ASIC which has been designed at Politecnico of Bari [9]. The whole acquisition [10] is controlled by means of an FPGA (Stratix II) and communicates with the PC via an USB interface. A coincidence board will allow the detection of photons from a single event in a 5 ns coincidence window, for a good noise rejection.

3. – SiPM matrices performances in imaging applications

SiPM matrices performances as detector for PET have been deeply investigated [5] via a read-out system based on MAROC2 chip and developed at (Linear Accelerator Laboratory) LAL in Paris. Detectors of 4×4 pixels have been coupled to LYSO scintillator crystals of different sizes and designs in order to study their time, energy and spatial resolution capabilities.

Continuous slab of LYSO of the same size of the detector and 0.5 mm thick have been used to carry out spectroscopic measurement with a ^{22}Na source. The typical energy resolution is about 15% FWHM, quite good for PET applications. Thanks to SiPM very low time jitter, the measured time resolution is dominated by LYSO decay time properties and detector efficiency. Tests have been performed both with continuous and pixellated crystals. By summing up the contribute of all SiPM channels, a time jitter of 1.8 ns (σ) in the former and a 1.3 ns (σ) time resolution in the latter configuration, have been measured.

Very encouraging results have been achieved for what concerns its spatial resolution capabilities. In this case both pixellated scintillators with the same pitch of the detectors, and continuous black slab have been employed. A ^{22}Na point source placed very near the detector module has been collimated performing a time coincidence with a LYSO single pixel of $1\,\text{mm}^2$ surface; in this way a light spot has been obtained, that can be

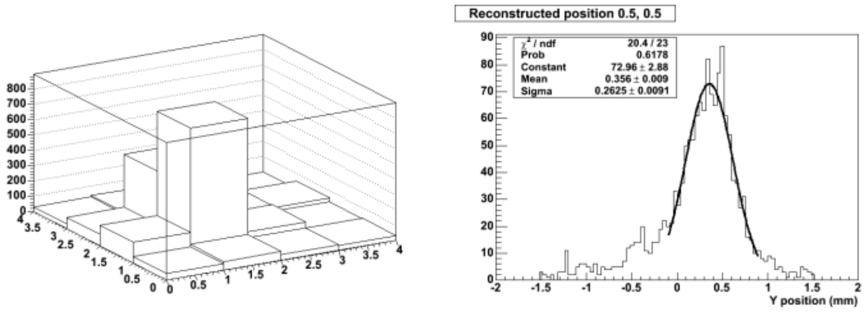

Fig. 1. – Spatial resolution performances of a SiPM matrix coupled to a pixellated LYSO crystal (left) and a continuous black slab of the same material (right). On the right, a slice view of the reconstructed light distribution exhibits a sigma below 0.3 mm.

used to scan the module moving the source and the crystal pixel contemporaneously. In the case of one-to-one coupling, it has been shown that shifts of 0.5 mm can be clearly distinguished in the resulting image (fig. 1 left). Results relative to the black continuous slab module are the most interesting, since it is the solution that will be implemented in the final scanner. In this case a light spot at 0.5 mm from the center of the FOV produces a very narrow light distribution with a sigma smaller than 0.3 mm (fig. 1 right).

4. – Conclusions

SiPM matrices have been demonstrated to be optimum candidates for the assessment of PET apparatuses. Their intrinsic features allow for the construction of PET systems with performances far better than those of the modern scanners. A small animal PET prototype is under development at University of Pisa in the framework of the INFN project DASiPM. It will provide DOI information and a sub-millimetric spatial resolution at the center of the FOV as predicted by Geant4 simulations and then confirmed by measurements on a smaller version of the final detector module.

* * *

This work is partially supported by MUR (Ministero dell'Università e della Ricerca) in the framework of the PRIN (Progetti di Rilevante Interesse Nazionale) program 2007 and partially by INFN, Scientific National Commission V, in the framework of DASiPM and DASiPM2.

REFERENCES

[1] Llosa G. *et al.*, *IEEE Trans. Nucl. Sci.*, **55** (2008) 877.
[2] Shao Y. *et al.*, *IEEE Trans. Nucl. Sci.*, **47** (2000) 1051.
[3] Pichler B. J. *et al.*, *J. Nucl. Med.*, **47** (2006) 639.
[4] Piemonte C. *et al.*, *NSS Conference Record*, **41** (2007) 2089.
[5] Llosa G. *et al.*, *MIC Conference Record*, **2** (2008) 3574.
[6] Llosa G. *et al.*, *IEEE Trans. Nucl. Sci.*, **56** (2009) 543.
[7] Collazuol G. *et al.*, *Nucl. Instrum. Methods A*, **581** (2007) 461.
[8] Moehrs S. *et al.*, *Phys. Med. Biol.*, **51** (2006) 1113.
[9] Corsi F. *et al.*, *NSS Conference Record*, **15** (2007) 360.
[10] Bisogni M. G. *et al.*, *NSS Conference Record*, **52** (2008) 3574.