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A small animal PET prototype based on Silicon Photomultipliers

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Summary. — Next generation PET scanners should 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 consisting of two detector heads based on LYSO continuous crystals. The use of large area multi-pixel Silicon Photomultiplier (SiPM) detectors requires the development of a multichannel Digital Acquisition system (DAQ) as well as of a dedicated front-end in order not to degrade the intrinsic detector capabilities. At the University of Pisa and INFN Pisa we developed a DAQ board for the read-out of 2 64-pixel SiPM matrices in time coincidence for Positron Emission Tomography (PET) applications. The proof of principle is based on 64-pixel detectors, but the whole system has been conceived to be easily scalable to a higher number of channels. Here we describe the Group-V INFN DASiPM2 (Development and Application of SiPM) project and related results.

PACS 87.57.uk – Positron emission tomography (PET).
PACS 29.40.-n – Radiation detectors.

1. – Introduction

In the last years, the Silicon Photomultiplier has been proposed by several research group worldwide as a photodetector for PET (Positron Emission Tomography) applications as a possible candidate for the replacement of the standard Photomultiplier Tube. Its excellent capabilities are, in fact, widely acknowledged: the high gain (up to 10^6) and the low noise level does not make the use of a sophisticated electronics necessary, the small intrinsic time jitter makes it ideal for the construction of TOF (Time Of Flight) PET scanners and its insensitivity to magnetic fields opens the way to the assessment of hybrid PET-MRI systems. Moreover, the development of large-area SiPM matrices grown on a common substrate and with uniform performances allows for the realization of a high-granularity imaging surface with negligible dead area.

At the University of Pisa we plan to build up a $4.8 \times 4.8\,\mathrm{cm}^2$ 4D-PET module constituted by two detection layers. It will provide high spatial resolution (x, y) with DOI (Depth Of Interaction) capabilities (z) in order to reduce the parallax error. The high timing resolution (t) that we expect will be used to perform the event TOF (Time Of Flight) and to increase the SNR (Signal-to-Noise Ratio).

In the framework of the INFN DASiPM (Development and Application of SiPMs) project we have deeply characterized both single elements SiPMs of different producers and matrices, and we have demonstrated that their characteristics in terms of energy resolution (below 15% FWHM), spatial resolution (0.9 mm FWHM) and time resolution (around 100 ps sigma for a single $3 \times 3\,\mathrm{mm}^2$ SiPM coupled to LSO:Ce,Ca) fulfill our requirements. In addition we have developed a dedicated front-end in order to manage signals from SiPM matrices without degrading their large dynamic range.

Currently we are developing an home-made modular acquisition system for the read-out of a first $2.1 \times 2.1\,\mathrm{cm}^2$ prototype of the 4D-PET block detector. This system consists of 9 identical DAQ boards housing an 8-channel version of the front-end chip, for the read-out of each detector head. A high-performance master FPGA will handle the acquisition of the signals from the front-end boards performing the time coincidence and the TOF algorithm.

2. – The need for an innovative photodetector in PET applications

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.

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 the 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 the detector layout. A small-pitch or a continuous detector, in fact, can result in a more accurate position determination and would make the sub-millimetric resolution required in small animal imaging feasible. 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 the detector surface is generally made, resulting in the possible determination of LORs not including the annihilation point. In addition, the Signal-to-Noise Ratio (SNR) can be improved by using the Time Of Flight (TOF) technique.

The knowledge of the time difference in the arrival of the two annihilation photons from a single event would permit to reduce the number of image voxels involved in the position determination, and hence, to reduce noise propagation in the image reconstruction process. 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 led to the development of hybrid imaging systems composed by a PET scanner associate to X-ray Computed Tomography (CT) apparatuses. Their use is nowadays widely diffuse in day-to-day clinical practice, allowing a more accurate activity quantitation as well as providing attenuation information for PET data correction. However, the main drawback of this combined approach, is that CT adds a significant contribution to the total dose delivered to the patient. So, in the last years, another possibility is currently being exploited, addressing the problem of an improved capability of structures determination. Magnetic Resonance Imaging (MRI) in addition to providing exceptionally high-resolution images, is a functional imaging technique able to investigate phenomena complementary to those of interest in PET without resulting in an additional dose delivering. However, the merger is not without hindrances. The PMT is inherently sensitive to magnetic fields, and the realization of a PMT-based PET scanner in a magnetic-field environment would be a technological challenge.

3. – The Silicon Photomultiplier

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 trough a polysilicon resistor. Each of the microcells permits the conversion of light in one photoelectron, thus, by summing up all the contributions 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. 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 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 [6]) 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.

4. – The 4D-PET module

The availability in 2006 of the first Silicon Photomultiplier matrices grown on a common substrate paved the way to the construction of a high-granularity, low-noise, high-timing-resolution imaging device based on silicon photodetectors. At the University of Pisa we are planning to build a high-spatial and time resolution PET module with

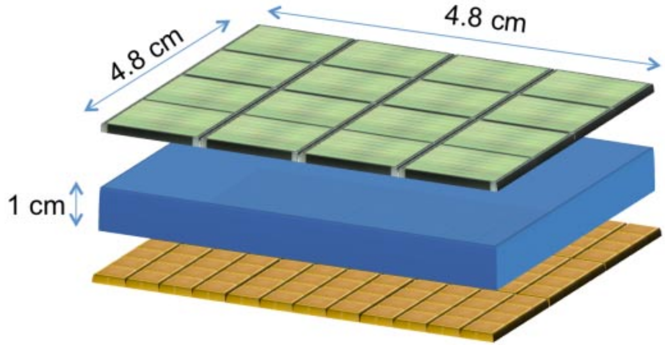

Fig. 1. – 4D-PET module design.

DOI capabilities. This module, with an overall size of $4.8 \times 4.8\,\mathrm{cm}^2$, could be considered the successor of the standard block detector of the clinical PET scanners.

The module will be based on a single LYSO monolithic scintillator read by two layers of SiPMs placed on the two opposite faces of the crystal. The bottom layer, which is the one where the radiation is entering, will be composed of 12×12 (144) Silicon Photomultiplier pixels with a size of $4 \times 4\,\mathrm{mm}^2$ each, while the top layer will be composed by 4×4 64-channel SiPM matrices (see fig. 1) on a 1.5 mm pitch. The low spatial granularity detection surface will provide improved timing information thanks to the larger photon collection surface of the single detector element. Conversely, the high granularity surface, thanks to the small pitch, will allow the reconstruction of the hit position with a high spatial resolution. Data from both sides will be used to reconstruct the depth of interaction (DOI) for each event so as to reduce the parallax error.

5. – Silicon Photomultipliers characterization as a photodetector for PET

SiPM pixels and matrices performances as detector for PET have been deeply investigated by the DASiPM Collaboration in the last four years. Detectors up to 8×8 pixels with a 1.5 mm pitch have been coupled to LYSO scintillator crystals of different sizes and designs in order to study their time, energy and spatial resolution capabilities.

Continuous slabs 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 [5]. The typical energy resolution is below 15% FWHM, adequate for PET applications.

The very low intrinsic time jitter (about 70 ps at single photoelectron level) of the SiPM has been measured [6] by using a Ti:sapphire laser with jitter below 100 fs and it has been demonstrated not to significantly affect the module performance when the SiPM is coupled to a scintillator crystal. Measurements performed with a $3 \times 3\,\mathrm{mm}^2$ SiPM pixel coupled to a LYSO:Ce,Ca crystal of the same area have shown a time jitter resolution slightly above 100 ps sigma for the single device [7] which is comparable to that expected considering LYSO decay time properties and detector efficiency.

Extremely encouraging results have been achieved for matrices spatial resolution capabilities when they are coupled to continuous LYSO slab painted black on the other faces. A ^{22}Na point source placed very near the detector module has been collimated performing a time coincidence with a LYSO single pixels of $1\,\mathrm{mm}^2$ surface; in this way a light spot has been obtained, that can be used to scan the module moving the source

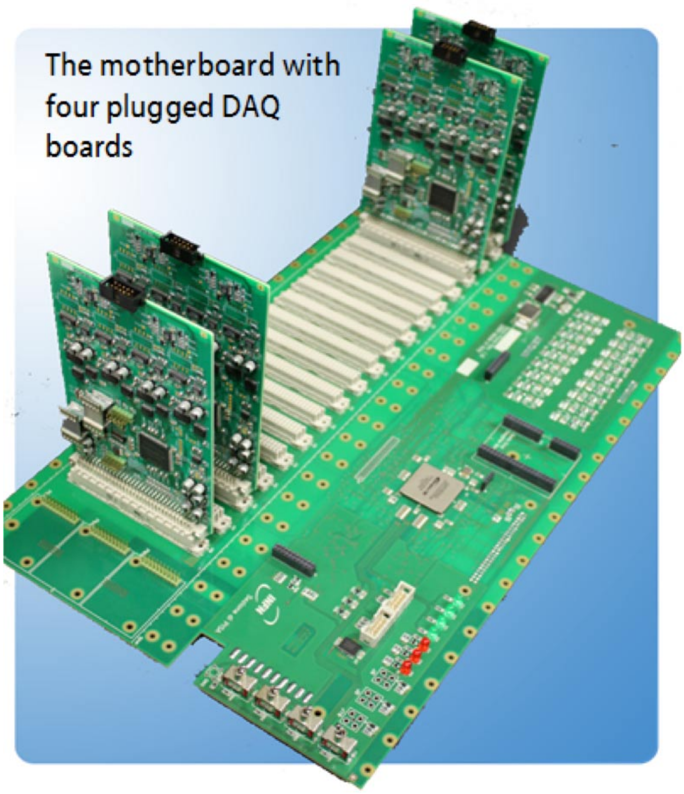

Fig. 2. – The mother board with four plagged DAQ boards.

and the crystal pixel simultaneously. With this set-up we were able to reconstruct the spot spatial position with a sub-millimetric resolution (FWHM) [8].

SiPM matrices required the development of a dedicated multichannel front-end capable to respect their high dynamic range and their excellent timing performance. At Politecnico of Bari, in the framework of the DaSiPM Collaboration, an ASIC for the read-out of SiPM matrices based on a current buffer approach has been developed. In this way the signal can be easily duplicated and split into two lines: a fast one, including a current discriminator, which provides the trigger signal, and a slow one, which yields the analog signal proportional to the energy deposited. The architecture includes also a fast-OR circuit for the trigger generation and a standard cell digital part which manages the multiplexing of the channels. An 8-channel version of this chip has already been tested [9] while the first 32-channel chip is already available and under test.

6. – Read-out system architecture

A flexible acquisition system for a modular dual head Positron Emission Mammography scanner based on flat panel photomultiplier tubes Hamamatsu H8500 [10] has already been developed. The core of the system is a cross-application acquisition board (called mother board) capable to handle up to 18 DAQ boards in which it is possible to place a dedicated front-end (see fig. 2).

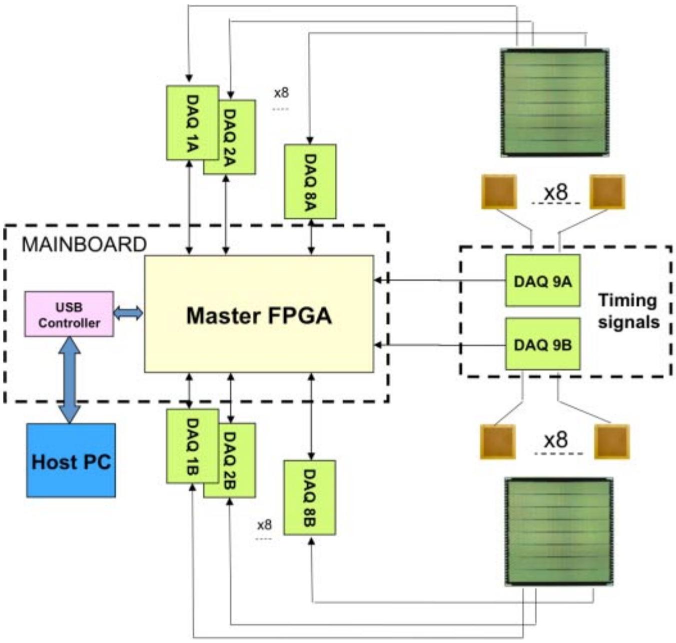

Fig. 3. – Acquisition architecture for the proof of principle prototype.

For the read-out of SiPM matrices a new architecture for the DAQ boards has been conceived while leaving the mother board unchanged. Each DAQ board will read from 8 up to 32 channels of the detector module depending on the version of the ASIC mounted. The ASIC is housed on a mezzanine board in order to allow an easy replacement of the chip which is possible thanks to the ASIC serial output and to the redundancy of the DAQ design. In each DAQ board, a single channel, 10 bit, 105 MSPS ADC allows for the conversion of the signals coming from the sample and hold circuit in the ASIC; an FPGA controls the data read-out and sends the energy and timing signals to the mother board when it receives a valid trigger. A high performance FPGA on the mother board manages the time coincidence algorithm with a time window of about 7 ns FWHM and the TOF signals. The communication with the host PC is via USB protocol.

7. – The proof of principle prototype

The acquisition system, together with the 8 channel version of the ASIC, will allow the construction of a smaller two head proof of principle prototype (see fig. 3). Each head will be composed by one 64-channel SiPM matrix to provide the spatial information on the one side, and by an array of 3×3 16 mm^2 SiPM pixels to provide the timing signal on the other side of the crystal. Hence, 8+8 DAQ boards are necessary to read the top layer of the two modules, while 2 spare DAQ boards remain for the read-out of the two bottom layers; the current version of the ASIC has got 8 channels, hence, neglecting one of the 9 bottom pixels placed at the corner, it is possible to manage the timing signals by using the same electronic architecture used for energy signals read-out. A fully digital, one channel TDC will be realized in the FPGA on the mother board in order to implement the TOF (Time Of Flight) technique.

Currently all the acquisition boards are available and most of the firmware has been written. First tests on the DAQ boards are on-going. We plan to perform a full characterization of all the logic functions implemented and an accurate calibration of the DAQ boards analog circuit. Then, SiPM matrices will be connected to the read-out system in order to validate the feasibility of the 4D-PET module proposed.

8. – 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 the 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.

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