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Development and characterization of a modular acquisition system for a 4D PET block detector

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ABSTRACT

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 4D PET module based on LSO continuous crystals, which is envisaged to replace the standard PET block detector. The expected spatial resolution of the module for the photon hit position is below 1 mm, and it will perform at the same time, the Depth Of Interaction (DOI) calculation and the Time Of Flight (TOF) measurement. 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 performances. We have developed a flexible and modular DAQ system for the read-out of two modules in time coincidence for Positron Emission Tomography (PET) applications. The DAQ system is based on a previously developed custom front-end ASIC chip (BASIC) which allows to read-out SiPM matrices preserving their spectroscopy and timing capabilities. Here we describe the acquisition system architecture and its characterization measurements.

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 in replacement of the standard Photomultiplier Tube [1,2]. In fact, its excellent capabilities are widely acknowledged: the high gain (up to 10^6) and the low noise level does not make it necessary the use of a sophisticated electronics; the small intrinsic time jitter makes it ideal for the construction of TOF (Time Of Flight) PET scanners and its insensitivity to magnetic field 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 high granularity imaging surface with negligible dead area.

Our goal at University of Pisa is to build a 4.8×4.8 cm^2 4D-PET module. The 4D refers to the four dimensions measurement capabilities, namely: it will provide high spatial resolution (x, y) with DOI (Depth Of Interaction) capability (z) in order to reduce the parallax error. The high timing resolution (t) we expect will be used to perform the event TOF (Time Of Flight) so as to increase the SNR (Signal to Noise Ratio).

In the framework of the DASiPM (Development and Application of SiPMs) project funded by INFN (Istituto Nazionale di Fisica Nucleare, Itay) 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 at 511 keV), spatial resolution (0.9 mm FWHM when coupled to LSO slabs painted black) and time resolution (around 100 ps sigma for a single 3×3 mm^2 SiPM coupled to LSO:Ce,Ca) [3,4] fulfill our requirements. In addition we have already developed a

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dedicated front-end in order to handle signals from SiPM matrices without degrading their large dynamic range [5,6].

Currently a custom modular acquisition system for the read-out of two heads of a reduced size (2.4×2.4 cm^2) prototype of the 4D-PET block detector is under development. This system consists of 9+9 identical DAQ boards housing a custom ASIC 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 managing the time coincidence and the TOF algorithm [7].

In this paper we present the acquisition system that includes a custom ASIC front-end, and its characterization measurements with and without the photodetector connected.

2. Four years of R&D on Silicon Photomultipliers

The performances of SiPM pixels and matrices as a photodetector for PET have been deeply investigated by the DASiPM collaboration in the last four years. Photodetectors up to 8×8 pixels with a 1.5 mm pitch produced at FBK-irst (Trento, Italy) [8] have been coupled to LSO scintillator crystals of different sizes and designs in order to study their time, energy and spatial resolution capabilities.

Continuous slabs of LSO of the same size of the detector and 0.5 cm thick have been used to perform spectroscopic measurement with a ^{22}Na source [3,4]. The typical ^{22}Na energy resolution at 511 keV in time coincidence 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 [9] using a Ti:sapphire laser with jitter below 100 fs. It has been demonstrated that SiPM intrinsic timing performances do not significantly affect the module performances when it is coupled to a scintillator crystal. Measurements made with a 3×3 mm^2 SiPM pixel coupled to a LSO:Ce,Ca crystal of the same area have shown a time jitter resolution slightly above 100 ps sigma for the single device [10] which is comparable to that expected considering LSO decay time properties and detector efficiency [11].

Extremely encouraging results have been achieved for the spatial resolution capabilities of SiPM matrices when they are coupled to continuous LSO 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 far away LSO single pixel of 1 mm^2 surface; in this way a light spot has been obtained, that can be used to scan the module moving the source and the crystal pixel simultaneously. With this set-up we were able to reconstruct the spot spatial position with a sub-millimetric resolution (FWHM) [12].

SiPM matrices require the development of a dedicated multichannel front-end capable to respect their high dynamic range and their excellent timing performances. At Politecnico of Bari, in the framework of the DaSiPM collaboration, a mixed signal ASIC (BASIC chip) for the read-out of SiPM matrices based on a current buffer approach has been developed, and its design and performances have already been described in a previous work [5]. 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, yielding the analog signal proportional to the energy deposited. The architecture includes also a fast-OR circuit for the ultimate trigger generation (FASTOR) and a standard cell digital module which manages the multiplexing of the channels. The BASIC can provide three different gains (1 V/pC, 0.5 V/pC, 0.33 V/pC). The lower gain guarantees a 70 pC dynamic range, which has been optimized for the read-out of SiPMs coupled to LSO crystals painted black. An 8 channel version of this chip has already been tested [13] while a 32 channel design is already available and it is currently under test [6].

3. The 4D-PET module

At University of Pisa and INFN Pisa we are planning to build a high spatial and time resolution PET module with DOI capabilities. In its final version this module will have an overall size of 4.8×4.8 cm^2, comparable to the size of the standard block detector [14], and hence, it might be considered its successor in the construction of clinical PET scanners.

The module will be based on a single LSO 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 4×4 mm^2 each, while the top layer will be composed of 4×4 64 channel SiPM matrices (see Fig. 1) on a 1.5 mm pitch. The low spatial granularity detection surface (bottom) is the one on which the gamma radiation enters, and it will provide improved timing information thanks to the larger photon collection surface of the single detector element. Conversely, the high granularity surface (top), thanks to the smaller 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. In order to avoid internal reflections and improve the spatial resolution capabilities of the module, LSO crystal will be painted black on the surfaces not facing the detectors.

Despite some aspects of the design are not unprecedented [15–17] for what concerns the DOI and TOF measurements or the continuous crystal approach, our detector will benefit of the additional advantages introduced by the use of SiPM matrices. Currently, the acquisition system for a proof of principle prototype of reduced size is under construction. It presents the same conceptual design of the previously described module but with only one-quarter of its detection surface (2.4×2.4 cm^2) and a smaller number of channels. The high granularity surface will be composed of 4 SiPM matrices (256 channels) while the low granularity one will be composed of 36 single SiPM pixels. Here we present the DAQ system and measurements concerning this 2.4×2.4 cm^2 prototype.

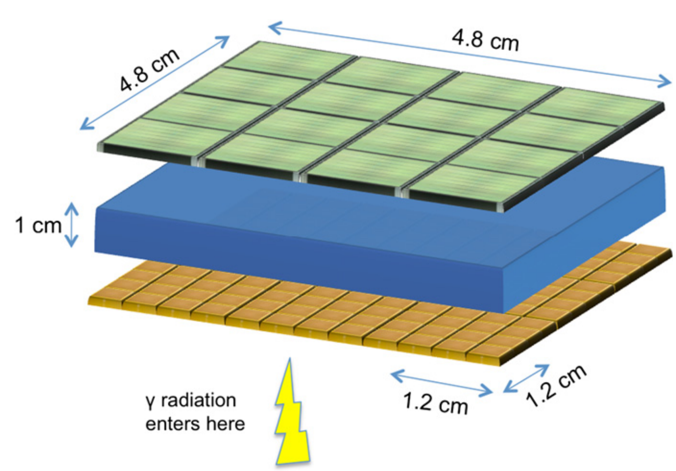

Fig. 1. Conceptual design of the 4D PET prototype. The top layer is composed of 4×4 64 channels SiPM matrices with a 1.5 mm pitch and it is expected to provide the spatial information with a submillimetric resolution. The bottom layer is composed of 12×12 single SiPM pixels of 4×4 mm^2 area and it will provide the timing information.