Nuclear Instruments and Methods in Physics Research A 659 (2011) 494–498

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

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

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ARTICLE INFO

Article history:
Received 5 August 2011
Accepted 22 August 2011
Available online 27 August 2011

Keywords:
SiPM matrices
PET
ASIC
DAQ

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 $4.8 \times 4.8\ cm^2$ 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 $3 \times 3\ mm^2$ SiPM coupled to LSO:Ce,Ca) [3,4] fulfill our requirements. In addition we have already developed a

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0168-9002/$ - see front matter
doi:10.1016/j.nima.2011.08.042

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 ($2.4\times 2.4\ cm^2$) 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 $3\times 3\ mm^2$ 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 multi-channel 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 $4.8\times 4.8\ cm^2$, 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 $4\times 4\ mm^2$ 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 ($2.4\times 2.4\ cm^2$) 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 $2.4\times 2.4\ cm^2$ prototype.

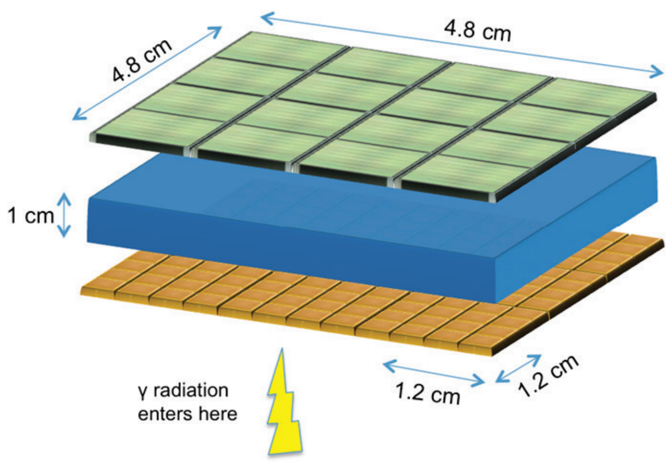

Fig. 1. Conceptual design of the 4D PET prototype. The top layer is composed of 4×4 64 channels SiPM matrices with a 1.5 mm pitch and it is expected to provide the spatial information with a submillimetric resolution. The bottom layer is composed of 12×12 single SiPM pixels of $4\times 4\ mm^2$ area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

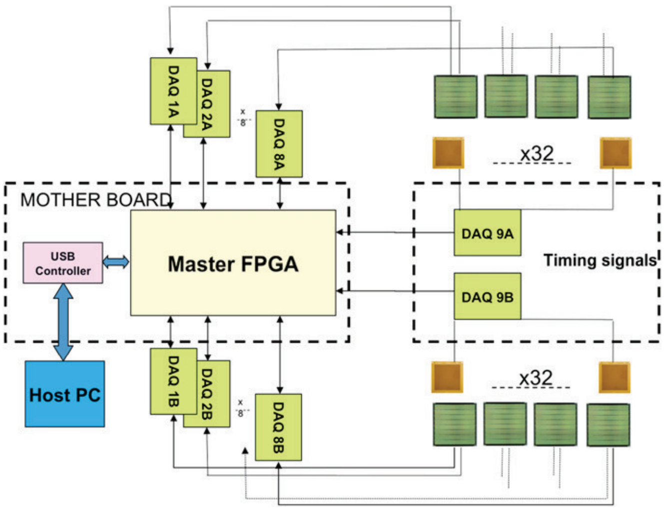

Fig. 2. Acquisition system architecture for the proof-of-principle prototype.

3.1. Read-out system architecture

We have developed an acquisition system for the read-out of two modules of the 4DPET detector. The core of the system is a cross-application acquisition board (called mother board) capable of handling up to 18 DAQ boards in each of which it is possible to place a dedicated front-end [7].

Each DAQ board can read from 8 up to 32 channels of the detector module depending on the version of the BASIC mounted. The BASIC is housed on a mezzanine board in order to allow an easy replacement of the chip which is possible thanks to the BASIC serial output. In each DAQ board, a single channel, 10 bit, 105 MSPS (Mega Samples Per Second) ADC allows for the conversion of the signals coming from the sample-and-hold circuit in the BASIC; an FPGA (Cyclone II from Altera, 101 Innovation Drive San Jose, CA, USA) 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 (Stratix III from Altera) on the mother board manages the time coincidence algorithm and also the TOF signals thanks to a fully digital one channel TDC. The communication with the host PC is via USB 2.0 protocol.

3.2. Acquisition system architecture

The acquisition system we have built allow the handling of two heads proof-of-principle prototype (see Fig. 2). Each head is composed of four 64 channel SiPM matrices to provide the spatial information on one side, and by an array of 6×6 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 two spare DAQ boards remain for the read-out of the two modules bottom layers. Although in the future we plan to develop a custom TDC chip to read-out the timing signals, the preliminary use of the BASIC allows us to use the same DAQ board design both for the high and low granularity detection surface by maintaining satisfying timing performances at the same time.

4. DAQ system performances

Currently all the acquisition boards are available and most of the firmware has been written. First tests of one DAQ board mounting an 8 channel version of the BASIC have been carried out in order to prove the excellent performances of our acquisition system in terms of linearity, uniformity and timing capabilities. Measurements have been performed with and without connecting the photodetector to the electronics.

4.1. System linearity and uniformity

Standard characterization measurements of the front-end chip have been carried out by injecting a variable charge to the eight BASIC inputs through a capacitor. The calibration curves for the analog stage of the eight channels (see Fig. 3 top) have been demonstrated to be uniform at a 2% level of accuracy. The response of the BASIC for the three different gains that are available has also been investigated: results are shown in Fig. 3 (bottom) for a single channel.

In order to prove the high uniformity of our system, eight channels of one FBK SiPM matrix on the same row have been connected to the BASIC inputs. Then a scanning of the detector has been performed by using a LSO pixel of 1×1 mm^2 area by 10 mm length. Spectra have been acquired for each scanning position with a 0.5 mm step and counts registered in each SiPM pixel have been plotted as a function of the LSO crystal actual position (see Fig. 4). Although data have not been corrected either for the gain differences among the pixels of the detector or for the gain differences and pedestals of the electronics, we were able to reconstruct the profile of each SiPM pixel. As it is shown in Fig. 4

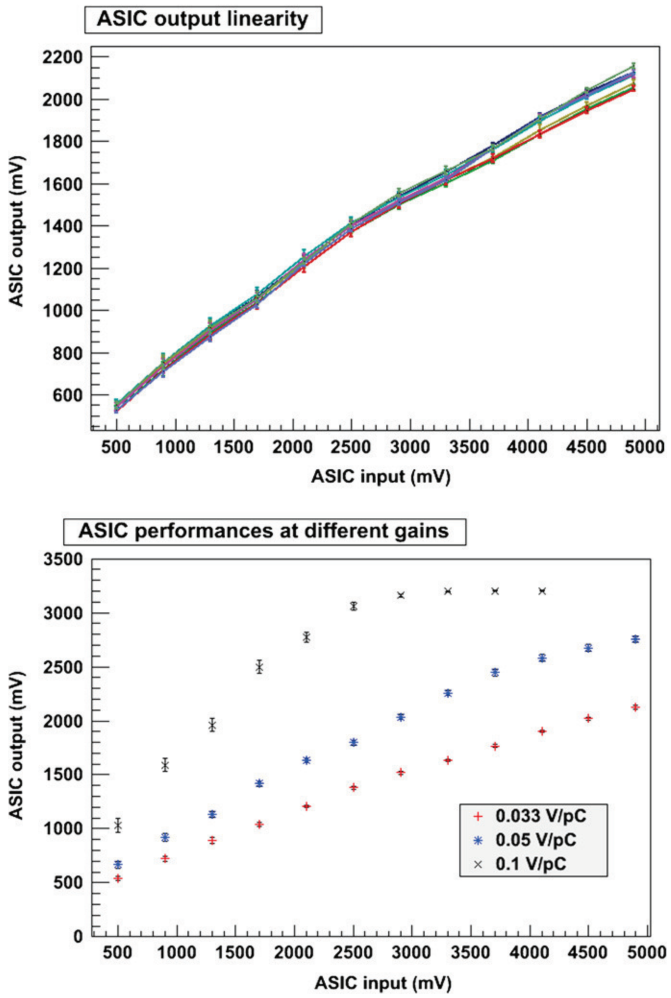

Fig. 3. The calibration curves for the analog stages of the eight channels of the BASIC chip are shown in the top graph. The response of the BASIC for the three different gains is reported in the bottom plot.

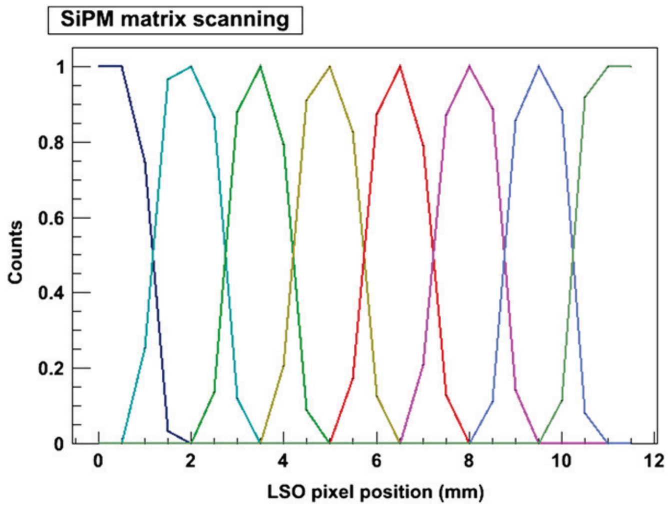

Fig. 4. Reconstructed profiles for eight channels in the same row of the SiPM matrix.

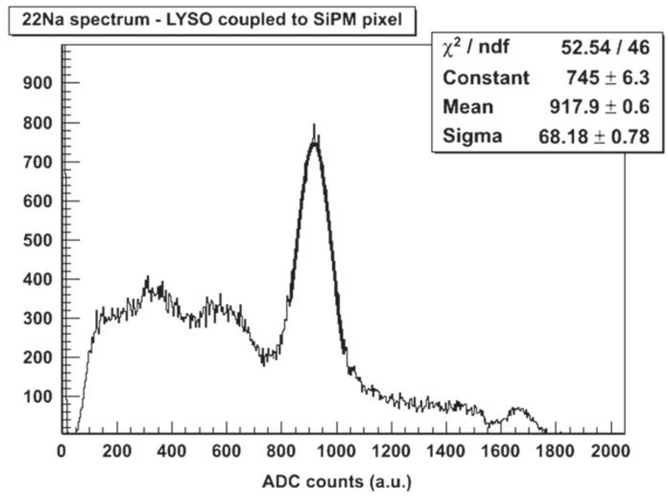

Fig. 6. ^{22}Na spectrum obtained by coupling a $3\times3\times10$ mm^3 LSO crystal wrapped with teflon to a 3×3 mm^2 area MPPC. The signal of the SiPM has been split into two BASIC inputs. A FWHM of 17% is measured at the photopeak.

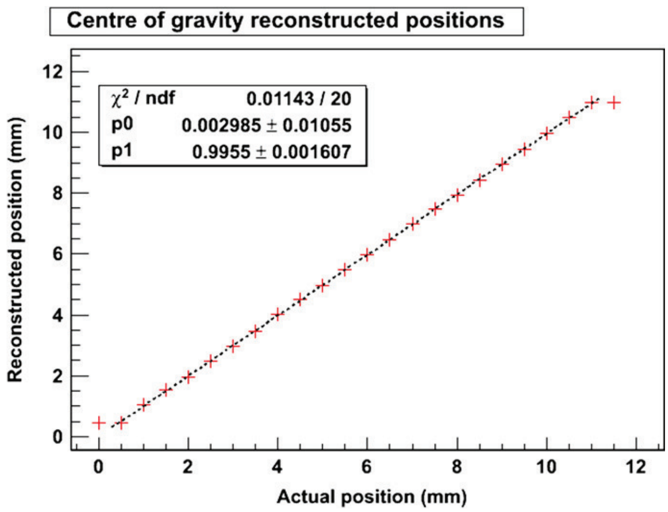

Fig. 5. The COG reconstructed crystal position is plotted versus the actual crystal position. The correspondence is linear along the whole surface of the matrix.

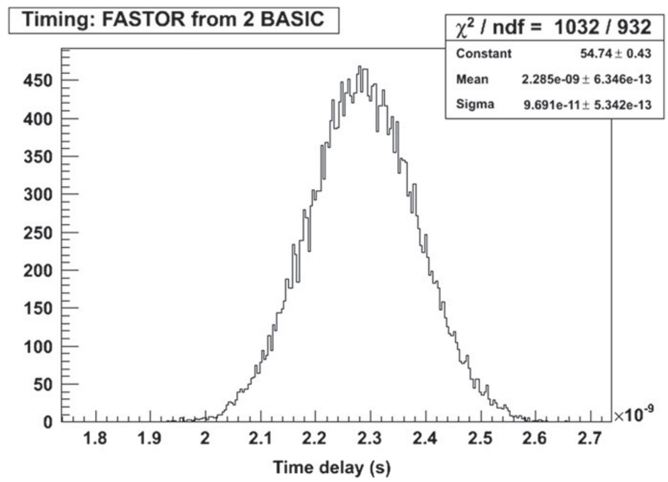

Fig. 7. Time delay distribution obtained by injecting a fixed charge at the input of two BASIC chips and measuring the arrival time of the resulting FASTOR triggers at the scope (97 ps sigma).

the response is very uniform, and the mean reconstructed pixel width is 1.5 mm, perfectly matching the SiPM matrix pitch.

By using the same measurement set-up, we also reconstructed the position of the LSO crystal with the COG (Center Of Gravity) algorithm and plotted the reconstructed positions versus the actual ones. The statistical error associated to the reconstructed position is below the point size. As it can be seen from the fit in Fig. 5, the correspondence is linear for all the crystal positions inside the SiPM matrix.

In order to test the whole acquisition chain, we have made use of a LSO crystal of $3\times3\times10$ mm^3 size wrapped with teflon and coupled to a 3×3 mm^2 MPPC by Hamamatsu. A ^{22}Na spectrum has been acquired with the developed DAQ system. The output of the MPPC has been split into two BASIC channels, since the dynamic range of this chip was optimized for the read-out of LSO crystals painted black and the entire signal from a wrapped scintillator was saturating the amplifier. The spectrum obtained (see Fig. 6) demonstrates that the DAQ system preserves the spectroscopy capabilities of the Silicon Photomultiplier, since its energy resolution of about 17% at 511 keV is compatible with results previously obtained without performing time coincidence [4].

4.2. System timing performances

The use of the BASIC front-end as a preliminary read-out system for the low granularity detection surface designed for TOF applications imposes a constrain of few hundreds picoseconds on the chip time jitter when reading a SiPM coupled to scintillator. Hence, extensive measurements have been performed in order to determine its timing performances.

BASIC intrinsic time jitter have been evaluated by using two DAQ boards housing one BASIC chip each. A fixed charge has been injected through a capacitor at the input of one channel of each BASIC so as to measure its time jitter without considering the time-walk introduced by the detector signal dynamic. At the oscilloscope we measured the time difference between the two FASTOR trigger signals generated by each BASIC obtaining a typical time jitter of about 97 ps sigma as it is shown in Fig. 7.

Subsequently, the BASIC have been connected to the detector in order to measure the ultimate time jitter that can be achieved with the final system. At this scope we coupled two $5\times5\times5$ mm^3 LSO:Ce,Ca crystals to two 4×4 mm^2 MPPCs by Hamamatsu and read them out in time coincidence by using the BASIC chips both to generate the triggers and to obtain the energy signals. The

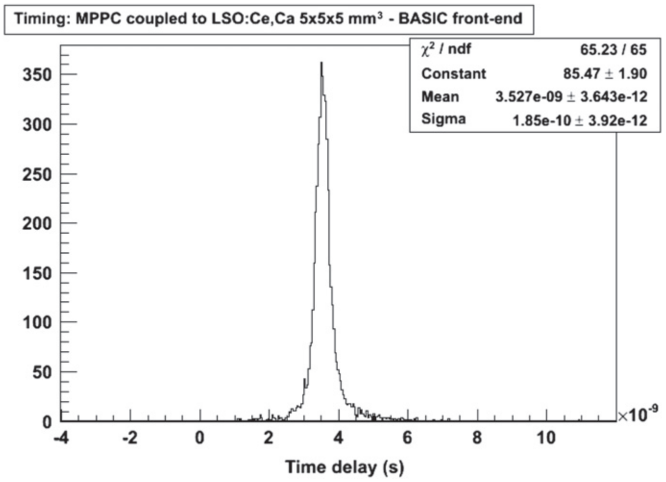

Fig. 8. Time delay distribution of two MPPC by Hamamatsu coupled to a $5\times5\times5\ mm^3$ LSO:Ce,Ca crystal each, read-out by two BASIC chips in time coincidence. A 185 ps sigma has been obtained.

measurements have been performed at the scope following the standard double threshold procedure for TOF: a high threshold corresponding to the Compton edge of the 511 keV gamma has been used for the coincidence events selection, while a threshold of few photoelectrons have been chosen to register the arrival time for each event. This has been possible by choosing the lowest achievable threshold (few photoelectrons) that can be set in the chip internal leading edge discriminator for the formation of the FASTOR trigger. However, since it is possible to set just one threshold in the ASIC, we also needed to use the analog output of the chip, that gives the energy signals, so as to cut the events below the Compton edge. The resulting time jitter for two LSO:Ce,Ca, coupled to a SiPM pixel each and read-out by two BASIC chips in time coincidence is 185 ps sigma (see Fig. 8). This result is compatible with the previously published one [10] of 194 ps sigma obtained by reading detectors of the same type and size directly at the scope, demonstrating that the time resolution of this system is indeed dominated by the scintillator response and not by the BASIC front-end. Hence, the BASIC front-end can be considered suitable for time of flight applications.

5. Conclusion

A 4D-PET module with TOF and DOI capabilities based on Silicon Photomultipliers is under development at University of Pisa and INFN Pisa. The final system with a detection surface of 4.8 by 4.8 cm^2 is proposed as a successor of the standard PET block detector based on PMT. Currently, we are developing the acquisition system to read out a reduced size prototype of 2.4 by 2.4 cm^2 detection area. The use of SiPM matrices has required the development of a custom multichannel ASIC front-end capable to respect their high dynamic range and their excellent timing performances. All together a modular and flexible acquisition system has been designed in order to read out two 4DPET modules in time coincidence.

First characterization measurements of the DAQ system with and without the detector connected have demonstrated its excellent performances in terms of uniformity, linearity and timing response. Its promising spatial resolution capabilities have been proved by reading a SiPM matrix coupled to a single 1 mm^2 LSO crystal placed at different positions. Previously published measurements on a SiPM matrix coupled to a continuous LSO slab painted black demonstrate that a 0.9 mm FWHM spatial resolution on the photon hit position is achievable. It has also been shown that our acquisition system does not degrade intrinsic SiPM energy resolution that is 17% FWHM in single mode. Moreover, extensive time jitter measurements confirm that the use of the BASIC for the read-out of the timing signals is suitable for time of flight applications, since this chip already assures an intrinsic time coincidence resolution below 200 ps sigma.

Acknowledgments

This work was supported by INFN (National Institute of Nuclear Physics), MIUR (Ministero dell'Istruzione, dell' Universitá e della Ricerca), by European Community in the framework of the FP7 ENVISION project (WP2) and in the framework of the FP7 Hadron Physics 2 project (WP28) and by Altera University Program. The support by projects AMIT (CENIT-CDTI, Spain's Ministry of Science & Innovation), ARTEMIS S2009/DPI-1802 (Comunidad de Madrid) and the European Regional Development Funds is also acknowledged.

References

[1] N. Otte, et al., Nuclear Physics B—Proceedings Supplements 150 (2006) 417.
[2] D.R. Schaart, et al., Physics in Medicine and Biology 54 (2009) 350112.
[3] G. Llosa, et al., IEEE Transactions on Nuclear Science NS-56 (3) (2009) 543.
[4] G. Llosa, et al., IEEE Transactions on Nuclear Science NS-56 (5) (2009) 2586.
[5] F. Corsi, et al., Nuclear Instruments and Methods in Physics Research A 617 (2010) 319.
[6] F. Corsi, et al., N47-92, Front-end electronics for silicon photo-multipliers coupled to fast scintillators, in: Conference Record of the 2010 IEEE NSS-MIC, 2010.
[7] G. Sportelli, et al., IEEE Transactions on Nuclear Science NS-58 (3) (2011) 695.
[8] C. Piemonte, et al., IEEE Transactions on Nuclear Science NS-54 (1) (2007) 236.
[9] G. Collazuol, et al., Nuclear Instruments and Methods in Physics Research A 581 (2007) 461.
[10] M.G. Bisogni, et al., Nuclear Instruments and Methods in Physics Research A 628 (1) (2011) 423.
[11] R. Post, L. Schiff, Physical Review 80 (1950) 1113.
[12] G. Llosa, et al., Physics in Medicine and Biology 55 (2010) 7299.
[13] F. Corsi, et al., N19-2, BASIC: an 8-channel front-end ASIC for silicon photomultiplier detectors, in: Conference Record of the 2009 IEEE NSS-MIC, 2009.
[14] M.E. Casey, R. Nutt, IEEE Transactions on Nuclear Science NS-33 (1) (1986) 460.
[15] M. Schmand, et al., IEEE Transactions on Nuclear Science NS-45 (6) (1998) 3000.
[16] R.S. Miyaoka, et al., IEEE Transactions on Nuclear Science NS-45 (3) (1998) 1069.
[17] W.W. Moses, et al., IEEE Transactions on Nuclear Science 46 (3) (1999) 474.