Journal of Instrumentation

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To cite this article: I. Sarasola *et al* 2017 *JINST* **12** P04016

Published by IOP Publishing for Sissa Medialab

Received: October 16, 2016
Revised: March 1, 2017
Accepted: March 22, 2017
Published: April 13, 2017

A comparative study of the time performance between NINO and FlexToT ASICs

I. Sarasola,[a,1] M.V. Nemallapudi,[b] S. Gundacker,[b] D. Sánchez,[c] D. Gascón,[c] P. Rato,[a] J. Marín[a] and E. Auffray[b,2]

[a] *CIEMAT, Avda. Complutense 40, Madrid, E-28040 Spain*
[b] *CERN, Geneva 23, CH-1211 Switzerland*
[c] *Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franqués 1, Barcelona, E-08028 Spain*

E-mail: iciar.sarasola@ciemat.com

Abstract: Universitat de Barcelona (UB) and CIEMAT have designed the FlexToT ASIC for the front-end readout of SiPM-based scintillator detectors. This ASIC is aimed at time of flight (ToF) positron emission tomography (PET) applications. In this work we have evaluated the time performance of the FlexToT v2 ASIC compared to the NINO ASIC, a fast ASIC developped at CERN. NINO electronics give 64 ps sigma for single-photon time resolution (SPTR) and 93 ps FWHM for coincidence time resolution (CTR) with $2 \times 2 \times 5\,\mathrm{mm}^3$ LSO:Ce,Ca crystals and S13360-3050CS SiPMs. Using the same SiPMs and crystals, the FlexToT v2 ASIC yields 91 ps sigma for SPTR and 123 ps FWHM for CTR. Despite worse time performace than NINO, FlexToT v2 features lower power consumption (11 vs. 27 mW/ch) and linear ToT energy measurement.

Keywords: Front-end electronics for detector readout; Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA)

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[1] Corresponding author.
[2] http://www.pubfacts.com/author/Etiennette+Auffray.

doi:10.1088/1748-0221/12/04/P04016

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1 Introduction

A time of flight (ToF) positron emission tomography (PET) scanner consists of a system capable of measuring the difference in the arrival times of two coincident 511 keV gamma photons with the aim of improving the estimation of the position of the annihilation events along the line of response (LoR) [1]. The ToF technique is especially advantageous for whole-body imaging and in particular for heavy patients. The accuracy in the estimated position depends on the timing resolution of the PET system, therefore, fast timing electronics are required for ToF-PET scanners in order to improve the image quality.

The typical PET readout electronic architecture is based on low-noise charge sensing amplifiers and on the adaptation of the signal for its digitalization. For fast timing electronics, an alternative solution consists in detecting the transition of the current signal using a current mode input stage [2, 3]. In this case, a valid event is detected when the current pulse exceeds a certain threshold regardless of the integrated charge. There are also other alternative solutions such as the time-over-threshold (ToT) technique [4]. It consists in measuring the time during which the signal is above a specific discrimination threshold, thus obtaining a digital signal with duration proportional to the deposited energy. The most appealing feature of this technique is the possibility to directly process the digital signal, instead of the amplitude of analog signals. When replacing ADCs to Time to Digital Converters (TDCs) the consumption is greatly reduced and the post processing is significantly simplified.

In this paper we report on precise timing measurements with two ASICs (described in 2.2) based on different schemes, the FlexTOT v2 ASIC [2] and the NINO ASIC [5]. We have performed comparative SiPM single-photon time resolution (SPTR) and coincidence time resolution (CTR) measurements between both ASICs. The timing performance of both NINO and FlexToT read-out electronics have been analyzed under different SiPM voltages and ASIC thresholds. In order to allow this comparison, we have used the same acquisition system for both NINO and FlexToT read-out electronics: a fast oscilloscope with 40 GS/s sampling rate for the CTR measurements and a scope with 10 GS/s for the SPTR. All measurements have been realized at CERN (Geneva, Switzerland).

2 Material and methods

2.1 Detectors

In this work we have used short LSO:Ce,Ca scintillators with a fast decay time of 30 ns [6, 7] wrapped in Teflon tape and coupled to the S13360-3050CS SiPM from Hamamatsu, a low afterpulse and low crosstalk device with cell sizes of $50 \times 50\ \mu\text{m}^2$ and effective photosensitive area of $3 \times 3\ \text{mm}^2$. Additionally, as a fast reference SiPM for the CTR measurements, we have utilized a NUV SiPM from the group at FBK (Fondazione Bruno Kessler) [7, 8] with cell sizes of $25 \times 25\ \mu\text{m}^2$.

2.2 Readout electronics

The NINO chip was developed at CERN [5]. It is a fully differential integrated circuit based on a current-to-voltage converter with a balanced common gate circuit configuration, followed by four cascade amplifiers. Each channel is designed with a fast amplifier with a peaking time of 1 ns (resolution of 20 ps rms), and input charge measurement with ToT. The output pulse has a time jitter lower than 25 ps. Each channel consumes 27 mW.

The FlexToT ASIC was developed in collaboration between "Universitat de Barcelona (UB)" (Barcelona, Spain) and CIEMAT (Madrid, Spain) for the front-end readout of SiPM arrays in time of flight positron emission tomography (ToF-PET) applications. The FlexToT ASIC implements independent threshold and bias control for each of its 16 DC-coupled channels, a current mode input, a linearized ToT output for each channel and a common fast trigger (OR of all 16 channels) for timing. Moreover, the FlexToT ASIC also provides a low power consumption of 11 mW per channel. The amplitude of the charge pulses at its inputs is encoded as duration of output pulses with linearity better than 5% for peak input currents ranging from 2.5 mA to 18 mA [2].

The characterization of the first version of FlexToT and an evaluation of its performance on the readout of scintillator matrices for PET imaging has been performed, with results showing a trigger jitter better than 45 ps rms for a signal equivalent to single photon, coincidence time resolution (CTR) of 269 ps (FWHM), energy resolution of 9.6% (FWHM) at 511 keV and reconstructed spatial resolution of 1.9 mm (FWHM) for a 0.25 mm diameter ^{22}Na point source [2, 9, 10].

The FlexToT v2 improves upon its predecessor by extending its linear dynamic range down to 0.7 mA and enhancing the channel gain uniformity in order to allow operation with monolithic scintillators. Preliminary results show a jitter floor of 7 ps rms, single-photon timing resolution (SPTR) below 150 ps (rms) using a laser with 50 ps (FWHM) pulses, and a coincidence time resolution below 250 ps (FWHM) for $2 \times 2 \times 20\ \text{mm}^3$ LYSO:Ce crystals. The ASIC has been used with monolithic, segmented and phoswich PET detectors, demonstrating its validity as a flexible solution for the readout of different SiPM-based scintillator designs [11].

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2.3 SiPM single-photon time resolution (SPTR) measurements

The SPTR was studied with the NINO and the FlexToT v2 read-out electronics using a Lecroy Wave Runner 104 Xi 1 GHz oscilloscope (10 GS/s). Each SiPM was illuminated by optical pulses from a Pilas laser (420 nm, 42 ps FWHM) driven at a rate of 100 kHz. The measurements were done inside a light-tight box at a temperature of 18.5°C (figure 1). The light intensity from the laser was reduced by using neutral density filters, providing a very low light flux, which enables the SiPMs to work in single photoelectron mode. With both NINO and FlexToT v2 measurements, the flux was fixed at the same intensity.

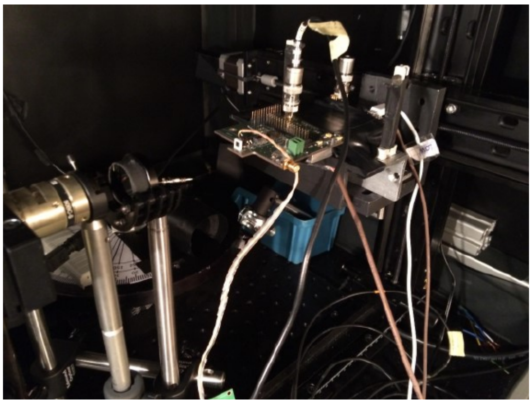

Figure 1. SPTR setup at CERN lab 27, showing the laser head illuminating a FlexToT v2 board.

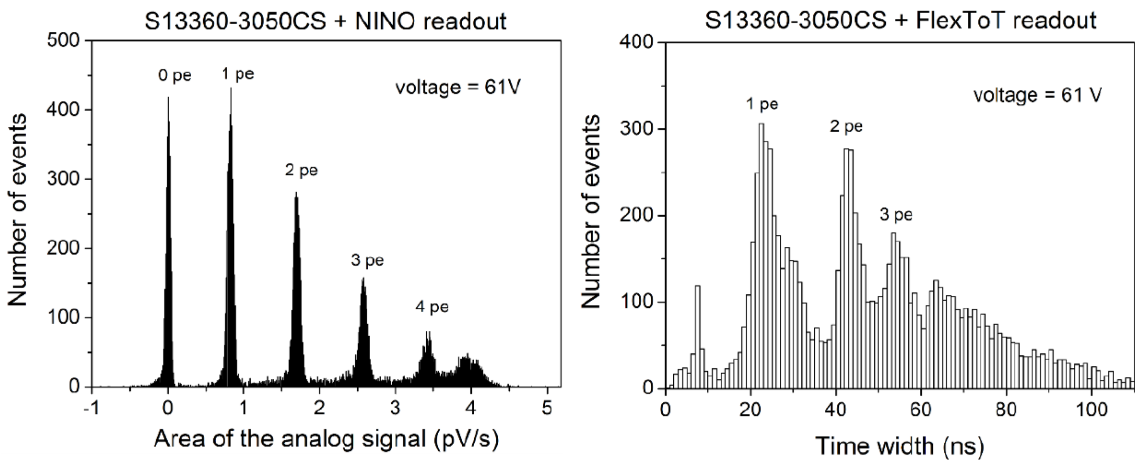

Figure 2. Photoelectron discrimination histograms obtained from the NINO measurements (left) and the FlexToT v2 measurements (right).

For NINO measurements we used the electronic boards described in [6], which provide an analog readout of the SiPM as well as the output signal provided by the ASIC. We selected the single photo-electron events by calculating the area of the analog SiPM signal after its corresponding amplification. For the FlexToT v2 measurements [2], the selection was done by observing the width of the time signal provided by the trigger output, since the ToT (energy) channel is not sensitive enough for detecting photons at single photon flux. The single photon events (1 pe in figure 2,

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right) are intrinsically discriminated by the FlexToT v2 ASIC. After single photon event selection (figure 2), the time delays between the timing signal and the laser trigger signal were analyzed.

2.4 Coincidence time resolution (CTR) measurements

The CTR of crystal coupled to SiPM was evaluated with NINO and FlexToT v2 read-out electronics with a Lecroy 735Zi DDA 3.5 GHz analyzer (40 GS/s) (figure 3). Both energy and time signals were recorded. The CTR measurements were restricted to 3-sigma from the mean of the 511 keV peak provided by the energy signals. The temperature inside the light tight box was 15°C. A ^{22}Na radioactive source was used (activity 4.5 MBq, Jun 2009) for providing coincidence events.

We have performed CTR measurements with NINO and FlexToT v2 electronics versus a fast reference SiPM with a $2 \times 2 \times 3\,mm^3$ LSO:Ce,Ca scintillator, which had a measured CTR of 73 ps FWHM. The reference SiPM is a NUV device from the group at FBK [7, 8]. The S13360-3050CS SiPM was biased at 62 V. The NINO threshold was set to 80 mV and the FlexToT v2 threshold 3 DAC steps above the pedestal for the FlexToT v2 channel. Under the same conditions, we have also analyzed two NINO boards in coincidence and two FlexToT v2 boards in coincidence.

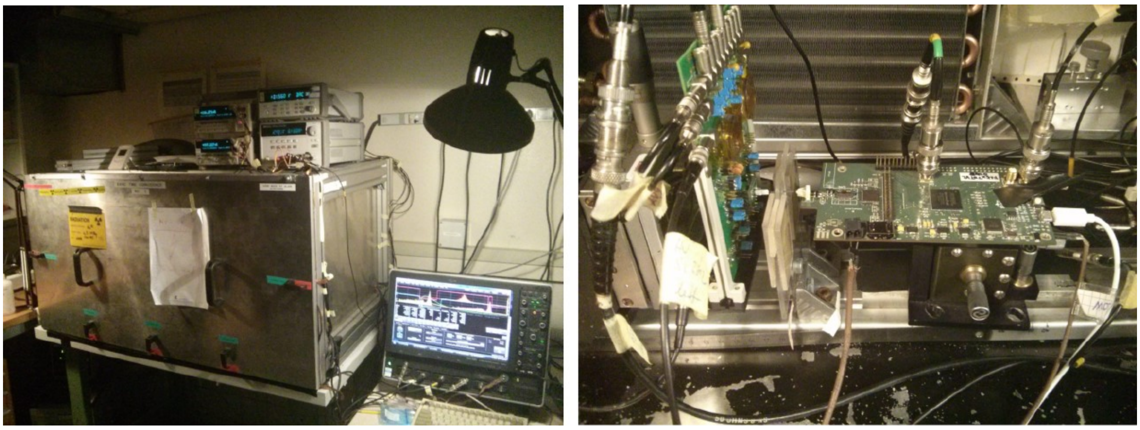

Figure 3. CTR setup at CERN (Lab 27) (left), showing the reference board in coincidence with a FlexToT v2 board (right).

3 Results

3.1 SPTR results

Using the NINO electronics, we achieved very good single photon time resolution values with the S13360-3050CS SiPM at 62 V, as low as 64 ps sigma. Moreover, its SPTR performance is quite flat along the overvoltages considered. Under the same conditions, the results achieved with the FlexToT v2 ASIC were as good as 91 ps sigma at 62 V (figure 4), showing a larger dependency with the overvoltage. Considering all detected events in single photon mode, we have also observed less time walk with NINO electronics (0.7 ns) than with FlexToT v2 boards (2.3 ns). The results are shown in table 1 without applying any time walk compensation.

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Table 1. The SPTR (sigma) obtained with the NINO and the FlexToT v2 acquisition boards.

Acquisition board	SPTR (sigma)
NINO	64 ps
FlexToT v2	91 ps

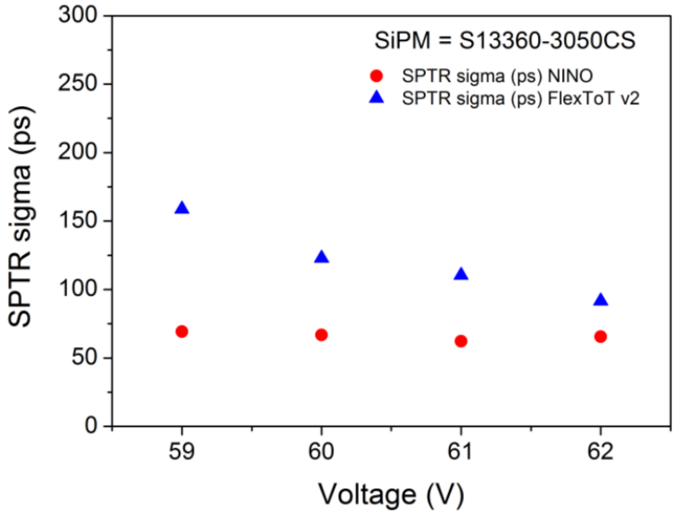

Figure 4. SPTR in sigma for the NINO and the FlexToT v2 acquisition boards.

3.2 CTR results

The following tables summarize the corrected CTR results obtained with NINO and FlexToT v2 ASICs versus the NUV reference SiPM from FBK, which had an estimated single time resolution of 52 ps FWHM (CTR of 73 ps FWHM). Correcting for this fast reference detector and providing the time resolution in coincidence values (eq. (3.1)) we obtained the results reported in table 2. As we can observe in this table, the NUV SiPM from FBK exhibits better time performance, since the CTR degrades from 73 ps to 86 ps when one of the two NUV SiPM is replaced by the S13360-3050CS from Hamamatsu.

$$52^2 + \left(\frac{\mathrm{FWHM}}{\sqrt{2}}\right)^2 = \mathrm{FWHM}^2_{\mathrm{measured}} . \tag{3.1}$$

Table 2. Corrected CTR results obtained with a $2 \times 2 \times 3\,\mathrm{mm}^3$ LSO:Ce,Ca crystal coupled to the SiPM S13360-3050CS. The results are given in coincidence FWHM.

Detector under test			Reference detector			CTR (ps FWHM)
ASIC	SiPM	Crystal	ASIC	SiPM	Crystal	
NINO	S13360-3050CS	LSO:Ce,Ca ($2{\times}2{\times}3\,\mathrm{mm}^3$)	NINO	NUV-FBK	LSO:Ce,Ca ($2{\times}2{\times}3\,\mathrm{mm}^3$)	86
FlexToT v2	S13360-3050CS	LSO:Ce,Ca ($2{\times}2{\times}3\,\mathrm{mm}^3$)	NINO	NUV-FBK	LSO:Ce,Ca ($2{\times}2{\times}3\,\mathrm{mm}^3$)	104

We have also evaluated the coincidence time resolution with LSO:Ce,Ca $2 \times 2 \times 5\,\text{mm}^3$ crystals coupled to S13360-3050CS SiPMs read out by two FlexToT v2 boards and by two NINO boards, obtaining 123 ps FWHM and 93 ps FWHM, respectively (table 3 and figure 5). Part of the CTR degradation observed between table 2 and table 3 is due to the increase of crystal depth, from 3 mm to 5 mm [14].

Table 3. Measured CTR (FWHM) with two NINO boards in coincidence and two FlexToT boards in coincidence.

Detectors in coincidence			CTR (ps FWHM)
ASICs	**SiPMs**	**Crystals**	
NINO	S13360-3050CS	LSO:Ce,Ca (2×2×5 mm^3)	93
FlexToT v2	S13360-3050CS	LSO:Ce,Ca (2×2×5 mm^3)	123

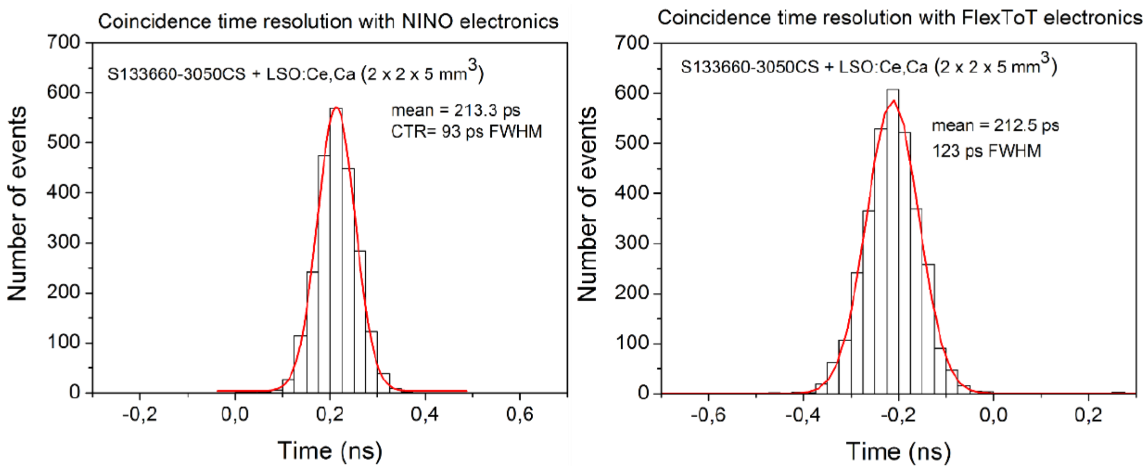

Figure 5. CTR obtained with two S13360-3050CS SiPMs coupled to $2 \times 2 \times 5\,\text{mm}^3$ LSO:Ce,Ca crystals readout by two NINO boards (left) and by two FlexToT v2 boards (right) (15°C).

The crystals used in this work are considerably shorter than those used in standard PET scanners. Given that, we wanted to study and compare the timing performance obtained due to different acquisition systems. However, it is important to mention that these timing resolutions would be degraded in a PET-ToF scanner with longer crystals due to light absorption and time dispersion in larger crystals [13, 14]. The increase of the crystal cross-section also leads to deterioration in the timing performance [8].

4 Conclusions

We have carried out a timing comparison between NINO and FlexToT v2 ASICs, using the same detectors and conditions. We have presented precise timing characterization of the FlexToT v2 ASIC with the acquisition system and devices available at CERN, obtaining 91 ps sigma for SPTR and 123 ps FWHM for CTR with $2 \times 2 \times 5\,\text{mm}^3$ LSO:Ce,Ca crystals and S13360-3050CS SiPMs.

The NINO electronics present 64 ps sigma for SPTR and 93 ps FWHM for CTR by using the same crystals and SiPMs.

Another important parameter to complete the comparison is the power consumption, as there is a trade-off between bandwidth (time resolution) and power consumption. NINO power consumption is 27 mW/ch [5] whereas FlexToT v2 is about 11 mW/ch [2]. Despite of worse time performace than NINO, FlexToT has lower power consumption and linearized ToT energy measurement which makes possible to achieve an energy resolution of 9.6% (FWHM) at 511 keV. Moreover, it can be connected to SiPMs with no additional components. For the aforementioned reason, we present the FlexToT ASIC as a possible front-end readout solution for a modular PET-ToF system.

Acknowledgments

This work has been performed in the framework of the Crystal Clear Collaboration and has received funding from the ERC grant no. 338953 (TICAL). This article is based upon work from COST Action (TD1401, FAST), supported by COST (European Cooperation in Science and Technology).

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