

## ORIGINAL RESEARCH

# Evaluation Of The PETsys TOFPET2 ASIC In Multi-Channel Coincidence Experiments

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## Abstract

**Background:** Aiming to measure the difference in arrival times of two coincident  $\gamma$ -photons with an accuracy in the order of 200 ps, time-of-flight positron emission tomography systems commonly employ silicon-photomultipliers and high-resolution digitization electronics, application specific integrated circuits (ASICs). This work evaluates the performance of the TOFPET2 ASIC released by PETsys Electronics S.A. in 2017 in multi-channel measurements.

**Methods:** SiPM arrays fabricated by different vendors (KETEK, SensL, Hamamatsu, Broadcom) were tested in combination with the ASIC. Scintillator arrays featuring different reflector designs, different materials for optical coupling between scintillator and SiPM, and different configurations of the TOFPET2 ASIC software parameters were evaluated. The benchtop setup used is provided with the TOFPET2 ASIC evaluation kit by PETsys Electronics S.A..

**Results:** In coincidence experiments, the TOFPET2 ASIC shows promising CRTs down to 219.9 ps in combination with two Hamamatsu S14161-3050-HS-08 SiPM arrays (128 channels read out, energy resolution 13.08 %) and 216.1 ps in combination with two Broadcom AFBR-S4N44P643S SiPM arrays (32 channels read out, energy resolution 9.46 %). As a side-effect of the dark count suppression scheme, satellite peaks appear in the time difference spectra depending on the configuration of the delay period in the channel trigger circuit. These peaks have been reported by us for prior single-channel experiments and can be reproduced. The length of the trigger delay has an impact on the ASIC performance and can be configured to further improve the coincidence resolution times. The integrator gain configuration has been investigated and allows an absolute improvement of the energy resolution by up to 1 % at the cost of the linearity of the energy spectrum.

**Conclusion:** Measuring up to the time-of-flight performance of state-of-the-art positron emission tomography systems while providing a uniform and stable readout for multiple channels at the same time, the TOFPET2 ASIC is treated as promising candidate for the integration in future ToF-PET systems.

**Keywords:** time-of-flight; application-specific integrated circuits; ASIC; positron emission tomography; PET; coincidence resolution time; CRT; energy resolution; TOFPET2

## 1 Background

A functional imaging modality widely used in the diagnosis and staging of cancer as well as in cardiology or neurology is positron emission tomography (PET) [1, 2, 3]. After an injected tracer undergoing a  $\beta^+$ -decay, the emitted positron annihilates with an electron in the surrounding tissue, resulting in the back-to-back release of two  $\gamma$ -photons. The  $\gamma$ -photons are detected by two opposing elements of a ring-shaped detector each consisting of a scintillator array coupled to a photo-detector array. Via a scintillation process, the  $\gamma$ -photons are stopped and converted into optical photons, which then reach the employed photo-detector.

In time-of-flight positron emission tomography (ToF-PET), the difference in arrival times of the two detected  $\gamma$ -photons can be resolved, which results in a more precise localization of the annihilation event along the line of response (LOR) connecting the two points of detection [4, 5]. The coincidence resolution time (CRT) assesses the capability of a PET system to resolve this ToF information. Studies have shown that incorporating ToF information into the image reconstruction process increases the signal-to-noise ratio (SNR) of a PET image and therefore improves the image quality [6, 7, 8]. For a precise measurement of the ToF information, CRTs in the order of few hundred picoseconds are required. A low energy resolution in the order of 10 % around 511 keV is of advantage to filter true coincidences from scattered events.

State-of-the art clinical PET systems reach CRTs ranging from 214 ps to 500 ps. The achieved energy resolutions lay between 9 % and 12 % [5]. For prototype PET systems CRTs between 200 ps to 450 ps and energy resolutions between 11 % and 12 % are reported [9, 10, 5]. For both cases, future systems aim to reach CRTs below 200 ps [11, 12, 13]. On benchtop level, this limit has already been excelled by various setups reaching CRTs below 100 ps [14, 15, 16].

Scintillators used in PET systems require a high stopping power, a short scintillation decay time, and high photon statistics [17]. Reflective foils or mixtures of glues and powders can be used to optically segment an array of scintillators. Here, various scintillator topologies can be considered, namely one-to-one coupling between single scintillator needles and photo-sensor channels, multiple scintillator needles on one photo-sensor channel as well as monolithic scintillator blocks or slabs on an array of photo-sensor channels. The latter ones allow for depth-of-interaction (DOI) positioning [18, 19, 20, 21, 22, 23].

In common state-of-the-art systems, photo-detectors such as photo-multiplier tubes (PMTs) and analog or digital silicon-photomultipliers (SiPMs) and custom-designed readout electronics are employed. SiPMs became popular due to the high photo detection efficiency (PDE) (up to 50 %, some up to 65 %), their high internal gain, their compactness, their fast response time, and their compatibility with magnetic fields, allowing simultaneous PET/MR imaging [24, 25, 16, 26, 27]. SiPMs consist of several thousands single-photon avalanche diodes (SPADs) which are connected in parallel and operated in Geiger-mode. An incident optical photon hitting a SPAD causes a self-sustaining charge carrier avalanche. The avalanche effect is used for signal amplification enabling the detection of single optical photons, whereby individual SPAD signals are overlaid to a sum signal forming an SiPM pulse with a steep rising edge [24]. The first prototype system making use of digital SiPMs

(dSiPMs) featuring direct binary digitization has been developed in recent years [28, 29, 30, 31, 32].

Typically, application-specific integrated circuits (ASICs) are employed to precisely digitize analog SiPM signals. This study specifically focuses on the application of ASICs in ToF-PET systems. Apart from exclusive ToF-PET systems, also hybrid imaging systems combining ToF-PET with other modalities, such as magnetic resonance imaging (MRI), electroencephalography (EEG) or ultrasound imaging (US), feature ASICs as readout and digitization electronics (MADPET4 [33, 34], TRIM-AGE [35, 36, 37], EndoToF PET-US [12, 38]). ASICs typically feature a comparator with a low threshold to trigger on the rising edge of the SiPM pulse, i.e. on the first optical photons arriving, and a time-to-digital converter (TDC) to assign a timestamp to an event. The energy of the respective event can then be measured either by signal integration featuring capacitors (qdc-method) or by measuring the time over a specified threshold (tot-method) [12, 39, 40]. The Weeroc series [35, 36, 41], the PETA series [42, 43, 44, 45, 46, 47, 26] and the TOFPET2 series by PETsys Electronics S.A. [48, 49] use such a qdc-method to measure the signal energy.

In this work, as a follow-up on single-channel studies, we evaluated the multi-channel applicability of the TOFPET2 ASIC (version 2b) released by PETsys Electronics S.A. in 2017 [50, 51]. The TOFPET2 ASIC is characterized by its compactness (14 mm × 14 mm chip size including bonding area [52]), 128 readout channels, a high data rate of up to 400 MHz per channel [48] and low power consumption [48, 53]. The goal of this study is to assess whether the TOFPET2 ASIC should be considered as a solution for digitizing and processing analog SiPM signals in future (whole-body) ToF-PET systems. The presented multi-channel studies are necessary to investigate detector-related effects such as crosstalk and light-sharing as well as the channel-spread of the ASIC performance handling data from multiple channels at once, which cannot be assessed in single-channel measurements. The compatibility of the ASIC with different SiPM types in combination with different materials for scintillator coupling and segmentation was tested. In addition, the parameters of the ASIC configuration related to the trigger circuit were varied. The impact of the hard- and software configuration on the ASIC performance was quantified.

## 2 Materials and Methods

### 2.1 TOFPET2 ASIC

Each of the 64 individual channels of the TOFPET2 ASIC is multi-buffered by four analog buffers and employs a three-threshold trigger logic with two discriminators D\_T1 and D\_T2 in the timing and one discriminator D\_E in the energy branch [54, 55, 48]. A global- and a channel-specific configuration register allow to change the ASIC configuration. The ASIC can be operated in a tot- or qdc-mode for energy measurement. The charge-to-digital converter (QDC) used in qdc-mode behaves linear for integration charges up to 1500 pC [56]. The TDC has a resolution of 30 ps. The chip runs with a clock cycle of 200 MHz.

Incoming SiPM signals are amplified by a transimpedance amplifier in the timing branch (nominal gain 3000 Ω) and a transimpedance amplifier energy branch (nominal gain 300 Ω), respectively [48]. As determined in an oscilloscope measurement, the pre-amplified SiPM pulses in the timing branch have a signal height of

about 300 mV. The thresholds of the three discriminators can be adjusted via the three dimensionless parameters  $vth\_t1$ ,  $vth\_t2$ , and  $vth\_e$  in the ASIC configuration. Increasing these parameters by one DAC step is equal to increasing the trigger level by approx. 2.5 mV, 15 mV, and 20 mV, respectively, over a baseline set during calibration [57]. For a proper operation of the trigger logic [51], it has to be ensured that the voltage thresholds at the discriminators  $Vth\_T1$  and  $Vth\_T2$  fulfill  $Vth\_T1 < Vth\_T2$ . The trigger circuit of each channel enables dark count rejection and high timing resolution by triggering on a low voltage threshold with the first discriminator  $D\_T1$  at a very early point in time, i.e., on the first optical photons hitting the SiPM. This trigger is delayed by a specified delay period and passes an AND gate opened by a second trigger activated on a higher voltage threshold with a second discriminator  $D\_T2$  (see Fig. 1). The delay period is in the order of few nanoseconds and can be configured by adjusting the parameter `fe_delay` of the ASIC configuration [48]. The design of the trigger logic allows the rejection of small noise pulses, but is associated with the generation of satellite peaks in the coincidence time difference spectra which are caused by a shift in timestamp generation from the delayed  $D\_T1$  to the non-delayed  $D\_T2$ . A detailed description on the operation of the trigger circuit and the generation of satellite peaks is given in [51].

## 2.2 Benchtop setup

To evaluate the TOFPET2 ASIC in combination with different SiPM types, we used the TOFPET2 ASIC evaluation kit designed by PETsys Electronics S.A. as it enables the user to test various ASIC-SiPM combinations under benchtop conditions. The kit comes along with two ASIC test boards each allowing to connect an SiPM array to a TOFPET2 ASIC via two SAMTEC connectors. A high-voltage digital-to-analog converter (HV-DAC) mezzanine board (version 08/2016) providing the bias voltage for the employed SiPMs, and a front end board (FEB/D) generating the global clock signal and holding the main power supply for the ASIC test boards are included as well. Data transmission to a readout computer is conducted via a 1-Gigabit Ethernet (GbE) mezzanine board. The ASIC test boards provide DC-coupling between the employed SiPMs and the ASIC.

Additionally, a breadboard for mounting the setup is provided with the kit (see Fig. 2). To conduct coincidence experiments, the breadboard allows to position both ASIC test boards face-to-face in different distances to the source holder mounting position. Featuring two cable inlets, which were used to connect the ASIC test boards to the FEB/D board via two flexible cables, the breadboard can be encapsulated light-proof by a top cover. A temperature sensor and a proportional-integral-derivative (PID) controller regulating a thermo-element were used to adjust the temperature inside the box. In addition, the whole benchtop setup was placed in a climate chamber to ensure a stable temperature control. A custom-designed source holder was employed to assemble the multi-source geometry. Molds were used to assemble the crystal-SiPM array configurations (see Fig. 3).

## 2.3 Detectors, scintillators, and coupling

To test the compatibility and performance of the TOFPET2 ASIC with different analog SiPM types, we used  $8 \times 8$  SiPM arrays fabricated by different vendors.

Two samples each of KETEK PA3325-WB-0808, SensL ArrayJ-30020-64P-PCB, Hamamatsu S14161-3050-HS-08, and Broadcom AFBR-S4N44P643S (see Tab. 1 and Fig. 4) were used to perform coincidence experiments. A multi-source geometry of five  $^{22}\text{Na}$  NEMA cube point sources with a total activity of approx. 3 MBq was placed in the center of the setup during these experiments. For the SensL ArrayJ-30020-64P-PCB SiPM arrays, additional adapter boards needed to be employed to establish the connection to the ASIC test board.

Using Sylgard® 527, a two-component dielectric gel fabricated by Dow Corning, for optical coupling, each SiPM array was successively one-to-one-coupled to  $8 \times 8$  or  $4 \times 4$  LYSO scintillator arrays featuring different segmentation layers (360  $\mu\text{m}$  or 110  $\mu\text{m}$  BaSO<sub>4</sub> powder mixed with epoxy and 67  $\mu\text{m}$  glued ESR foil, see Fig. 4). Additionally, to investigate the influence of the coupling on the performance, Sylgard® 527 was replaced by BC-630, a silicon grease fabricated by Saint-Gobain crystals for one SiPM-scintillator configuration.

#### 2.4 Setup calibration

The setup was calibrated using the PETsys calibration routine implemented in the software coming along with the evaluation kit [55]. For each SiPM type, a calibration was run once at default ASIC configuration applying an overvoltage of 4 V at an environment temperature of 16 °C. The required bias voltages were specified depending on the SiPM type employed. It is not necessary to calibrate the setup for every threshold or overvoltage change. A radioactive source can be left in the setup during calibration since this does not affect the determined parameters [57].

#### 2.5 Parameter studies

For each SiPM-crystal configuration, the discriminator threshold  $v_{th.t1}$  was varied between 10 and 50 in steps of 10, while  $v_{th.t2}$  and  $v_{th.e}$  were kept at constant values ( $v_{th.t2} = 20$ ,  $v_{th.e} = 15$ ). This roughly corresponds to triggering between the 1 p.e. to 3 p.e. For each setting, raw data were acquired for 120 s at an overvoltage of 2.75 V to 7.75 V. Additionally, the crystal top-to-source distance was varied between 18 mm to 58 mm in steps of 20 mm. For the configuration featuring 360  $\mu\text{m}$  BaSO<sub>4</sub> as segmentation layer, these experiments were repeated using BC-630 instead of Sylgard® 527 for optical coupling.

For the KETEK PA3325-WB-0808 arrays coupled to the scintillator arrays featuring 360  $\mu\text{m}$  BaSO<sub>4</sub> as segmentation layer, the trigger delay period was configured as different lengths in the range of few nanoseconds (0.0 ns to 12.9 ns) for  $v_{th.t1} = 10$  and  $v_{th.t1} = 50$  and overvoltages between 2.75 V to 7.75 V. For the Hamamatsu S14161-3050-HS-08 arrays coupled to the scintillator arrays featuring 360  $\mu\text{m}$  BaSO<sub>4</sub> as segmentation layer, the integrator gain settings  $G_{Q1}$  and  $G_{Q2}$  were varied between 0.32-2.25 and 1.00-1.68, respectively, to evaluate the linearity of the acquired energy value spectra and the influence on the resulting energy resolution. For each setting, raw data were acquired for 120 s at an overvoltage of 4.75 V and with  $v_{th.t1} = 20$ ,  $v_{th.t2} = 20$ , and  $v_{th.e} = 15$ . Effects due to the assembly of SiPM and scintillator array can be excluded since groups of measurements varying the trigger delay and gain configuration as well as the discriminator thresholds are performed with the same assembly directly after each other.

## 2.6 Data collection and processing

For data collection we used the data acquisition routine implemented by PETsys. We prepared the acquired raw data with the `convert_raw_to_singles` method implemented by PETsys and provided with the evaluation kit [55]. Using this routine, raw data were converted into single-raw-hit information by applying the acquired calibration data. A table containing a timestamp, an energy value, and a channel id for each single event acquired was returned.

These single events were further processed using an analysis software developed at our institute [51]. The energy values returned by the PETsys routine were sorted into channel-individual energy value histograms. Afterwards, the noise background of this spectrum was estimated and subtracted [58, 59, 60]. The positions of the 511 keV and 1274.5 keV peaks were determined applying a Gaussian peak finder routine [61]. A saturation model neglecting offsets and optical crosstalk was applied to the found position, parametrizing the saturation corrected energy as

$$E = c \cdot s \cdot \log \left( \frac{1}{1 - \frac{e}{s}} \right) \quad (1)$$

where  $E$  is the energy in keV,  $c$  is a correction factor in calibrated energy units $^{-1}$ ,  $s$  is a saturation factor in calibrated energy units and  $e$  is the acquired energy value in calibrated energy units. Now, all acquired energy values are converted and sorted into channel-individual energy histograms. An energy filter ranging from 400 keV to 700 keV was applied to filter true coincidences, which should have an energy around 511 keV, from scattered events. A Gaussian was fitted to the remaining histogram data corresponding to the 511 keV peak. The energy resolution was determined as the full width at half maximum (FWHM) of the fitted Gaussian summing up all channel-individual energy histograms to a global energy histogram. The fit range was iteratively adjusted by 10 % of the FWHM to account for fitting errors. Filtered events were checked for coincidences applying a coincidence window of 7.5 ns. To evaluate the effects of different trigger delay configurations, this window was extended to 35 ns. The time difference between two events matched as a coincidence was calculated. All computed time differences were filled into a time difference histogram. A Gaussian was fitted to the histogram peak while iteratively adjusting the fit range by 10 % of the FWHM to account for fitting errors. The coincidence resolution time (CRT) was determined as the FWHM of the fitted Gaussian.

The obtained performance parameters were always plotted as a function of the offset-corrected overvoltage  $U_{\text{ov,cor}}$  computed via

$$U_{\text{ov,cor}} = U_{\text{ov,set}} - U_{\text{off}} \quad (2)$$

The overvoltage voltage set  $U_{\text{ov,set}}$  via the acquisition routine was corrected by an offset  $U_{\text{off}}$  (approx. 750 mV [62]).

## 3 Results

The energy value spectra of different SiPM types allow to determine 511-keV and 1275-keV peak positions in acquired ADC energy values for all operated channels.

The peak positions are shifted to higher energy values for higher overvoltages (see Fig. 5a and Fig. 5b). The spread of the position observed for individual channels increases for higher overvoltages. Furthermore, the peak positions are sorted according to the SiPM gains, i.e., higher energy values are reported for Broadcom and Hamamatsu SiPMs, which both feature higher gains than SensL and KETEK SiPMs (see Tab. 1). In addition, the peak positions are shifted to higher energy values if a thicker segmentation layer is used in the scintillator array and if BaSO<sub>4</sub> is used instead of ESR (see Fig. 5c and Fig. 5d). Again, for higher overvoltages, the peaks are shifted to higher energy values and the channel-spread of the peak positions increases. The spatial structure of the channel spread of the peak positions as well as the determined energy resolution and CRT is shown exemplary for a Hamamatsu S14161-3050-HS-08 array in Fig. 6. The channel spread in peak position and energy resolution shows a Gaussian behavior with few outliers. For the CRTs, which were calculated as mean of the CRTs of the respective channel with its coincident channels, the lower part of the histogram behaves Gaussian, but a cut-off is visible at approx. 237 ps for the upper part.

Determining these performance parameters globally, operating two Hamamatsu S14161-3050-HS-08 SiPM array at a range of overvoltages shows an improvement in CRT and energy resolution for higher overvoltages before deteriorating again (see Fig. 7). Triggering on higher thresholds vth\_t1 further improves the CRT. The energy resolution is rarely affected by this parameter change. Generally, these effects are observed for all investigated SiPM types, coupling materials and segmentation layers. The point of transition from the negative to the positive influence of higher overvoltages and discriminator thresholds vth\_t1 varies according to the SiPM type and scintillator array used. For example, with the KETEK PA3325-WB-0808 SiPM arrays, the improvement of the performance parameters dependent on triggering on higher thresholds vth\_t1 is only visible at overvoltages higher than 4 V.

To compare the influence of the investigated parameters, the lowest CRT achieved with each configuration along the investigated range of overvoltages is reported together with the corresponding energy resolution in Tab. 2 and Tab. 3. Depending on the SiPM type, changing the threshold vth\_t1 results in a CRT improvement of approx. 3 ps to 9 ps (approx. 1 % to 3 % relative improvement). Among the different scintillator arrays, both scintillator types employing BaSO<sub>4</sub> powder mixed with epoxy as segmentation layer outperform the type featuring ESR foil. A segmentation layer of 360 µm BaSO<sub>4</sub> reaches approx. 100 ps to 200 ps lower CRTs than a segmentation layer of 67 µm ESR foil (see Tab. 2). This is equal to a relative performance gain of approx. 29 % to 43 % depending on the SiPM type. Comparing the corresponding energy resolutions, an absolute improvement of up to approx. 2.5 % (relative performance gain of up to approx. 19 %) can be reported (see Tab. 3). Here, the thicker BaSO<sub>4</sub>-layer of 360 µm shows better performance results (approx. 20 ps to 45 ps lower CRTs depending on the SiPM type, i.e., approx. 6 % to 14 % relative performance gain) than the thinner layer of 110 µm.

Replacing Sylgard® 527 with BC-630 as optical coupling material between scintillator and SiPM array leads to a CRT deterioration of approx. 4 ps to 16 ps (approx. 2 % to 6 % relative performance loss) depending on the SiPM type (see Tab. 2). The corresponding energy resolution deteriorates less than 1 % (absolute change) for all

investigated SiPM types (see Tab. 3).

Triggering at larger distances between sensor and the employed multi-source geometry leads to an improvement of the CRT and energy resolution by about 10 ps to 20 ps, which corresponds to 4 % to 8 % relative improvement, and by up to approx. 1.7 % (approx. 13 % relative change) for a distance variation of 20 mm (see Tab. 2 and 3). In case of the KETEK PA3325-WB-0808 SiPM arrays, fluctuations of up to 0.4 % (absolute change) are observed for the determined energy resolutions. Additionally, the lowest CRT achieved with the Hamamatsu S14161-3050-HS-08 SiPM arrays fluctuates by approx. 4 ps (approx. 2 % relative deterioration).

Due to limited availability of materials, the parameter study was only partly performed for the Broadcom AFBR-S4N44P643S SiPM arrays. Here, triggering on a higher threshold  $v_{th.t1}$  improved the lowest CRT achieved by up to approx. 25 ps, which corresponds to approx. 9 % relative performance gain (see Tab. 4). The corresponding energy resolution only showed minor fluctuations less than 0.3 % (absolute change). Again, the scintillator type employing BaSO<sub>4</sub> powder mixed with epoxy as segmentation layer outperform the type featuring ESR foil regarding the CRT (approx. 80 ps, i.e., approx. 26 % relative performance gain) and improves the corresponding energy resolution by approx. 2 % (approx. 19 % relative performance gain).

Among the four SiPM types tested in combination with the TOFPET2 ASIC, the 8 × 8 Hamamatsu S14161-3050-HS-08 SiPM arrays outperform the other SiPM arrays achieving CRTs down to  $219.9 \pm 0.7$  ps ( $dE/E = 13.08 \pm 0.03$  %) with an 8 × 8 12-mm-high scintillator array featuring 360 μm BaSO<sub>4</sub> mixed with epoxy as segmentation layer for 128 channels read out. Broadcom AFBR-S4N44P643S SiPM arrays reached comparable CRTs down to  $216.1 \pm 2.6$  ps ( $dE/E = 9.46 \pm 0.09$  %) with a 4 × 4 12-mm-high scintillator array featuring a thinner BaSO<sub>4</sub> layer (110 μm) for 32 channels read out. With a 4 × 4 19-mm-high scintillator array featuring 155 μm air-coupled ESR-foil as the inter-crystal layer, the Hamamatsu arrays reached CRTs down to  $247.5 \pm 2.4$  ps ( $dE/E = 10.46 \pm 0.08$  %) for 32 channels read out.

Satellite peaks, which were observed for measurements with single SiPMs [51], also appear in the coincidence time difference spectra of multi-channel measurements with all investigated SiPM types (see Fig. 8). The peaks are generated by small noise pulses that trigger the first discriminator and are validated by a true coincidence event triggering on the second discriminator occurring shortly after the noise event and while the AND gate connecting first and second discriminator is still active. As Fig. 8 depicts, the shift of the peaks from the center peak in the time difference histogram is related to the configured trigger delay between the first and second discriminator of the ASIC channel circuit. The fraction of events causing the formation of satellite peaks is higher for higher overvoltages and lower discriminator thresholds  $v_{th.t1}$ . A broader explanation is given in [51]. As Fig. 9 depicts, changing the delay period between the first and second discriminator, not only leads to the shift of satellite peaks over the range of the coincidence time difference spectrum but also causes a systematic deterioration in energy resolution for shorter delay periods. Comparing the lowest energy resolutions achieved for each trigger delay period, these resolutions deteriorate by up to approx. 1 %, which corresponds to a relative deterioration of about 10 %. Additionally, the lowest CRTs achieved

vary by up to approx. 30 ps (up to approx. 11 % relative change) depending on the configured trigger delay. Repeating the measurements and evaluation with different discriminator thresholds  $vth\_t1$  or narrower coincidence windows did not lead to a change of these effects.

Fig. 10 depicts the linearity ratio computed as the ratio of the 511 keV and 1275 keV peak positions in the ADC value spectra as well as the energy resolution for different integrator gains  $G_{Q1}$  and  $G_{Q2}$ . Comparing the linearity ratios and achieved energy resolutions, we find that the default integrator gain setting  $G_{Q1} = 1.0$  and  $G_{Q2} = 1.0$  results in the most linear energy spectra (linearity ratio of 0.71,  $dE/E \approx 13\%$ ). The energy resolution can be improved by approx. 5 % (relative improvement) changing the  $G_{Q1}$ -setting to  $G_{Q1} = 2.5$  at the cost of energy linearity (linearity ratio of 0.81,  $dE/E \approx 12.5\%$ , relative improvement of approx. 3.8 %). The absolute spread in energy resolution for both of these settings is in the order of approx. 0.6 %. The spread is generally increased by higher gains, which also result in a deterioration of the energy resolution to up to 14 %.

#### 4 Discussion

The peak positions reported for the energy value spectra (see Fig. 5 and Fig. 6) suggest that all channels on one ASIC operate uniformly. Since especially in Fig. 5 128 channel, i.e., two ASICs, are considered when computing the channel spread, the operation of two different ASICs is uniform as well. Since single channels not matching the peak position pattern were only identified for one of the Hamamatsu S14161-3050-S-08 SiPM arrays (outliers in Fig. 5a and 5b), but not for other SiPM arrays, this behavior is probably due to the connected SiPMs and not the operation of ASIC channels. This channel was excluded from further evaluation steps. Since all channels operate uniformly, reporting the CRT and energy resolution as globally computed parameters is justified.

In single- and multi-channel studies, a similar behavior of the CRT and energy resolution dependent on the applied overvoltage was observed. However, the impact of the discriminator threshold  $vth\_t1$  on the achieved performance is stronger in multi-channel than in previous single-channel investigations [51]. While in single-channel measurements with two KETEK PM3325-WB-A0 the effect was only visible for overvoltages lower than 3 V and no reverse effect was observed for higher overvoltages, for multi-channel measurements with two KETEK PA3325-WB-0808, the impact of  $vth\_t1$  was visible over the whole investigated overvoltage range and reversed itself for overvoltages higher than 4 V. The observed differences in behavior could be due to effects on the SiPM array such as crosstalk and light-sharing.

The effect of improved performance for BaSO<sub>4</sub> as reflector material is probably due to the thickness of the segmentation layer. Both scintillator arrays employing BaSO<sub>4</sub> as reflector have an almost twice as thick (110 µm) and a roughly five times thicker (360 µm) reflector layer than the scintillator array employing ESR foil (67 µm). A thinner reflector material results in a higher probability of light-sharing between channels and thus, a lower fraction of  $\gamma$ -events depositing their whole energy on one SiPM channel. This leads to a higher number of small pulses being acquired resulting in a higher raw data rate. The observation is supported by higher energy values acquired for individual channels if thicker segmentation layers are used as shown in

Fig. 5c and Fig. 5d. The different reflective behaviors of BaSO<sub>4</sub> (diffusive reflection) and ESR foil (specular reflexion) are also suspected to contribute to the reduced and increased event rate, respectively. Setting higher thresholds vth\_t2 and vth\_e could be used to filter out these events, while still triggering on the first optical photons with a low thresholds vth\_t1, which preserve the ToF information of the detected event. Studies need to be conducted to verify if this approach leads to an improved performance of the detector configurations employing ESR foil as a reflector. An improved performance seen in experiments with larger distances to the employed sources, which also is associated with a lower raw data rate, additionally indicates a raw-data-rate-dependent performance. Using BC-630, better performance is expected since BC-630 features a slightly higher refractive index than Sylgard® 527. This should result in either equal or slightly better prevention of total reflection at the surface between crystal and optical coupling and therefore, a lower loss of optical photons. However, a slightly worse performance (2 % to 6 %) of BC-630 compared to Sylgard® 527 is observed. We suggest further investigations to optimize the layer thickness of the optical coupling to exclude effects from a non-optimal assembly of the SiPM array and scintillator array. Among the different hard- and software parameters changed for each SiPM type, the scintillator segmentation layer has the largest relative impact on the achieved performance (29 % to 43 %).

Concerning the configuration of the trigger delay period, communication with PETsys lead to the assumption that the systematic deterioration in energy resolution is probably related to the configuration of the energy integration window. Acquiring data in qdc-mode, the integrated charge is corrected by an estimate for a charge offset related to the time difference between trigger\_Q, which starts the energy integration, and the delayed trigger\_T1, which sets the event timestamp, i.e. the time of arrival of the optical photons hitting the SiPM channel. The latter one is prolonged or shortened with respect to the configuration of the trigger delay period, which results in an adaptation of the charge offset applied as a correction. The energy integration window is not adapted for different trigger delay periods and thus, needs to be adjusted manually. In all investigations so far, the energy integration window has been kept at a fixed default value of approx. 290 ns. Further experiments to investigate the influence of adjusting the energy integration window for a configured delay period on the energy resolution are on-going. The difference in behavior as a function of overvoltage and the different best achievable CRT values for different configurations of the trigger delay period cannot be understood without profound knowledge of the details of the ASIC implementation. Discussions with PETsys regarding this matter are on-going.

Investigations with two Hamamatsu S14161-3050-HS-08 arrays show that the integrator gain setting can be used to linearize the acquired energy spectra and optimize the energy resolution. The absolute spread in the energy resolution of all investigated channels is in the order of less than 1 %. Thus, it can be concluded that the SiPM and ASIC channels operated uniformly in this experiment. In this study, the ASIC is already operated at the most linear setting possible. None of the used SiPM types caused problems during energy measurement via signal integration with the used setting. Therefore, this setting is recommended to be used for further investigations featuring high-gain SiPMs. Switching to a more non-linear setting to

improve the energy resolution at 511 keV is possible as long as the saturation correction method can be applied on the calibrated energy values, i.e., as long as the two peaks of the Na<sup>22</sup>-spectrum remain separable.

Comparing the performance of different analog SiPM types, Hamamatsu S14161-3050-HS-08 and Broadcom AFBR-S4N44P643S show the lowest CRTs in combination with the TOFPET2 ASIC. Both SiPM types feature a higher gain and a larger SPAD size than the investigated KETEK and SensL SiPMs (see Tab. 1). However, it has to be kept in mind that this study only reports performance results for the combination of SiPM type and ASIC using the delivered benchtop setup "as-is". Since the coupling between SiPM and ASIC was not individually optimize for each SiPM type, this study cannot be used to compare the performance of solely the SiPM types among each other, but only their performance in combination with the TOFPET2 ASIC for the specific coupling scheme given by the electronics provided. Individual optimization of the SiPM-ASIC coupling is expected to improve the reported performance [63, 64].

On benchtop level, the TOFPET2 ASIC measures up to the performance of state-of-the art ASICs in single-channel coincidence experiments. An overview on single-channel experiments is provided in [51]. In comparison with other multi-channel performance experiments, the TOFPET2 ASIC measures up to state-of-the-art system performance regarding its ToF capability. An 18-channel ASIC using a tot-method to digitize energies achieved a CRT of 275 ps and an energy resolution of 11.8 % in coincidence experiments with two 12 × 12 Hamamatsu C13500-4075LC-12 modules coupled to 20-mm-high scintillator arrays and read out by 8 ASICs in total [65]. Module tests with the PETA5 ASIC and SiPMs fabricated by Fondazione Bruno Kessler (FBK, RGB-HD technology) achieved an average CRT of 230 ps and an energy resolution of about 14 % when one-to-one-coupled to 10-mm-high LYSO scintillator arrays [46]. PETsys reports a CRT of 260 ps between two Hamamatsu S13361-3050AE-04 arrays each one-to-one-coupled to an array of 15-mm-high LYSO needles [11]. On system level, the TRIMAGE scanner equipped with the TRIROC ASIC reaches CRTs of 515 ps and an energy resolution between 20 % to 22 % employing a two-layered scintillator geometry consisting of LYSO needles with a total height of 20 mm on FBK SiPMs (NUV-HD technology) [66]. A study on a prototype PET scanner employing digital SiPMs (DPC 3200-22 by Philips Digital Photon Counting) coupled to 10-mm-high LYSO scintillator arrays reports CRTs down to  $215.2 \pm 0.4$  ps (energy resolution:  $11.381 \pm 0.007$  %) [10]. The Biograph Vision PET/CT (computed tomography) scanner recently released by Siemens also achieves 214 ps on system level, using 3.2 mm × 3.2 mm × 20 mm LSO needles [67, 68].

## 5 Conclusion

Generally, the TOFPET2 ASIC evaluation kit enables the user to easily test various SiPM types and scintillator topologies in combination with the TOFPET2 ASIC. The ASIC is compatible with all SiPM types (see Tab. 1) tested in this study. We observe that high discriminator thresholds ( $v_{th\_t1} = 40 - 50$ ), thicker reflector layers, and lower data rates (larger distances to the sources and diffusive inter-crystal reflexion) result in an improved performance regarding both CRT and energy resolution.

Among the SiPM types used, so far, Broadcom AFBR-S4N44P643S and Hamamatsu S14161-3050-HS-08 SiPMs show the most promising performance results in combination with the TOFEPET2 ASIC. Adjustments of the integrator gain can be used to linearize the energy value spectra acquired in qdc-mode or improve the energy resolution. The default integrator gain setting results in the most linear energy value spectra and therefore is recommended for further investigations with high-gain SiPMs.

Even without optimizing the SiPM-to-ASIC coupling, the CRTs and energy resolutions reported for a coincidence setup of two detector blocks lay in the order of the performance of clinical and pre-clinical ToF-PET systems. It was successfully demonstrated that the TOFPET2 ASIC fits the requirement of digitizing events including ToF information in the order of 200 ps while providing a uniform and stable readout of multiple channels at the same time. Therefore, it will be considered for integration in (whole-body) ToF-PET applications.

## 6 Outlook

As the TOFPET2 ASIC shows promising time-of-flight performance, it is worth to be considered for integration into a ToF-PET system. Moreover, further performance studies should include monolithic scintillator blocks as well as slabs to obtain DOI information with the TOFPET2 ASIC. First experiments featuring DOI-capable scintillator geometries have been conducted [21, 69].

Possibilities to optimize the CRT, e.g., the trigger delay configuration can be considered after additional experiments regarding their effect on the energy resolution. The proposed solution, i.e., adjusting the energy integration window, needs to be evaluated.

In addition, when designing a PET system or a MR-compatible PET insert, one has to keep in mind other system requirements such as power supply limitations or interference problems [70]. Therefore, the power consumption of the TOFPET2 ASIC and its influence on the ASIC performance were evaluated in an additional study [53]. Regarding MR-compatibility tests, similar test protocols to the protocols used to evaluate the MR-compatibility of digital sensors need to be defined and executed [71, 72, 27]. Furthermore, different techniques to couple SiPMs and ASIC are required to be investigated.

## 7 Abbreviations

- ASIC – application-specific integrated circuit
- BGO – bismuth germanate
- CRT – coincidence resolution time
- CT – computed tomography DOI – depth of interaction
- FBK – Fondazione Bruno Kessler
- FEB – front end board
- GbE – Gigabit Ethernet
- HV-DAC – high-voltage digital-to-analog converter
- LOR – line of response
- LYSO – lutetium-yttrium oxyorthosilicate
- MRI – magnetic resonance imaging
- PDE – photo detection efficiency PET – positron emission tomography
- QDC – charge-to-digital converter
- SiPM – silicon-photomultiplier
- TDC – time-to-digital converter
- ToF – time-of-flight

**Declarations**

Ethics approval and consent to participate  
Not applicable.

Consent for publication  
Not applicable.

**Availability of data and material**

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Competing interests**

The authors declare that they have no competing interests.

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**Authors' contributions**

All authors participated in the design of the study. VN contributed the experiments and data evaluation and wrote the manuscript. DS established a framework for data analysis. BW designed additional electronic parts for the setup. All authors contributed to the manuscript by discussing and revising its content. All authors gave their approval for the final version of the manuscript.

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**References**

1. Bailey, D.L., Townsend, D.W., Valk, P.E., Maisey, M.N.: Positron Emission Tomography: Basic Sciences, 1st edn. Springer Science and Business Media, ??? (2005). doi:[10.1007/b136169](https://doi.org/10.1007/b136169)
2. Phelps, M.E.: PET: Physics, Instrumentation, and Scanners, 1st edn. Springer, ??? (2006). doi:[10.1007/0-387-34946-4](https://doi.org/10.1007/0-387-34946-4)
3. Vaquero, J.J., Kinahan, P.: Positron Emission Tomography: Current Challenges and Opportunities for Technological Advances in Clinical and Preclinical Imaging Systems. Annual Review of Biomedical Engineering **17**(1), 385–414 (2015). doi:[10.1146/annurev-bioeng-071114-040723](https://doi.org/10.1146/annurev-bioeng-071114-040723). PMID: 26643024
4. Surti, S., Karp, J.S.: Advances in time-of-flight PET. *Physica Medica* **32**(1), 12–22 (2016). doi:[10.1016/j.ejmp.2015.12.007](https://doi.org/10.1016/j.ejmp.2015.12.007)
5. Vandenberghe, S., Mikhaylova, E., D'hoe, E., Mollet, P., Karp, J.: Recent developments in time-of-flight PET. *EJNMMI physics* **3**(1) (2016). doi:[10.1186/s40658-016-0138-3](https://doi.org/10.1186/s40658-016-0138-3)
6. Conti, M.: Focus on time-of-flight PET: the benefits of improved time resolution. *European journal of nuclear medicine and molecular imaging* **38**(6), 1147–1157 (2011). doi:[10.1007/s00259-010-1711-y](https://doi.org/10.1007/s00259-010-1711-y)
7. Gundacker, S., Knapitsch, A., Auffray, E., Jarron, P., Meyer, T., Lecoq, P.: Time resolution deterioration with increasing crystal length in a TOF-PET system. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **737**, 92–100 (2014). doi:[10.1016/j.nima.2013.11.025](https://doi.org/10.1016/j.nima.2013.11.025)
8. Surti, S.: Update on time-of-flight PET imaging. *J Nucl Med* **56**(1), 98–105 (2015). doi:[10.2967/jnumed.114.145029](https://doi.org/10.2967/jnumed.114.145029)
9. UC Davis: Explorer Product Website (2019). accessed: 2019-01-16. <https://explorer.ucdavis.edu/about-explorer/>
10. Schug, D., Wehner, J., Dueppenbecker, P.M., Weissler, B., Gebhardt, P., Goldschmidt, B., Salomon, A., Kiessling, F., Schulz, V.: PET performance and MRI compatibility evaluation of a digital, ToF-capable PET/MRI insert equipped with clinical scintillators. *Physics in Medicine and Biology* **60**(18), 7045 (2015). doi:[10.1088/0031-9155/60/18/7045](https://doi.org/10.1088/0031-9155/60/18/7045)
11. Bugalho, R., Di Francesco, A., Ferramacho, L., Leong, C., Niknejad, T., Oliveira, L., Pacher, L., Rolo, M., Rivetti, A., Silveira, M., et al.: Experimental results with TOFPET2 ASIC for time-of-flight applications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* (2017). doi:[10.1016/j.nima.2017.11.034](https://doi.org/10.1016/j.nima.2017.11.034)
12. Chen, H., Brigg, K., Fischer, P., Gil, A., Harion, T., Munwes, Y., Ritzert, M., Schimansky, D., Schultz-Coulon, H.-C., Shen, W., et al.: A dedicated readout ASIC for time-of-flight positron emission tomography using silicon photomultiplier (SiPM). In: Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2014 IEEE, pp. 1–5 (2014). doi:[10.1109/NSSMIC.2014.7431045](https://doi.org/10.1109/NSSMIC.2014.7431045). IEEE

13. Rolo, M.D., Bugalho, R., Goncalves, F., Rivetti, A., Mazza, G., Silva, J.C., Silva, R., Varela, J.: A 64-channel ASIC for TOFPET applications. 2012 IEEE Nuclear Science Symposium and Medical Imaging Conference Record (NSS/MIC), 1460–1464 (2012)
14. Nemallapudi, M.V., Gundacker, S., Lecoq, P., Auffray, E., Ferri, A., Gola, A., Piemonte, C.: Sub-100 ps coincidence time resolution for positron emission tomography with LSO:Ce codoped with Ca. *Physics in Medicine and Biology* **60**(12), 4635 (2015). doi:[10.1088/0031-9155/60/12/4635](https://doi.org/10.1088/0031-9155/60/12/4635)
15. Sarasola, I., Nemallapudi, M.V., Gundacker, S., Sánchez, D., Gascón, D., Rato, P., Marín, J., Auffray, E.: A comparative study of the time performance between NINO and FlexToT ASICs. *Journal of Instrumentation* **12**, 04016 (2017). doi:[10.1088/1748-0221/12/04/P04016](https://doi.org/10.1088/1748-0221/12/04/P04016)
16. Gundacker, S., Turtos, R.M., Auffray, E., Paganoni, M., Lecoq, P.: High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET. *Physics in Medicine & Biology* **64**(5), 055012 (2019). doi:[10.1088/1361-6560/aafd52](https://doi.org/10.1088/1361-6560/aafd52)
17. Lecoq, P.: Development of new scintillators for medical applications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **809**, 130–139 (2016). doi:[10.1016/j.nima.2015.08.041](https://doi.org/10.1016/j.nima.2015.08.041). Advances in detectors and applications for medicine
18. Borghi, G., Tabacchini, V., Schaart, D.R.: Towards monolithic scintillator based TOF-PET systems: practical methods for detector calibration and operation. *Physics in Medicine and Biology* **61**(13), 4904–4928 (2016). doi:[10.1088/0031-9155/61/13/4904](https://doi.org/10.1088/0031-9155/61/13/4904)
19. Müller, F., Schug, D., Hallen, P., Grahe, J., Schulz, V.: A novel DOI Positioning Algorithm for Monolithic Scintillator Crystals in PET based on Gradient Tree Boosting. *IEEE Transactions on Radiation and Plasma Medical Sciences* **3**(4), 465–474 (2019). doi:[10.1109/TRPMS.2018.2884320](https://doi.org/10.1109/TRPMS.2018.2884320)
20. Müller, F., Schug, D., Hallen, P., Grahe, J., Schulz, V.: Gradient Tree Boosting-Based Positioning Method for Monolithic Scintillator Crystals in Positron Emission Tomography. *IEEE Transactions on Radiation and Plasma Medical Sciences* **2**(5), 411–421 (2018). doi:[10.1109/TRPMS.2018.2837738](https://doi.org/10.1109/TRPMS.2018.2837738)
21. Peng, P., Judenhofer, M.S., Cherry, S.R.: Compton PET: a layered structure PET detector with high performance. *Physics in Medicine and Biology* (2019)
22. Gross-Weege, N., Schug, D., Hallen, P., Schulz, V.: Maximum likelihood positioning algorithm for high-resolution pet scanners. *Medical Physics* **43**, 3049–3061 (2016). doi:[10.1118/1.4950719](https://doi.org/10.1118/1.4950719)
23. Schug, D., Weissler, B., Gebhardt, P., Schulz, V.: Crystal Delay and Time Walk Correction Methods for Coincidence Resolving Time Improvements of a Digital-Silicon-Photomultiplier-Based PET/MRI Insert. *IEEE Transactions on Radiation and Plasma Medical Sciences* **1**(2), 178–190 (2017). doi:[10.1109/TNS.2017.2654920](https://doi.org/10.1109/TNS.2017.2654920)
24. Bisogni, M.G., Morrocchi, M.: Development of analog solid-state photo-detectors for Positron Emission Tomography. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **809**, 140–148 (2016). doi:[10.1016/j.nima.2015.09.114](https://doi.org/10.1016/j.nima.2015.09.114). Advances in detectors and applications for medicine
25. Bisogni, M.G., Guerra, A.D., Belcaro, N.: Medical applications of silicon photomultipliers. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **926**, 118–128 (2019). doi:[10.1016/j.nima.2018.10.175](https://doi.org/10.1016/j.nima.2018.10.175). Silicon Photomultipliers: Technology, Characterisation and Applications
26. Weissler, B., Gebhardt, P., Lerche, C.W., Wehner, J., Solf, T., Goldschmidt, B., Mackewn, J.E., Marsden, P.K., Kiessling, F., Perkuhn, M., Heberling, D., Schulz, V.: MR compatibility aspects of a silicon photomultiplier-based PET/RF insert with integrated digitisation. *Physics in Medicine and Biology* **59**(17), 5119–5139 (2014). doi:[10.1088/0031-9155/59/17/5119](https://doi.org/10.1088/0031-9155/59/17/5119)
27. Weissler, B., Gebhardt, P., Dueppenbecker, P.M., Wehner, J., Schug, D., Lerche, C.W., Goldschmidt, B., Salomon, A., Verel, I., Heijman, E., Perkuhn, M., Heberling, D., Botnar, R.M., Kiessling, F., Schulz, V.: A digital preclinical pet/mri insert and initial results. *IEEE Transactions on Medical Imaging* **34**(11), 2258–2270 (2015). doi:[10.1109/TMI.2015.2427993](https://doi.org/10.1109/TMI.2015.2427993)
28. Frach, T., Prescher, G., Degenhardt, C., de Gruyter, R., Schmitz, A., Ballizany, R.: The digital silicon photomultiplier — principle of operation and intrinsic detector performance. In: 2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC), pp. 1959–1965 (2009). doi:[10.1109/NSSMIC.2009.5402143](https://doi.org/10.1109/NSSMIC.2009.5402143)
29. Haemisch, Y., Frach, T., Degenhardt, C., Thon, A.: Fully Digital Arrays of Silicon Photomultipliers (dSiPM) – a Scalable Alternative to Vacuum Photomultiplier Tubes (PMT). *Physics Procedia* **37**, 1546–1560 (2012). doi:[10.1016/j.phpro.2012.03.749](https://doi.org/10.1016/j.phpro.2012.03.749). Proceedings of the 2nd International Conference on Technology and Instrumentation in Particle Physics (TIPP 2011)
30. Schaart, D.R., Charbon, E., Frach, T., Schulz, V.: Advances in digital sipms and their application in biomedical imaging. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **809**, 31–52 (2015). doi:[10.1016/j.nima.2015.10.078](https://doi.org/10.1016/j.nima.2015.10.078). Advances in detectors and applications for medicine
31. Hallen, P., Schug, D., Weißler, B., Gebhardt, P., Salomon, A., Kiessling, F., Schulz, V.: PET performance evaluation of the small-animal Hyperion II PET/MRI insert based on the NEMA NU-4 standard. *Biomedical Physics & Engineering Express* **4** (2018). doi:[10.1088/2057-1976/aae6c2](https://doi.org/10.1088/2057-1976/aae6c2)
32. Schug, D., Lerche, C., Weissler, B., Gebhardt, P., Goldschmidt, B., Wehner, J., Dueppenbecker, P.M., Salomon, A., Hallen, P., Kiessling, F., Schulz, V.: Initial PET performance evaluation of a preclinical insert for PET/MRI with digital SiPM technology. *Physics in Medicine and Biology* **61**(7), 2851 (2016). doi:[10.1088/0031-9155/61/7/2851](https://doi.org/10.1088/0031-9155/61/7/2851)
33. Omidvari, N., Topping, G., Cabello, J., Paul, S., Schwaiger, M., Ziegler, S.: MR-compatibility assessment of MADPET4: a study of interferences between an SiPM-based PET insert and a 7 T MRI system. *Physics in Medicine and Biology* **63**(9) (2018). doi:[10.1088/1361-6560/aab9d1](https://doi.org/10.1088/1361-6560/aab9d1)
34. Omidvari, N., Cabello, J., Topping, G., Schneider, F.R., Paul, S., Schwaiger, M., Ziegler, S.I.: PET performance evaluation of MADPET4: a small animal PET insert for a 7 T MRI scanner. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*

- 62(22), 8671–8692 (2017). doi:[10.1016/j.nima.2017.11.097](https://doi.org/10.1016/j.nima.2017.11.097)
35. Ahmad, S., Fleury, J., de Taille, C., Seguin-Moreau, N., Dulucq, F., Martin-Chassard, G., Callier, S., Thienpont, D., Raux, L.: Triroc: A Multi-Channel SiPM Read-Out ASIC for PET/PET-ToF Application. *IEEE Transactions on Nuclear Science* **62**(3), 664–668 (2015). doi:[10.1109/TNS.2015.2397973](https://doi.org/10.1109/TNS.2015.2397973)
36. Ahmad, S., de Taille, C., Fleury, J., Seguin-Moreau, N., Raux, L., Callier, S., Martin-Chassard, G., Dulucq, F., Thienpont, D.: Triroc, a Versatile 64-Channel SiPM Readout ASIC for Time-of-Flight PET. *IEEE Nuclear Science Symposium, Medical Imaging Conference and Room-Temperature Semiconductor Detector Workshop (NSS/MIC/RTSD)* (2016). doi:[10.1109/NSSMIC.2016.8069882](https://doi.org/10.1109/NSSMIC.2016.8069882)
37. Sportelli, G., Ahmad, S., Belcaro, N., Bisogni, M.G., Camarlinghi, N., Pasquale, A.D., Dussoni, S., Fleury, J., Morrochi, M., Zaccaro, E., Guerra, A.D.: The TRIMAGE PET Data Acquisition System: Initial Results. *IEEE Transactions on Radiation and Plasma Medical Sciences* **1**(2), 168–177 (2017). doi:[10.1109/TRPMS.2016.2633237](https://doi.org/10.1109/TRPMS.2016.2633237)
38. Shen, W., Brigg, K., Chen, H., Fischer, P., Gil, A., Harion, T., Ritzert, M., Schultz-Coulon, H.C.: STiC – a Mixed Mode Chip for SiPM ToF Applications. *2012 IEEE Nuclear Science Symposium and Medical Imaging Conference Record (NSS/MIC) N14-37*, 877–881 (2012)
39. Corsi, F., Foresta, M., Marzocca, C., Matarrese, G., Guerra, A.D.: ASIC development for SiPM readout. *Journal of Instrumentation* **4** (2009). doi:[10.1088/1748-0221/4/03/P03004](https://doi.org/10.1088/1748-0221/4/03/P03004)
40. Orita, T., Koyama, A., Yoshino, M., Kamada, K., Yoshikawa, A., Shimazoe, K., Sugawara, H.: The current mode Time-over-Threshold ASIC for a MPPC module in a TOF-PET system. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* (2017). doi:[10.1016/j.nima.2017.11.097](https://doi.org/10.1016/j.nima.2017.11.097)
41. Fleury, J.: PETIROC2A : New measurement results on fast ToF SiPM read-out chip. Talk at TIPP 2017, Beijing, China (2017)
42. Fischer, P., Peric, I., Ritzert, M., Koniczek, M.: Fast Self Triggered Multi Channel Readout ASIC for Time- and Energy Measurement. *IEEE Transactions on Nuclear Science* **53**(3), 1153–1158 (2009). doi:[10.1109/TNS.2008.2008807](https://doi.org/10.1109/TNS.2008.2008807)
43. Fischer, P., Peric, I., Ritzert, M., Solf, T.: Multi-Channel Readout ASIC for ToF-PET. In: *2006 IEEE Nuclear Science Symposium Conference Record*, vol. 4, pp. 2523–2527 (2006). doi:[10.1109/NSSMIC.2006.354423](https://doi.org/10.1109/NSSMIC.2006.354423)
44. Piemonte, C., Gola, A., Tarolli, A., Fisher, P., Ritzert, M., Schulz, V., Solf, T.: Performance of FBK SiPMs coupled to PETA3 read-out ASIC for PET application. Elsevier: *Nuclear Instruments and Methods in Physics Research A* **718**, 345–346 (2012). doi:[10.1016/j.nima.2012.10.012](https://doi.org/10.1016/j.nima.2012.10.012)
45. Sacco, I., Fischer, P., Ritzert, M.: PETA4: a multi-channel TDC/ADC ASIC for SiPM readout. *Journal of Instrumentation* **8** (2013). doi:[10.1088/1748-0221/8/12/C12013](https://doi.org/10.1088/1748-0221/8/12/C12013)
46. Sacco, I., Dohle, R., Fischer, P., Piemonte, C., Ritzert, M.: A compact, high-density gamma-detection module for Time-of-Flight measurements in PET applications. *Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers Detectors and Associated Equipment* **824** (2015). doi:[10.1016/j.nima.2015.11.004](https://doi.org/10.1016/j.nima.2015.11.004)
47. Schug, D., Gebhardt, P., Weissler, B., Gross-Weege, N., Dey, T., Schulz, V.: Measurements with a PET Coincidence Setup Based on the PETA5 ASIC and FBK RGB-HD SiPMs. In: *2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*, pp. 1–3 (2017). doi:[10.1109/NSSMIC.2017.8532761](https://doi.org/10.1109/NSSMIC.2017.8532761). IEEE
48. PETsys Electronics S.A.: TOFPET 2 SiPM Readout ASIC (rev.2 ), 1st edn. PETsys Electronics SA, Taguspark - Lisboa Science and Technology Park, Edificio Tecnologia I, 26, 2740-257 PORTO SALVO, Portugal (2018). PETsys Electronics S.A. <http://www.petsyselectronics.com/>
49. PETsys Electronics S.A.: TOFPET ASIC V1 – Short Data Sheet (Rev. 1.2), 1.2 edn. PETsys Electronics SA, Taguspark - Lisboa Science and Technology Park, Edificio Tecnologia I, 26, 2740-257 PORTO SALVO, Portugal (2014). PETsys Electronics S.A. <http://www.petsyselectronics.com/>
50. PETsys Electronics S.A.: Website (2019). accessed: 2019-02-27. <http://www.petsyselectronics.com/>
51. Schug, D., Nadig, V., Weissler, B., Gebhardt, P., Schulz, V.: Initial Measurements with the PETsys TOFPET2 ASIC Evaluation Kit and a Characterization of the ASIC TDC. *IEEE Transactions on Radiation and Plasma Medical Sciences*, 1–1 (2018). doi:[10.1109/TRPMS.2018.2884564](https://doi.org/10.1109/TRPMS.2018.2884564)
52. PETsys Electronic S.A.: PETsys TOF ASIC Evaluation Kit (Flyer), v15 edn. (2018). PETsys Electronic S.A. <http://www.petsyselectronics.com/>
53. Nadig, V., Weissler, B., Radermacher, H., Schulz, V., Schug, D.: Investigation of the Power Consumption of the PETsys TOFPET2 ASIC. submitted to IEEE TRPMS Special Issue 2019 (2019). doi:[arXiv:1908.05878](https://arxiv.org/abs/1908.05878)
54. PETsys Electronics SA.: TOFPET2 ASIC Evaluation Kit - Hardware User Guide (v1.2), v1.2 edn. (2018). PETsys Electronics SA. <http://www.petsyselectronics.com/>
55. PETsys Electronics SA.: TOFPET2 ASIC Evaluation Kit - Software User Guide V2018.04, v2018.04 edn. (2018). PETsys Electronics SA. <http://www.petsyselectronics.com/>
56. Di Francesco, A., Bugalho, R., Oliveira, L., Pacher, L., Rivetti, A., Rolo, M., Silva, J., Silva, R., Varela, J.: TOFPET2: a high-performance ASIC for time and amplitude measurements of SiPM signals in time-of-flight applications. *Journal of Instrumentation* **11**(03), 03042 (2016). doi:[10.1088/1748-0221/11/03/C03042](https://doi.org/10.1088/1748-0221/11/03/C03042)
57. PETsys Electronics S.A.: Personal Communication. Emails, conferences (2018)
58. Burgess, D., Tervo, R.: Background estimation for gamma-ray spectrometry. *Nuclear Instruments and Methods in Physics Research* **214**, 431–434 (1983). doi:[10.1016/0167-5087\(83\)90612-9](https://doi.org/10.1016/0167-5087(83)90612-9)
59. Morháč, M., Klíman, J., Matoušek, V., Veselský, M., Turzo, I.: Background elimination methods for multidimensional coincidence  $\gamma$ -ray spectra. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **401**(1), 113–132 (1997). doi:[10.1016/S0168-9002\(97\)01023-1](https://doi.org/10.1016/S0168-9002(97)01023-1)
60. Ryan, C.G., Clayton, E., Griffin, W.L., Sie, S.H., Cousens, D.R.: SNIP, a statistics-sensitive background treatment for the quantitative analysis of PIXE spectra in geoscience applications. *NIM B* **34**(3), 396–402 (1988). doi:[10.1016/0168-583X\(88\)90063-8](https://doi.org/10.1016/0168-583X(88)90063-8)

61. Morháč, M., Kliman, J., Matoušek, V., Veselský, M., Turzo, I.: Identification of peaks in multidimensional coincidence  $\gamma$ -ray spectra. Nuclear Instruments and Methods in Physics Research A **443**, 108–125 (2000). doi:[10.1016/S0168-9002\(99\)01005-0](https://doi.org/10.1016/S0168-9002(99)01005-0)
62. PETsys Electronics SA.: TOFPET2 ASIC Evaluation Kit - Software User Guide V2019.01, v2019.01 edn. (2019). PETsys Electronics SA. <http://www.petsyselectronics.com/>
63. Huizenga, J., Seifert, S., Schreuder, F., Dam, H.T., Dendooven, P., Loehner, H., Vinke, R., Schaart, D.: A fast preamplifier concept for sipm-based time-of-flight pet detectors. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **695**, 379–384 (2012). doi:[10.1016/j.nima.2011.11.012](https://doi.org/10.1016/j.nima.2011.11.012)
64. Acerbi, F., Gundacker, S.: Understanding and simulating sipms. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **926**, 16–35 (2019). doi:[10.1016/j.nima.2018.11.118](https://doi.org/10.1016/j.nima.2018.11.118). Silicon Photomultipliers: Technology, Characterisation and Applications
65. Goertzen, A.L., Van Elburg, D.: Performance characterization of mppc modules for tof-pet applications. IEEE Transactions on Radiation and Plasma Medical Sciences **3**(4), 475–482 (2019). doi:[10.1109/TRPMS.2018.2885439](https://doi.org/10.1109/TRPMS.2018.2885439)
66. Belcaro, N., Bisogni, M.G., Camarlinghi, N., Carra, P., Cerello, P., Morrocchi, M., Patera, A., Sportelli, G., Del Guerra, A.: Design and detector performance of the pet component of the trimage pet/mr/eeg scanner. IEEE Transactions on Radiation and Plasma Medical Sciences **3**(3), 292–301 (2019). doi:[10.1109/TRPMS.2019.2906407](https://doi.org/10.1109/TRPMS.2019.2906407)
67. Siemens Healthcare: Biograph Vision Product Website, Siemens Healthcare GmbH, Henkestr. 127, 91052 Erlangen, Germany. accessed 04 sept 2019. <https://www.siemens-healthineers.com/molecular-imaging/pet-ct/biograph-vision>
68. Siemens Healthineers - Biograph Vision: Website (2019). accessed: 2019-11-12. <https://www.siemens-healthineers.com/nl/molecular-imaging/pet-ct/biograph-vision>
69. Mohan Li and Shiva Abbaszadeh: Depth-of-interaction study of a dual-readout detector based on TOFPET2 application-specific integrated circuit. Physics in Medicine and Biology (2019). doi:[10.1088/1361-6560/ab3866](https://doi.org/10.1088/1361-6560/ab3866)
70. Vandenberghe, S., Marsden, P.K.: PET-MRI: a review of challenges and solutions in the development of integrated multimodality imaging. Physics in Medicine and Biology **60**(4) (2015). doi:[10.1088/0031-9155/60/4/R115](https://doi.org/10.1088/0031-9155/60/4/R115)
71. Wehner, J., Weissler, B., Dueppenbecker, P.M., Gebhardt, P., Goldschmidt, B., Schug, D., Kiessling, F., Schulz, V.: MR-compatibility assessment of the first preclinical PET-MRI insert equipped with digital silicon photomultipliers. Physics in Medicine and Biology **60**(6), 2231–2255 (2015). doi:[10.1088/0031-9155/60/6/2231](https://doi.org/10.1088/0031-9155/60/6/2231)
72. Wehner, J., Weissler, B., Dueppenbecker, P., Gebhardt, P., Schug, D., Ruetten, W., Kiessling, F., Schulz, V.: PET/MRI insert using digital SiPMs: Investigation of MR-compatibility. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **734**, 116–121 (2014). doi:[10.1016/j.nima.2013.08.077](https://doi.org/10.1016/j.nima.2013.08.077). PSMR2013 - PET-MR and SPECT-MR: Current status of Instrumentation, Applications and Developments
73. KETEK GmbH: Product Data Sheet SiPM – Silicon Photomultiplier Array PA3325-WB-0808. (2017). KETEK GmbH. Accessed: 10 Aug 2018. <https://www.ketek.net/>
74. SensL: J-Series - High PDE and Timing Resolution SiPM Sensors in a TSV Package. (2017). SensL. <https://www.sensl.com/>
75. Hamamatsu: Product Flyer MPPC for Scintillation S14160/S14161 Series. (2017). Hamamatsu. Accessed: 29 Oct 2018. <https://www.hamamatsu.com/>
76. Broadcom: AFBR-S4N44P643 - 8x8 NUV-HD Silicon Photo Multiplier Array - Target Data Sheet. (2018). Broadcom. Accessed: 29 Oct 2018. <https://www.broadcom.com/>

#### Tables

**Table 1 Characteristics of the investigated analog SiPM types. Parameters are taken from the respective data sheet.**

	KETEK PA3325-WB- 0808	SensL Array-J-30020- 64P-PCB	Hamamatsu S14161-3050- HS-08	Broadcom AFBR- S4N44P643S
Pitch	3.36 mm	3.36 mm	3.20 mm	3.93 mm
Active area	$3.0 \times 3.0 \text{ mm}^2$	$3.07 \times 3.07 \text{ mm}^2$	$3.0 \times 3.0 \text{ mm}^2$	$3.72 \times 3.72 \text{ mm}^2$
No. of SPADs	13920	14850	3531	15060
SPAD size	25 $\mu\text{m}$	20 $\mu\text{m}$	50 $\mu\text{m}$ (pitch)	30 $\mu\text{m}$ (pitch)
Breakdown voltage	27 V	24.2 V to 24.7 V	37 V	26.9 V
Gain	$1.74 \cdot 10^6$ (5 V)	$1.9 \cdot 10^6$ (5 V)	$2.5 \cdot 10^6$ (2.7 V)	$3.3 \cdot 10^6$ (7 V)
Dark count rate	$100 \text{ kHz mm}^{-2}$ (5 V)	$125 \text{ kHz mm}^{-2}$ (5 V)	-	$270 \text{ kHz mm}^{-2}$ (7 V)
PDE	43 % (5 V)	38 % (5 V)	50 % (2.7 V)	55 % (7 V)
Reference	[73]	[74]	[75]	[76]

**Table 2 Coincidence resolution time. Parameter study for multi-channel configurations featuring SiPMs by different vendors. Table reports the lowest CRT achieved with the corresponding settings and materials used. If not indicated differently, data were acquired at  $vth\_t1 = 50$ ,  $vth\_t2 = 20$ ,  $vth\_e = 15$ , with 360 µm BaSO<sub>4</sub> for scintillator segmentation, and at a distance of 38 mm. The overvoltage setting varies according to the parameter setting and SiPM type used.**

	KETEK PA3325-WB-0808	SensL Array-J-30020-64P-PCB	Hamamatsu S14161-3050-HS-08
<b>threshold <math>vth\_t1</math></b>			
10	$273.8 \pm 0.7$ ps	$265.2 \pm 0.6$ ps	$224.1 \pm 0.7$ ps
20	$271.4 \pm 0.7$ ps	$265.4 \pm 0.6$ ps	$221.2 \pm 0.7$ ps
30	$268.6 \pm 0.7$ ps	$263.7 \pm 0.6$ ps	$221.1 \pm 0.7$ ps
40	$266.1 \pm 0.6$ ps	$262.8 \pm 0.6$ ps	$219.9 \pm 0.7$ ps
50	$264.6 \pm 0.6$ ps	$262.4 \pm 0.6$ ps	$220.0 \pm 0.7$ ps
<b>segmentation layer</b>			
BaSO <sub>4</sub> (360 µm)	$264.6 \pm 0.6$ ps	$262.4 \pm 0.6$ ps	$220.0 \pm 0.7$ ps
BaSO <sub>4</sub> (110 µm)	$282.8 \pm 0.6$ ps	$306.5 \pm 0.6$ ps	$242.9 \pm 0.5$ ps
ESR (67 µm, glued)	$371.4 \pm 0.8$ ps	$463.4 \pm 0.8$ ps	$328.1 \pm 0.7$ ps
<b>distance</b>			
18 mm	$277.3 \pm 0.4$ ps	-	-
38 mm	$264.6 \pm 0.6$ ps	$262.4 \pm 0.6$ ps	$220.0 \pm 0.7$ ps
58 mm	$245.3 \pm 0.8$ ps	$253.3 \pm 0.8$ ps	$224.4 \pm 0.7$ ps
<b>coupling (@ 58 mm)</b>			
BC-630	$252.9 \pm 0.9$ ps	$269.5 \pm 0.8$ ps	$228.3 \pm 1.1$ ps
Sylgard®	$245.3 \pm 0.8$ ps	$253.3 \pm 0.8$ ps	$224.4 \pm 0.7$ ps
<b>clinical</b>			
ESR (155 µm, air-coupled)	$317.3 \pm 1.9$ ps	$325.1 \pm 1.7$ ps	$247.5 \pm 2.4$ ps

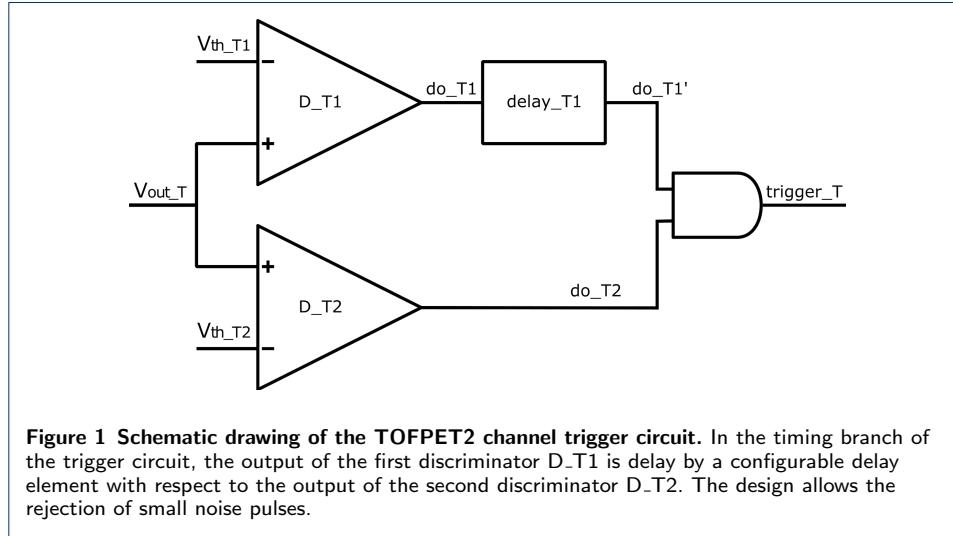
**Table 3 Energy resolution. Parameter study for multi-channel configurations featuring SiPMs by different vendors. Table reports the energy resolution corresponding to the lowest CRTs achieved (see Tab. 2). If not indicated differently, data were acquired at  $vth\_t1 = 50$ ,  $vth\_t2 = 20$ ,  $vth\_e = 15$ , with 360 µm BaSO<sub>4</sub> for scintillator segmentation, and at a distance of 38 mm. The overvoltage setting varies according to the parameter setting and SiPM type used.**

	KETEK PA3325-WB-0808	SensL Array-J-30020-64P-PCB	Hamamatsu S14161-3050-HS-08
<b>threshold <math>vth\_t1</math></b>			
10	$10.35 \pm 0.02$ %	$11.20 \pm 0.02$ %	$13.10 \pm 0.02$ %
20	$10.44 \pm 0.02$ %	$10.92 \pm 0.02$ %	$13.15 \pm 0.03$ %
30	$10.84 \pm 0.02$ %	$11.22 \pm 0.02$ %	$13.12 \pm 0.03$ %
40	$10.85 \pm 0.02$ %	$11.06 \pm 0.02$ %	$13.08 \pm 0.03$ %
50	$11.08 \pm 0.02$ %	$11.23 \pm 0.02$ %	$13.13 \pm 0.03$ %
<b>segmentation layer</b>			
BaSO <sub>4</sub> (360 µm)	$11.08 \pm 0.02$ %	$11.23 \pm 0.02$ %	$13.13 \pm 0.03$ %
BaSO <sub>4</sub> (110 µm)	$12.60 \pm 0.02$ %	$11.64 \pm 0.02$ %	$14.70 \pm 0.02$ %
ESR (67 µm, glued)	$12.58 \pm 0.02$ %	$13.78 \pm 0.02$ %	$14.74 \pm 0.02$ %
<b>distance</b>			
18 mm	$10.94 \pm 0.01$ %	-	-
38 mm	$11.08 \pm 0.02$ %	$11.23 \pm 0.02$ %	$13.13 \pm 0.03$ %
58 mm	$10.67 \pm 0.02$ %	$10.66 \pm 0.02$ %	$11.39 \pm 0.03$ %
<b>coupling (@ 58 mm)</b>			
BC-630	$11.23 \pm 0.03$ %	$11.55 \pm 0.03$ %	$11.53 \pm 0.04$ %
Sylgard®	$10.67 \pm 0.02$ %	$10.66 \pm 0.02$ %	$11.39 \pm 0.03$ %
<b>clinical</b>			
ESR (155 µm, air-coupled)	$10.74 \pm 0.05$ %	$10.72 \pm 0.04$ %	$10.46 \pm 0.08$ %

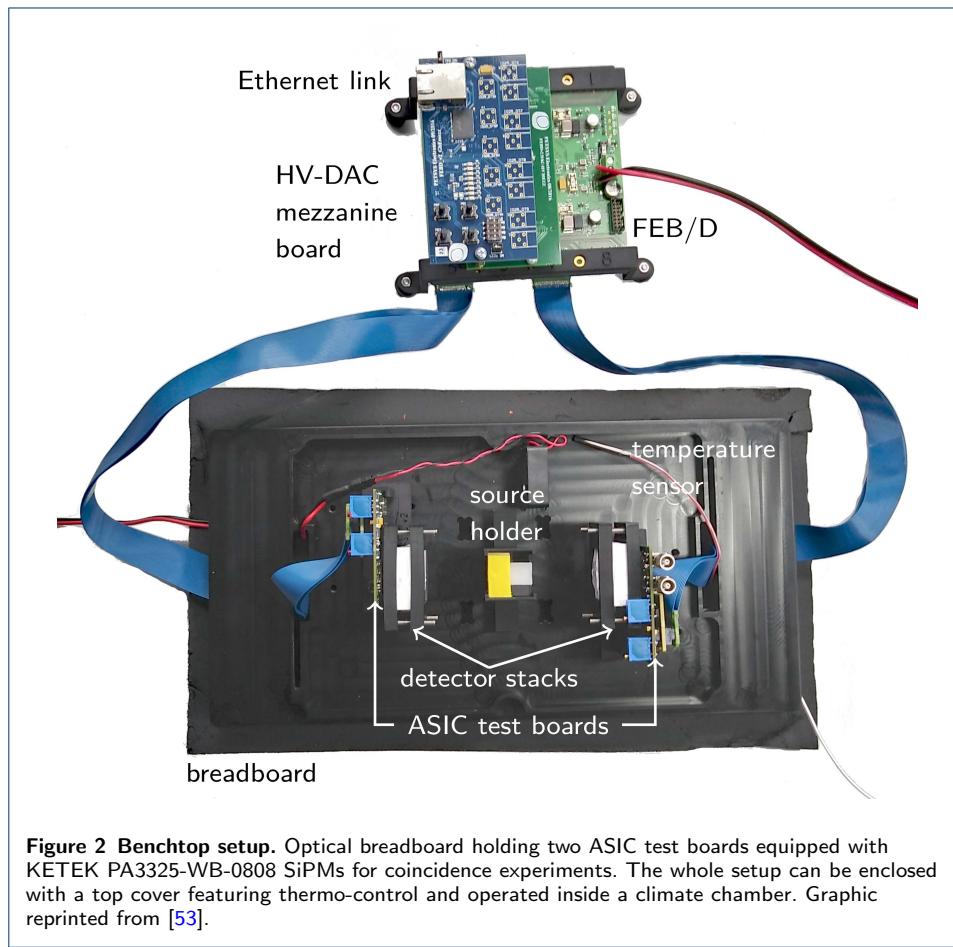
**Table 4 Supplementary results contributing to the parameter study.** Table reports the lowest CRT achieved with the corresponding settings and materials used and the energy resolution at the selected operation point. Data were acquired with two Broadcom AFBR-S4N44P643S SiPM array, where only 16 channels per array were read out. If not indicated differently, data were acquired at  $v_{th.t1} = 50$ ,  $v_{th.t2} = 20$ ,  $v_{th.e} = 15$ , with 110  $\mu\text{m}$  BaSO<sub>4</sub> for scintillator segmentation, and at a distance of 58 mm. The overvoltage setting varies according to the parameter setting used.

Broadcom AFBR-S4N44P643S		
	CRT / ps	dE/E / %
threshold $v_{th.t1}$		
10	$240.2 \pm 2.9$	$9.37 \pm 0.08$
20	$232.6 \pm 2.8$	$9.38 \pm 0.08$
30	$223.5 \pm 2.7$	$9.65 \pm 0.09$
40	$220.1 \pm 2.6$	$9.40 \pm 0.08$
50	$216.1 \pm 2.6$	$9.46 \pm 0.09$
segmentation layer		
BaSO <sub>4</sub> (110 $\mu\text{m}$ )	$216.1 \pm 2.6$	$9.46 \pm 0.09$
ESR (67 $\mu\text{m}$ , glued)	$293.6 \pm 2.6$	$11.64 \pm 0.08$

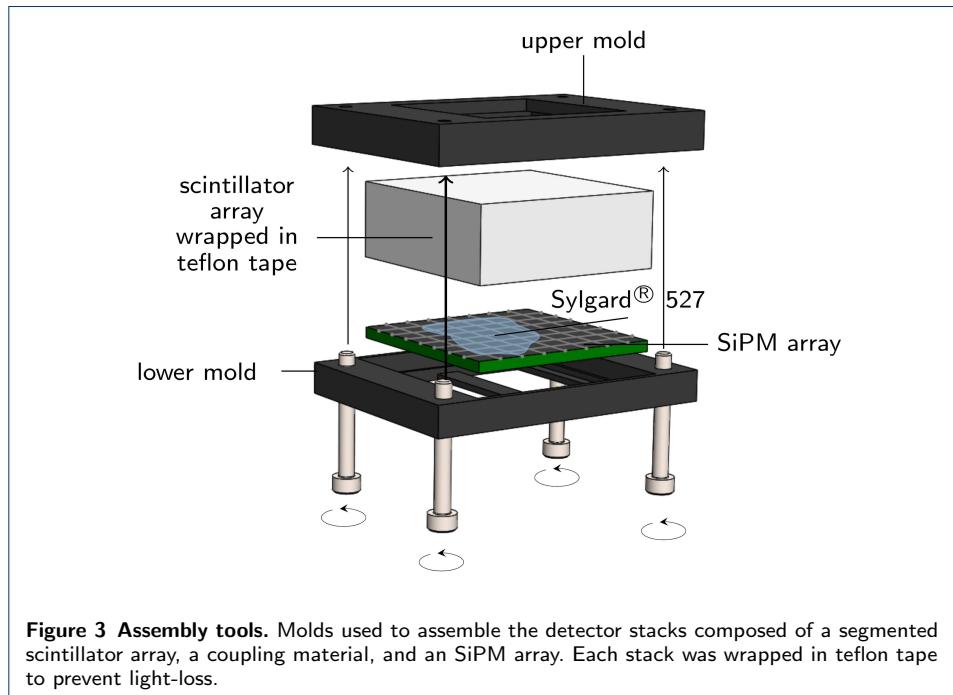
## Figures



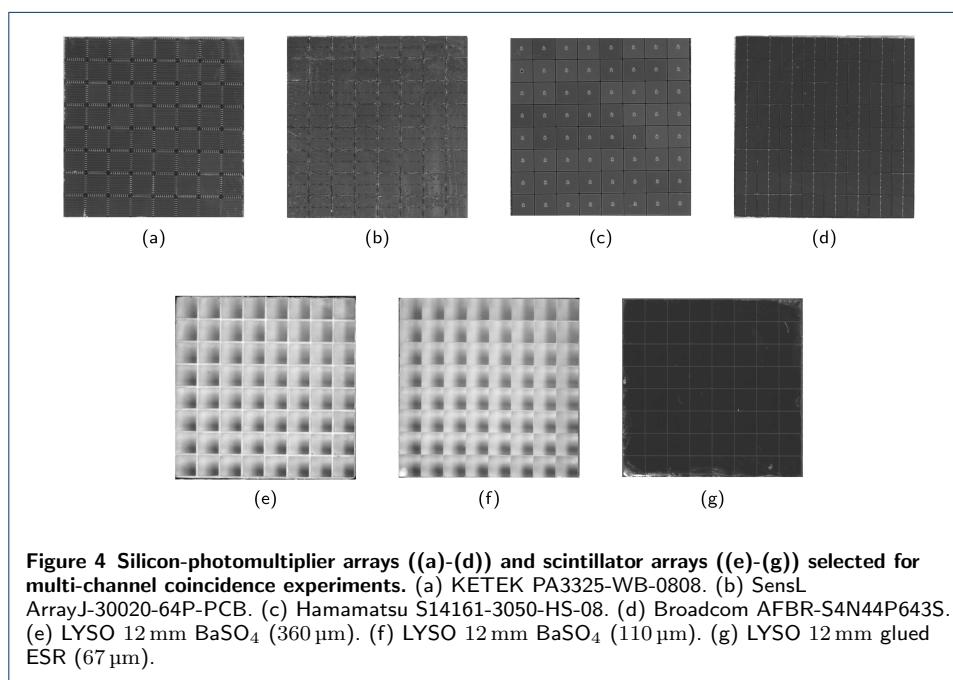
**Figure 1 Schematic drawing of the TOFPET2 channel trigger circuit.** In the timing branch of the trigger circuit, the output of the first discriminator D\_T1 is delay by a configurable delay element with respect to the output of the second discriminator D\_T2. The design allows the rejection of small noise pulses.



**Figure 2 Benchtop setup.** Optical breadboard holding two ASIC test boards equipped with KETEK PA3325-WB-0808 SiPMs for coincidence experiments. The whole setup can be enclosed with a top cover featuring thermo-control and operated inside a climate chamber. Graphic reprinted from [53].



**Figure 3 Assembly tools.** Molds used to assemble the detector stacks composed of a segmented scintillator array, a coupling material, and an SiPM array. Each stack was wrapped in teflon tape to prevent light-loss.



**Figure 4 Silicon-photomultiplier arrays ((a)-(d)) and scintillator arrays ((e)-(g)) selected for multi-channel coincidence experiments.** (a) KETEK PA3325-WB-0808. (b) SensL ArrayJ-30020-64P-PCB. (c) Hamamatsu S14161-3050-HS-08. (d) Broadcom AFBR-S4N44P643S. (e) LYSO 12 mm BaSO<sub>4</sub> (360 µm). (f) LYSO 12 mm BaSO<sub>4</sub> (110 µm). (g) LYSO 12 mm glued ESR (67 µm).

