Initial Measurements with the PETsys TOFPET2 ASIC Evaluation Kit 
and a Characterization of the ASIC TDC

David Schug¹, Vanessa Nadig¹, Bjoern Weissler¹, Pierre Gebhardt¹, and Volkmart Schulz¹

Abstract—For a first characterization, we used the two KETEK-PM3325-WB SiPMs each equipped with a 3 mm × 3 mm × 5 mm LYSO scintillation crystal provided with the PETsys TOFPET2 ASIC Evaluation Kit. We changed the lower of two discriminator thresholds (D_T1) in the timing branch from \( v_{\text{th}1} = 5-30 \). The overvoltage was varied in a range of 1.25 V–7.25 V. The ambient temperature was kept at 16 °C. For all measurements, we performed an energy calibration including a correction for saturation. We evaluated the energy resolution, the coincidence resolving time (CRT) and the coincidence rate. At an overvoltage of 6 V, we obtained an energy resolution of about 10% FWHM, a CRT of approximately 210 ps FWHM and 400 ps FWTM, the coincidence rate showed only small variations of about 5%. To investigate the influence of the ambient temperature, it was varied between 12 °C–20 °C. At 12 °C and an overvoltage of 6.5 V, a CRT of approx. 195 ps FWHM and an energy resolution of about 9.5% FWHM could be measured. Observed satellite peaks in the time difference spectra were investigated in more detail. We could show that the location of the satellite peaks is correlated with a programmable delay element in the trigger circuit.

I. INTRODUCTION

POSITRON emission tomography (PET) is an imaging technique based on the annihilation of a positron with an electron and the resulting emission of two 511 keV gamma photons in opposite directions. For clinical usage, tracers – biologically active molecules labeled with positron-emitting radionuclides – are injected into the body. The emitted gamma photons have to be detected in coincidence by a PET scanner. One assumes that the line connecting the locations of the two gamma interactions with the PET detector (line of response, LOR) includes the point of annihilation and thus the location of the tracer. By measuring many LORs and using a tomographic image reconstruction, the spatial distribution of the tracer in the patient’s body is computed [1]–[3]. PET is an essential tool in the diagnosis and staging of cancer as well as, e.g., in measuring cardiac perfusion and the assessment of Alzheimer’s disease [4]–[9].

Typically, PET detectors are arranged in a ring geometry and consist of scintillators, which convert the energy of the annihilation gamma photon into optical photons, photo detectors, readout and digitization electronics as well as mechanics, housing and cooling elements. Performance parameters of a PET detector are the spatial resolution, the timing resolution and the energy resolution. If the timing resolution of the PET detectors is sufficient, the difference in arrival times of the two gamma interactions can be used to localize the annihilation event along the LOR resulting in a non-uniform probability distribution of the position of the annihilation event along the LOR. This is called time-of-flight PET (TOF-PET). TOF-PET systems were developed in the late 1980s and require to measure the time difference of the two gamma interactions (coincidence resolving time, CRT) with a timing resolution in the order of a few hundred picoseconds [1], [2].

In most state-of-the-art PET systems, lutetium( yttrium) oxy-orthosilicate (L(Y)SO) scintillators are used to convert the gamma photons into optical photons due to their favorable properties such as high light output (≈ 25 000 ph./MeV), short decay time (≈ 40 ns) and fast rise time (≈ 70 ps), which result in excellent CRT values [1], [10], [11]. In addition to a fast scintillator to improve the timing resolution in PET systems [3], it is important to employ fast photodetectors to convert the optical photons into an electrical signal. Today, Silicon photomultipliers (SiPMs) are used for this purpose due to their compactness and lower voltage requirements compared to photomultiplier tubes (PMTs). Furthermore, SiPMs can be operated in a magnetic field why they are the photosensor of choice for applications that integrate a PET into an MRI [1]–[3]. An SiPM consists of several thousands of Geiger-mode cells, so-called single-photon avalanche diodes (SPAD), each generating a very similar analog signal upon breakdown [10]. This breakdown is ideally caused by an impinging optical photon but can also be thermally induced in the semiconductor material. This material and temperature dependent noise rate is typically in the order of 50 kcps/mm²–100 kcps/mm² at room temperature. In a single analog SiPM, also referred to as pixel or channel, several thousand SPADs are connected in parallel. The total signal of the analog SiPM is proportional to the number of detected optical photons and the rising edge of the signal contains timing information in the order of a few tens of picoseconds [10], [12]–[15].

TOF-PET systems that utilize fast scintillators coupled to analog SiPMs often employ an application-specific integrated circuit (ASIC) to digitize the analog SiPM signals with the goal to precisely measure the energy and timestamp of the gamma interaction with the scintillator material. In general, there’s a wide variety of ASICs designed for various applications in medical imaging or nuclear physics [16]. The present work concentrates on ASICs specifically designed for TOF-PET applications. These ASICs must be capable of digitizing the timestamp and the energy with a high precision in order not to significantly deteriorate the information provided with the analog SiPM signal. The timestamp is often acquired

¹Department of Physics of Molecular Imaging Systems, Institute for Experimental Molecular Imaging, RWTH Aachen University, Aachen, Germany. This project has been received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 667211. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 667211.
using a comparator set to a very low threshold to trigger on the rising edge of the SiPM signal. The timing resolution is thus influenced by the characteristics of the scintillator, the SiPM, the ASIC employed and the electrical interconnections of these components. There are benchtop experiments which can achieve coincidence time resolutions below 100 ps [17], [18]. On system level, several TOF-PET-ASIC-development projects aim to allow for a CRT better than 300 ps or even as low as 200 ps [19]–[21]. Energy can be measured using a second timestamp on the falling edge of the SiPM signal. From the difference between the two timestamps, the time-over-threshold (ToT) value can be deducted which contains information about the integral of signal [20], [22]. An integration of the analog SiPM signal can be realized using capacitors to store the energy of the signal [23].

The recently developed TOF-PET ASICs are designed in standard CMOS technology with a varying number of input channels ranging from 8 channels [23] over 16 channels [24], [25], 32 channels [26], 36 channels [27] and 64 channels [19], [20], [28]–[30]. Of these previously mentioned TOF-PET ASICs, for example the PETA series [24], [27], [31]–[33] as well as the Weeroc series are using an integration method for the energy measurement [26], [29], [30]. A PET insert for a 7T MRI scanner (MADPET4) using the TOFPET v1 ASIC [34], a tri-modal PET/MR/EEG scanner (TRIMAGE) using the Triroc ASIC [29], [30], [35] and a multi-modal setup combining TOF-PET with ultrasound endoscopy (EndoToFPET-US) using the STiC ASIC [20], [25] are only three of many examples for the application of TOF-PET ASICs.

A promising candidate for high-performance TOF-PET applications is the 64-channel TOFPET2 ASIC recently developed and presented by PETsys Electronics S.A. Designed in standard CMOS technology, this ASIC provides independent energy and time digitization for each of the 64 input channels. The digital part of the ASIC is clocked with a frequency of 200 MHz [36], [37]. Compared to its prior version, time binning was optimized from 50 ps to 30 ps [28], [36] and the trigger scheme was changed from a dual mixed-mode to a three-threshold readout scheme (for detailed description see section II). Moreover, the energy measurement method can be switched between a ToT mode and an integration mode (called "qdc" mode by PETsys) [19], [38].

PETsys distributes a so-called TOFPET2 ASIC evaluation kit, which provides the electronics and software required to test the ASIC in a small bench-top setup. It includes two ASIC evaluation boards and a data acquisition board to synchronize and configure the ASICs as well as capture the digitized data which can be connected via a network link to a computer running a control and data acquisition software. The kit is pre-equipped with two single KETEK SiPMs coupled to small LYSO crystals enabling the user to easily acquire measurements with two SiPMs in coincidence. Larger SiPM arrays and scintillator matrices may be connected to the setup and would allow the investigation of the ASIC performance with two TOFPET2 ASICs, with 64 channels each, in coincidence. In this work, we present initial results obtained with the provided single-channel setup, report the performance results obtained and artifacts observed in the time difference measurements and investigate their cause.

II. MATERIALS

In this work, we used the TOFPET2 ASIC evaluation kit, which provides two TOFPET2 ASIC evaluation boards. Each board houses a TOFPET2 ASIC with 64 analog input
Details on Trigger and Timestamp Generation

To avoid confusion, we use the naming convention for components, thresholds and signals that PETsys uses in their ASIC datasheet documentation [39].

The input voltage $V_{\text{out}_T}$ that is evaluated by the timing-trigger circuit is generated by a transimpedance amplifier from the SiPM input signal and should already be corrected for baseline. The TOFPET2 ASIC uses a two-level analog trigger scheme in the timing branch to discriminate noise events without introducing dead time (Figure 3). The first discriminator $D_{\text{T1}}$ is set to a low voltage threshold $V_{\text{th}_1}$ and its output $d_{\text{T1}}$ is hold back by a configurable delay element $\text{delay}_T$ resulting in a delayed signal $d_{\text{T1}'}$ which is fed into one input of an AND gate. A second discriminator $D_{\text{T2}}$ is set to a value $V_{\text{th}_2}$ corresponding to a higher voltage value as $V_{\text{th}_1}$. The output of that second discriminator $d_{\text{T2}}$ is delayed when routed to the second input of the AND gate. If both inputs of the AND gate are active, the trigger_T signal is generated, which is routed to the time-to-digital converter and which defines the time stamp of the light-pulse event recorded by that ASIC channel. For a rising voltage signal, the $d_{\text{T2}}$ signal will always be generated at a later point in time $t_{\text{T2}}$ than the $d_{\text{T1}}$ signal at $t_{\text{T1}}$. To invert the order of the discriminator signals at the AND gate, the $d_{\text{T1}}$ element should be set to a value that is higher than the highest expected value of the time difference between $t_{\text{T2}}$ and $t_{\text{T1}}$ which then ensures that $d_{\text{T1}'}$ is always reaching the AND gate after $d_{\text{T2}}$. In the separated energy branch, the discriminator threshold $D_{\text{E}}$ can be set to reject noise events.

III. METHODS

The ambient temperature in the box was set to 16 °C for the measurements performed to investigate the performance as a function of the $V_{\text{th}_1}$ threshold and overvoltage. According to the Software user guide [41], the LSB of the discriminator $D_{\text{T1}}$ was set to $\text{disc}_\text{lsb}_t = 60$, which should result in approximately 2.5 mV per DAC step [39]. The discriminator thresholds $D_{\text{T2}}$ and $D_{\text{E}}$ operate on a different lsb scale and were kept at their default settings $\text{disc}_\text{lsb}_t = 48$ and $\text{disc}_\text{lsb}_e = 40$, which correspond to about 15.0 mV and 20.0 mV per DAC step, respectively [39], [42]. We used the energy integrating “qdc” mode. The calibration routine, which is part of the software tools provided with the evaluation kit, was run at an overvoltage of $V_{\text{OV}} = 4.25$ V with the discriminator thresholds set to the following default values of DAC steps above the baseline $v_{\text{th}_1} = 20$, $v_{\text{th}_2} = 20$ and $v_{\text{th}_e} = 15$ [41]. By default, we programmed the length of the delay_T element by setting $fe_{\text{delay}} = 14$ which corresponds to a theoretical delay length of $t_{\text{delay}_T} = 5.8$ ns [42]. As the theoretical delay value $t_{\text{delay}_T}$ reported by PETsys is not the result of a calibration of the delay_T element, the actual value might be slightly different. For the main measurement series, we changed the discriminator threshold $v_{\text{th}_1} = 5 - 30$ in steps of 5 and the overvoltage $V_{\text{OV}} = 1.25$ V – 7.25 V in steps of 0.25 V and acquired data during 60 s. At an overvoltage of $V_{\text{OV}} = 4.25$ V, the discriminator threshold range set should correspond to a signal height in photo electrons (or SPAD breakdowns) of about 0.5-3. The obtained ASIC calibration
was used for all measurements of this series. We developed an analysis software which works with the corrected hits (called ”singles” by PETsys) provided by the PETsys software “convert_raw_to_singles”.

For each of the 150 measurements, an individual energy calibration per detector was performed and then used during data processing. The 511 keV and 1275 keV peaks in the energy value histogram (Figure 4a) were identified by calculating and subtracting the background [43]–[45] and performing a peak search using a Markov chain algorithm [46]. A Gaussian was fitted to the peaks. A simple saturation model was applied and parameterized using the positions of the two energy peaks neglecting energy offsets or optical crosstalk (cf. eq. (1)). The result is the saturation-corrected energy $E$, determined by the energy value $e$, the energy factor $c$ in keV per unit of $e$ and the saturation parameter $s$ in units of $e$ (Figure 4b). These parameters were determined numerically using the fitting routine of ROOT. No noise pedestal or energy offset besides the constant correction determined during the calibration routine was calculated. Singles with an energy of 400 keV-700 keV were considered for the coincidence search using a coincidence window of 35 ns to be sensitive to any problems that might lead to timestamp errors up to several clock cycles.

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

For all measurements, the time difference between the two detectors and the energy spectrum of coincident events were evaluated. The energy resolution and CRT as full width at half maximum (FWHM) were determined by fitting a Gaussian to a defined range of the respective spectrum (details of the fitting methods are described in [47], see Figure 4c). To probe the tail behavior of the time difference distribution, we determined the full width at tenth maximum (FWTM).

To investigate the performance as a function of temperature, a further measurement series was conducted. For these measurements the ambient temperature was varied between 12 °C-20 °C in steps of 2 °C using a constant setting for the $V_{th\_T1}$ threshold of $V_{th\_T1} = 30$ and the same overvoltage range as for the first measurement series. Data was processed in the same way as for the measurement series described above.

To qualitatively investigate the cause of observed satellite peaks (two smaller peaks in the time difference histogram located symmetrically around the main peak) in the time difference spectrum further we conducted four measurements using the non-default values for $f_{e\_delay}$ of 11, 12 and 13 which correspond to a delay length $t_{delay\_T1}$ of 12.9 ns, 0.39 ns and 2.95 ns, respectively additionally to the default value [42].

Then, we set the discriminator threshold $vth\_t1$ to the minimum value of 1, which should result in the highest fraction of coincidence events with an abnormal time difference above, and varied the overvoltage for values of the delay element $t_{delay\_T1}$ of 2.95 ns, 5.8 ns and 12.9 ns. For these measurements, the calibration method was repeated before each of the three delay settings applied. In the time difference spectrum we determined the difference of the satellite peak positions with respect to the central peak by fitting a Gaussian to all three peaks. This measurement series was conducted to reveal a dependence of the peak position with the slope of the SiPM signal. The peak position was evaluated by fitting a Gaussian to all peaks appearing in the time difference spectrum and then computing the distance of the satellite peaks to the main peak.

IV. RESULTS

The locations of the 511 keV and 1275 keV photopeaks (Figure 4a) showed the expected monotonous increase with a rising overvoltage and are independent of the used discriminator threshold $V_{th\_T1}$. While the 511 keV peak position showed an almost linear increase with rising overvoltage, the 1275 keV peak position showed a stronger saturation effect (Figure 5). Only minor differences in the peak positions were observed for the two detectors.
No significant difference was observed for different values of the discriminator threshold \( V_{\text{th}} \). For higher voltages, a clear difference was measured for different settings of \( V_{\text{th}} \). For lower voltages, no difference could be measured. If the voltage was increased above \( V_{\text{OV}} = 6.00 \text{ V} \), the CRT showed a degradation (Figure 7).

The coincidence rate showed only small variations of about 5% in the evaluated parameter range. At an overvoltage of \( V_{\text{OV}} = 5.00 \text{ V} - 6.00 \text{ V} \), a coincidence rate of about 172 cps was measured. The different settings of the \( D_{\text{T1}} \) discriminator did not show a significant influence on the measured coincidence rate (Figure 8).

The CRT and the energy resolution showed a performance improvement for lower temperatures and were observed to be stable up to higher voltages compared to 72°C.

The energy resolution for coincident events (Figure 6) for the 511 keV photopeak improved from the lowest values of \( V_{\text{OV}} \) up to \( V_{\text{OV}} = 3.50 \text{ V} \). At this voltage, the energy resolution was determined to be 9.7% FWHM and slightly deteriorated for higher voltages to values of about 9.8%-10.2% FWHM and worsened for \( V_{\text{OV}} > 6.50 \text{ V} \) more quickly to 11% FWHM. No significant difference was observed for different values of the discriminator threshold \( V_{\text{th}} \) (Figure 6).

The CRT showed a clear improvement with increasing voltage in the range of \( V_{\text{OV}} = 1.25 \text{ V} - 5.00 \text{ V} \). The optimum was reached for about \( V_{\text{OV}} = 5.00 \text{ V} - 6.00 \text{ V} \) with approximate values of 210 ps FWHM and 400 ps FWTM. For lower voltages, a clear difference was measured for different settings of the \( D_{\text{T1}} \) discriminator with lower values of \( V_{\text{th}} \) showing a better CRT performance. For voltages above approximately \( V_{\text{OV}} > 4.25 \text{ V} \), no difference could be measured. If the voltage was increased above \( V_{\text{OV}} > 6.00 \text{ V} \), the CRT showed a degradation (Figure 7).

The CRT and the energy resolution showed a performance improvement for lower temperatures and were observed to be stable up to higher voltages compared to 72°C.

Figure 5. Energy value of (a) the 511 keV peak and the (b) the 1275 keV over voltage for one of the two crystals for different values of the discriminator threshold \( V_{\text{th}} \).

Figure 6. Energy resolution of the 511 keV peak over overvoltage for the measured values of the discriminator threshold \( V_{\text{th}} \) at an ambient temperature of 16°C.

Figure 7. (a) FWHM and (b) FWTM of the time difference histogram over overvoltage for the measured values of the discriminator threshold \( V_{\text{th}} \) at an ambient temperature of 16°C.

Figure 8. Coincidence rate over overvoltage for the measured values of the discriminator threshold \( V_{\text{th}} \) at an ambient temperature of 16°C.
degradation was observed towards the highest voltages applied (Figure 9 and Figure 10). Higher temperatures showed worse performance values over about 9.5% FWHM were measured in the voltage range of \(195\) ps FWHM (370 ps FWTM) and an energy resolution of \(0.16\) % for the maximum overvoltage (Figure 12). The satellite peak fraction increased for higher temperatures when all other parameters where kept constant (Figure 13).

We observed satellite peaks in many of the time difference spectra. The effect was more prominent for higher overvoltages and lower values of \(V_{th T1}\) (Figure 11a and Figure 11b). For a quantative evaluation of all measurements conducted with the default settings, we defined coincidences with a time difference larger than 2.5 ns to contribute to the satellite fraction. A baseline of the satellite fraction of about 0.3% was observed. All applied values for \(V_{th T1}\) showed a significant increase of the satellite fraction above the baseline when surpassing a threshold-specific overvoltage. For \(V_{th T1} = 5\), the satellite fraction increased above the baseline for overvoltages higher than 2.0 V and reached the highest value of about 16% for the maximum overvoltage (Figure 12). The satellite peak fraction increased for higher temperatures when all other parameters were kept constant (Figure 13).

The location of the satellite peaks was observed to be correlated with the programmed length of the \(delay_{T1}\) element (Figure 14). For the shortest theoretical value of \(delay_{T1} =
SiPM. Furthermore, the jitter of the point in time when the
first photon and the subsequent photons are detected by the
SiPM is larger. Setting a lower trigger threshold therefore leads
to a better time resolution, as this requires the SiPM to detect
less photons, which leads to the timestamp of the event being
generated at an earlier point in time with a smaller jitter than
for higher thresholds and less photons being detected by the
SiPM. This is known as the time walk effect [53]. The non-
existing performance difference for the investigated values of
$v_{th,T1}$ over a wide range of higher overvoltages suggests that
the photon flux at a very early time point is high for all
these overvoltages and the SiPM signals rise quickly and reach
the set discriminator thresholds. The general time resolution
degradation, which can be noticed for overvoltages over 6 V, is
probably related to an increased noise contribution with rising
overvoltage.

Lower temperatures are beneficial for the performance. The
dark count rate of the SiPM will increase with rising tempera-
ture. To clearly attribute the observed superior performance at
low temperatures to either the SiPM or the ASIC or both, one
would need to control the temperature for both components
separately which is not possible with the current setup.

The timing effects of the trigger scheme resulting in the
appearance of satellite peaks in the coincidence time difference
spectrum have not been reported so far. We could show that
the effect is clearly related to $t_{delay,T1}$ and not a
errorneous timeshift by one clock cycle which would very
likely be observed at $\pm 5\,\text{ns}$. Our working hypothesis is that
if the trigger circuit (section II and Figure 3) operates as
expected, it allows to reject noise events with a signal height
smaller than $V_{th,T2}$ but still preserves the timestamp precision
of the lower $V_{th,T1}$ threshold. In this nominal operation case,
the time stamp is generated by the delayed signal $d_{o,T1}'$
which is $t_{T1}' = t_{T1} + t_{delay,T1}$. If there is too much noise
on $V_{out,T}$ which is higher than $V_{th,T1}$, the $d_{o,T1}$ and $d_{o,T1}'$
signals might be active due to noise for a significant amount of
time. If this is the case and a signal pulse from a scintillation
event surpasses the voltage level
$V_{th,T2}$ in a time window in
which $d_{o,T1}'$ is already enabled, the $d_{o,T2}$ arrival at the
AND gate will immediately generate the $t_{delay,T1}$ signal.
Compared to the nominal trigger generation, the timestamp
will not incorporate the $t_{delay,T1}$ time span. If there is a
mixture of events that are generated nominally and events
that arrive during a noise-induced activation of $d_{o,T1}'$, the
relative time difference between those events will be $\Delta t =$

| ASIC          | SiPM                  | scintillator     | temp. / °C | CRT FWHM / ps | e. res. FWHM / % | ref.       |
|---------------|-----------------------|------------------|------------|---------------|------------------|-----------|
| TOFPET2       | KETEK PM3325-WB-A0    | LYSO             | 3.0 mm × 3.0 mm × 5 mm | 18 | 229 | 10.5 | [21], [48] |
| TOFPET2       | KETEK PM3325-WB-A0    | LYSO             | 3.0 mm × 3.0 mm × 5 mm | 18 | 202 | 8.0  | [49]      |
| TOFPET1       | FBK NUV-HD            | LYSO             | 3.1 mm × 3.1 mm × 15 mm | 22 | 214 | n.a. | [20], [51] |
| ToT ASIC      | S13361-3050AE-08 MPPC | GFAG             | 2.0 mm × 2.0 mm × 2 mm | 25 | 200 | 13.5 | [22]      |
| PETA3         | FBK                  | LYSO             | 3.0 mm × 3.0 mm × 5 mm | 20 | 190 | 12.0 | [27], [32] |
| PETA3         | FBK                  | LYSO             | 3.0 mm × 3.0 mm × 15 mm | 20 | 250 | n.a. | [32]      |
| PETA5         | FBK RGB-HD           | LYSO             | 2.5 mm × 2.5 mm × 10 mm | 20 | 205 | n.a. | [33]      |
| Pettroci       | KETEK                | LYSO             | 3.0 mm × 3.0 mm × 8 mm | 23 | 420 | 10.7 | [35]      |
| Triroc         | ADVANSID NUV         | LYSO             | 3.0 mm × 3.0 mm × 10 mm | n.a. | 433 | 11.0 | [30]      |

Figure 13. Temperature dependency of the satellite peak fraction over
overvoltage for the different ambient temperatures investigated at a discriminator
threshold of $v_{th,T1} = 30$. 0.39 ns the satellite peaks were presumably merged into the
main peak and could not be resolved anymore (Figure 14a).

Figure 15 shows the difference between the main peak and
the satellite peak locations as a function of overvoltage for the
three higher values of $t_{delay,T1}$ that could still be resolved. We
observed an increase in the satellite peak distance to the main
peak in the time difference spectrum with increasing voltage.

V. DISCUSSION AND CONCLUSIONS

The results obtained with small LYSO crystals, read out by
a KETEK PM3325-WB-A0 SiPM each coupled to a
single input channel of a TOFPET2 ASIC, obtained in this
work are in agreement with the previously published results by
PETsys [21], [48]. They demonstrate the state-of-the-art
performance of the ASIC under these artificial test conditions.
Other groups using the same setup report results in the same
order of magnitude [49]. The results obtained with TOFPET2
ASIC are comparable to similar setups employing other TOF-
PET ASICs, mentioned in the introduction (see Table I for
a comprehensive overview). CRT values below 300 ps seem
to be feasible on system level using the TOFPET2 ASIC.
[19]–[21].

Only the lowest voltages applied revealed an influence of the
$V_{th,T1}$ discriminator threshold on the CRT due to the reduced
photon detection efficiency of SiPMs at lower overvoltages.
A reduced photon detection efficiency results in slower slopes of
the SiPM signal since less photons are detected by the
SiPM. Furthermore, the jitter of the point in time when the
Figure 14. Time difference spectra for different settings of the delay\_T1 element. The theoretical value provided by PETsys is marked with red lines. (a) \( t_{\text{delay\_T1}} \) set to 12 which should correspond to \( t_{\text{delay\_T1}} = 0.39 \) ns. (b) \( t_{\text{delay\_T1}} \) set to 13 which should correspond to \( t_{\text{delay\_T1}} = 2.95 \) ns. (c) \( t_{\text{delay\_T1}} \) set to 14 which should correspond to \( t_{\text{delay\_T1}} = 5.80 \) ns. (d) \( t_{\text{delay\_T1}} \) set to 11 which should correspond to \( t_{\text{delay\_T1}} = 12.90 \) ns.

The baseline in the satellite peaks calculation for low overvoltages is caused by the background of statistical random coincidences. Increasing the overvoltage increases the dark count rate and lowering the discriminator threshold \( V_{\text{th\_T1}} \) makes it more prone to be activated by small noise signals, ultimately leading to a higher number of events with a timestamp defined by \( t_{T2} \).

The slight increase of the peak position difference with rising overvoltage (Figure 15) can be explained by the decrease of the time difference between the two discriminator timestamps \( t_{T1} \) and \( t_{T2} \), the dynamic part of the observed time difference \( \Delta t \). A higher overvoltage results in a higher gain and a steeper signal slope which results in a smaller time difference between \( t_{T1} \) and \( t_{T2} \) and thus in a higher \( \Delta t = t_{\text{delay\_T1}} - (t_{T2} - t_{T1}) \).

The operation point of the TOFPET2 ASIC discriminator thresholds should be chosen carefully for a stable and undeteriorated performance. Especially the delay\_T1 discriminator should be configured carefully and set to a safe, high-enough value in order to prevent satellite peaks from appearing. Wrong time stamps could lead to an increased loss of coincidences, an enhanced random rate or wrong TOF information.

VI. OUTLOOK

Next steps will be to develop a protocol to find stable and suitable threshold settings in order to avoid the appearance of satellite peaks in the coincidence time difference spectra.
and thus optimize the measurement settings and ASIC performance. This will most-probably mean to scan the trigger thresholds independently and measure the noise and photon-electron pedestals and to decide on which photoelectron to trigger. We will investigate if a certain dark count-rate per channel should not be surpassed in order to suppress the wrong timestamp generation.

Various different single-channel SiPMs as well as SiPM arrays of different vendors will be tested in the future using a similar evaluation protocol as presented in this work. This will lead to operating multiple channels of the ASIC simultaneously and to change the scintillator geometry to a design that could actually be used to build up a PET detector block. The required increase in scintillator thickness is expected to deteriorate the timing resolution. A decline in the energy resolution is expected for larger arrays of scintillator elements coupled to a sensor board built from multiple SiPMs.

If the TOFPET2 ASIC proves to be a viable candidate to build larger systems with, we plan to design a MR-compatible sensor board and test the ASIC under MRI conditions employing similar interference-test protocols as we used for the evaluation of our previously evaluated PET/MRI technology which employs digital SiPMs [54]–[57].

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