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The new TOFPET3 ASIC

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Introduction

- The current efforts to improve the performance of crystals and light-sensors in PET applications need to be matched by equivalent progress in the electronics systems.

- The ultimate goal is that the electronics introduces a negligeable contribution to the PET time resolution
  - but still providing sufficient integration and low power as required by large scale systems, in particular Total Body PET.
- The present work is a contribution in this direction. A new PETsys ASIC in the TOFPET series, named TOFPET3, has been developed aiming at high performance PET applications.

From TOFPET2 to TOFPET3

- TOFPET2 is a mixed-mode low-power ASIC dedicated to PET developed by PETsys Electronics, which received considerable attention from the academic and industrial communities.
  - Published measurements indicate that **TOFPET2 adds in quadrature about 100 ps to CTR.**
- Relative to TOFPET2:
  - **TOFPET3 improves the timing performance: the electronics contribution to CTR is ~25 ps**
  - Improves the linearity and resolution of the energy measurement
  - Preserves the high-rate capability and low power consumption
  - Four additional channels with sums of 16, 32 or 64 cannels (configurable) suitable for light sharing applications
  - Advanced triggering features allowing the selective readout of a group of channels triggered by the energy of one channel.

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Main specifications

- The new chip has a 64-channel analog front-end, which performs
  - baseline stabilization
  - pulse tail cancelation
  - dark noise rejection
  - gain configuration
- Positive and negative pre-amplifiers (configurable)
- In each channel, three 10-bit digitizations of pulses above a configurable threshold:
  - Two time measurements (2 TDC)
  - One charge measurement (1 QDC)
- Sum channels and advanced triggering features
- The maximum event rate per channel is 500 kHz
- The output bandwidth is 3.8 Gb/s matching the input rate

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Analog frontend

- The circuit is designed to **process the input current without the usual conversion to voltage.**
  - Full current-mode increases the bandwidth using low power
- **Pulse filtering** is included in the post-amplifiers
  - mitigates the deterioration of time resolution due to DCR and pile-up of LYSO pulse tails.
- **Baseline stabilization** for accurate timing
  - baseline holding feedback loop with a single low frequency pole in the mHz region
- **Continuous time integration block**
  - to smooth out the pulse shape with crystals of long decay time and low light yield.

Discriminators

- **TOFPET3 has three discriminators per channel.**
  - The first discriminator has very low threshold, for timing measurement
  - The second discriminator is used to reject dark counts and low energy hits
  - The third discriminator provides the selection of the signals for digitization.

- **Four ranges** in each discriminator (configurable)

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TDC

- **The TDC has two components:**
  - Time to Amplitude Converter (TAC) and Analog To Digital Converter (ADC)

- The TAC measures the fine time within a clock cycle.
  - **The time bin is 8 ps.**
  - The analog TAC allows good time resolution with low power consumption.

- Two TDCs allow for **two measurements of time** (configurable)
  - used for pulse ToT and slew rate measurements and for pulse shape reconstruction

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QDC

- **The QDC has two components:** Charge to Amplitude Converter (QAC) and Analog To Digital Converter (ADC)
- **Configurable integration window**
- **Linear amplitude measurement** in the full dynamic range (3000 p.e., G=3.5x10^6).
- Can measure the **charge of single photons** with S/N>10 (SiPM G=3.5x10^6).
- **QAC baseline cancellation** removes the DC value, maximizing the available dynamic range.

Simulation of the analog front-end

- Simulation of the time resolution of the analog front-end was performed with the following conditions:
  - LYSO smooth pulses associated to SiPM S14160-3050HS (gain 3.5×10^6)
  - Photo-electron yield of 3000 p.e (estimated yield for small LYSO crystals)
  - Electronics noise is included in the simulation
  - Photo-statistics and SiPM jitter is not included.
  - Time resolution is extracted at the output of the timing discriminator.

Simulated timing resolution

TOFPET v3 – timing resolution

Summary

Timing resolution (ps)	G=1.75e6		G=3.5e6	
	Npe=1500	Npe=3000	Npe=1500	Npe=3000
Direct amp (T1)	6.08	4.75	4.68	3.46
Direct amp (T2)	1.83	1.24	1.25	0.89
Reverse amp (T1)	6.86	5.4	5.4	1.43
Reverse amp (T2)	2.2	3.21	1.43	1.01
	Ith1 33uA above threshold			
Direct amp (T1)	2.32	1.61	1.61	1.39
Reverse amp (T1)	2.65	1.95	1.95	1.45

A channel time resolution of ~1.5 ps (rms) is obtained, which translates in a contribution to CTR of 5 ps FWHM.

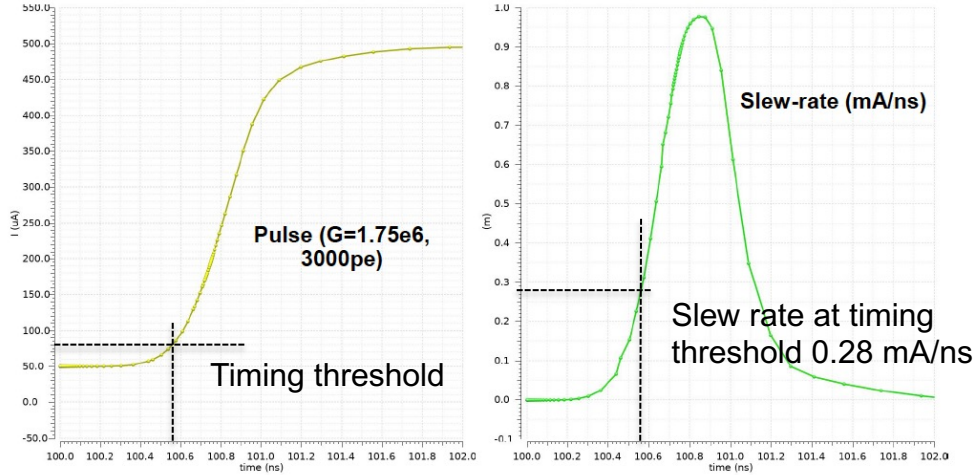
Threshold of 33 uA suitable for PET timing

Understanding time resolution

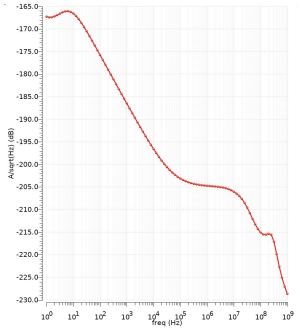
Pulse SR simulation: 0.28 mA/ns

TOFPET 3 – Direct amplifier

Slew-rate (G=1.75e6, 3000pe)



Noise simulation: 450 nA (rms)



Electronics noise contribution to time resolution:

$$\sigma_t^{elect} = \frac{\sigma_{noise}}{Slew\ rate}$$

$$\sigma_t^{elect} = \frac{0.45\ \mu A}{0.28\ \mu A/ps} = 1.6\ ps\ (rms)$$

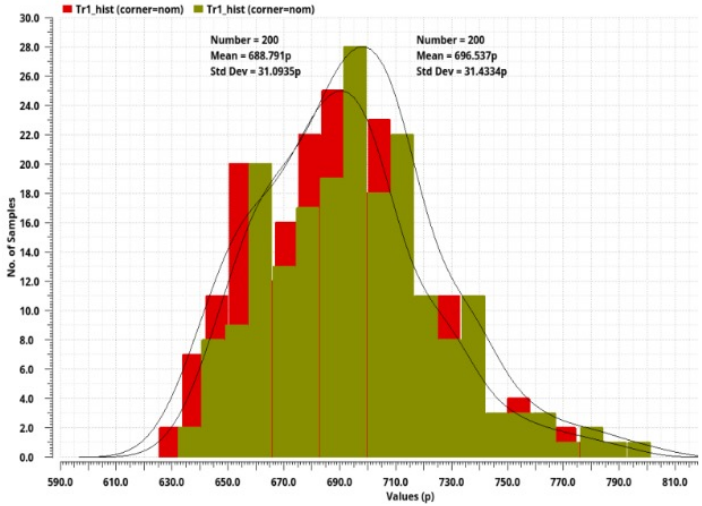
Simulation with SiPM jitter and photostatistics

- Detailed simulation of the ASIC associated to the sensor.
  - ASIC inputs are connected to the equivalent electrical model of the SiPM
  - Individual simulation of 3000 p.e. randomly distributed following LYSO exponential decay
  - SiPM jitter is included (35 ps rms)
  - TDC not included

1 p.e. @ discriminator input:	Baseline:	SiPM gain:	SiPM jitter:	# p.e.:
23uA	52uA	3.5M	35ps	3000

Analog front-end:

No noise (red) vs with noise (green)



TDC resolution

- TDC LSB = 8.1 ps (clock 240 MHz)

- TAC resolution:
  - Noise at TAC output: 0.25 mV = 0.63 LSB
  - TAC resolution: 5.1 ps rms
- ADC resolution:
  - ADC noise (electronics + quantization): 0.59 LSB rms = 4.7 ps rms

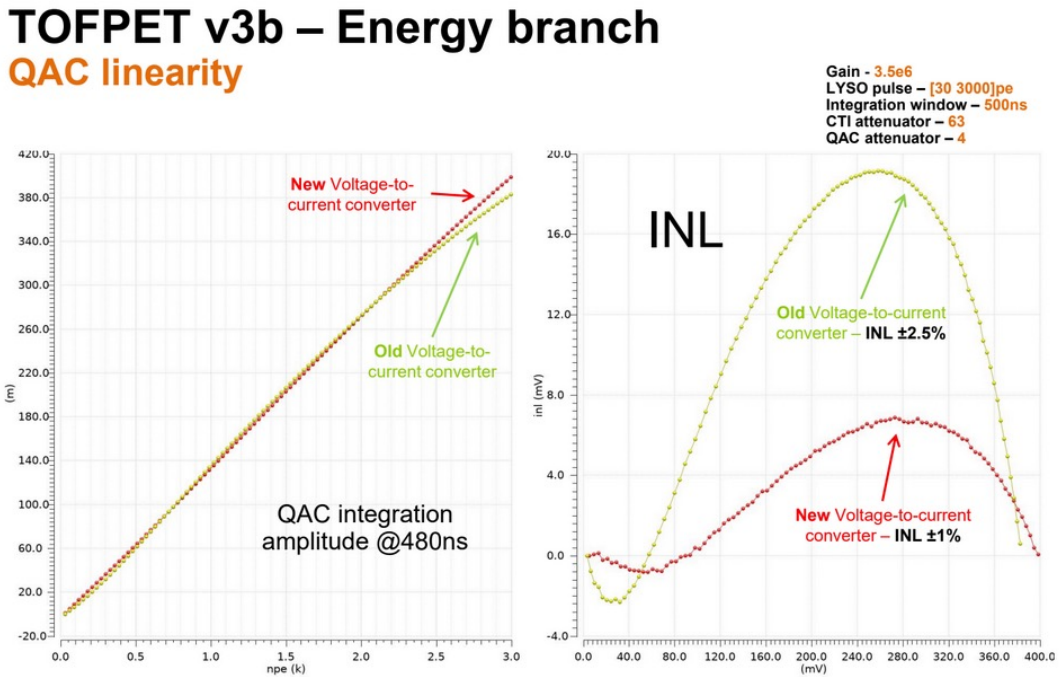
- **TDC resolution:**
  - **5.1 ⊕ 4.7 = 6.9 ps rms (16 ps FWHM)**

TOFPET3 contribution to CTR

- The simulated TOFPET3 contribution to CTR is 23.5 ps (FWHM)
- CTR=80 (120) ps (photo-statistics and SiPM jitter) becomes 83 (122) ps with TOFPET3

Energy linearity

- Deviation to linearity in the range 3000 p.e. for SiPM gain of $3.5e^6$ is $\pm 1\%$



Energy resolution

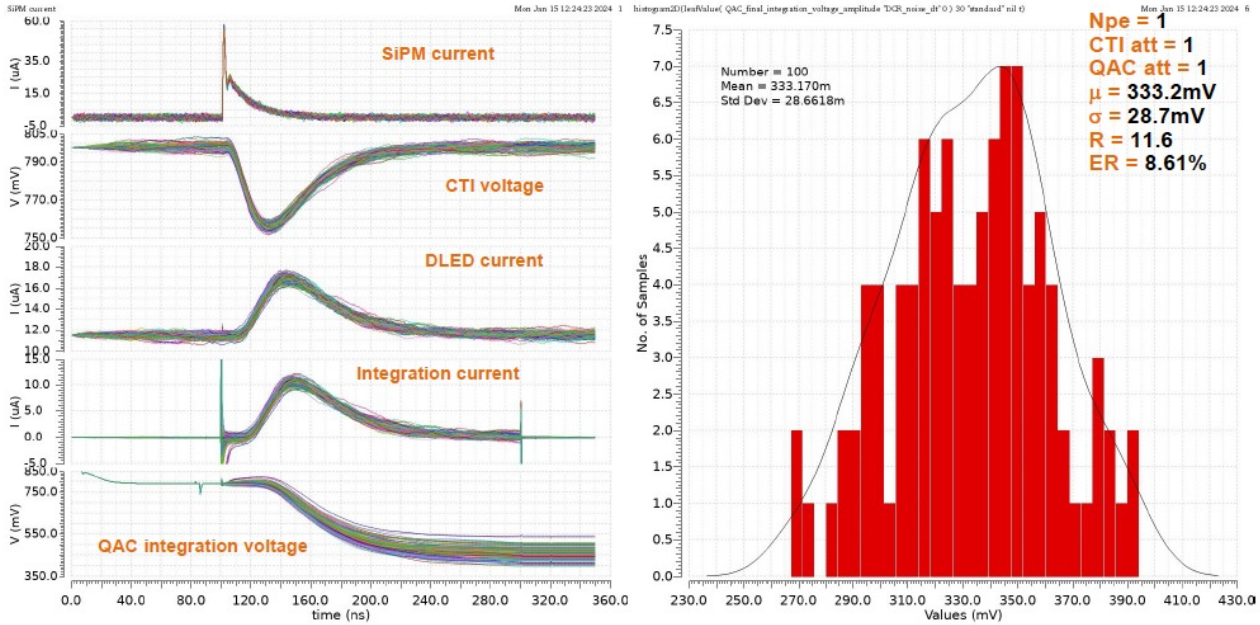
- The energy resolution depends on the QAC and ADC noise
  - Simulation of QAC noise: 1.33 mV rms
  - Simulation of ADC noise: 0.3 mV rms
  - Total QDC noise: 1.33 ⊕ 0.3 = 1.4 mV rms

- Full ADC range is 400 mV. Assuming 511keV photopeak configured at ¾ of the range with obtain:
  - Energy resolution=1.1% FWHM

Single photon simulation

TOFPET 3b – Single photon energy resolution

Gain=3.5e6, int. window =200ns, High Gain



TOFPET3 specifications

	TOFPET3
Number of channels	64
Overall contribution to CTR (3000p.e., G=3.5.10^6) (FWHM)	24
Contribution of analog front-end to CTR (3000p.e., G=3.5.10^6) (FWHM)	5 ps
TDC resolution (FWHM)	16 ps
SPTR of analog front-end for SiPM G=3.5.10^6 (FWHM)	35 ps
S/N of single photon energy for SiPM G=3.5.10^6	12
QDC contribution to energy resolution of 511 keV photopeak (FWHM)	1.1%
Energy non-linearity (INL) for LYSO and SiPM G=3.5.10^6 @ 3000 p.e.	±1%
Pulse filtering and charge integration configurable for different crystals	yes
Sum channels	yes
Advanced triggering (regional readout)	yes
Maximum input rate per channel (events/s)	500 kHz
Max clock frequency (MHz)	480
Max output bandwidth (Gb/s)	3.8
Power consumption per channel (mW)	8

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Prototyping Plan

- Prototype chip with full functionality and 32 channels
  - Submitted to fabrication in the end of May 2024
  - Evaluation kit expected in the fall 2024
- The final chip has 64 channels and is expected to be submitted in the fall 2024
- TOFPET3 is fully compatible with the PETsys Readout System.

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Summary

- The new TOFPET3 ASIC is expected to contribute less than 5% to CTR~80 ps
  - Analog front-end with outstanding performance
    - Contribution to CTR (3000p.e., G=3.5.10^6) is 5ps FWHM
  - TDC resolution 16 ps FWHM
- Energy measurement (3000 pe, G=3.5e^6) with non-linearity of 1% and resolution of 1.1% (photopeak 511keV)
- Single photon sensitivity:
  - SPTR 35 ps (FWHM)
  - Energy measurement with S/N=12
- Sum channels and selective readout for light sharing applications