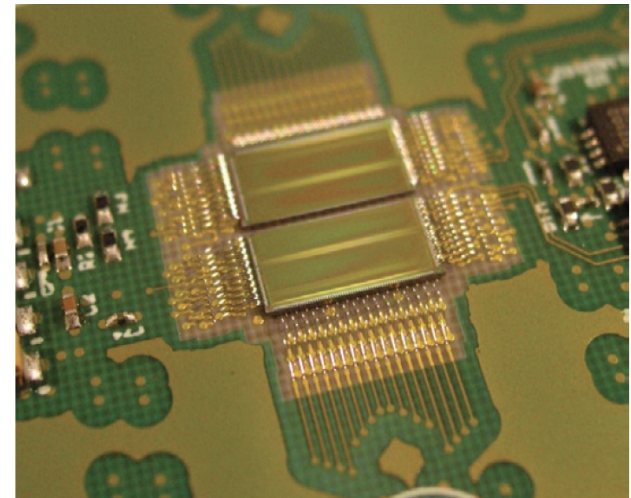
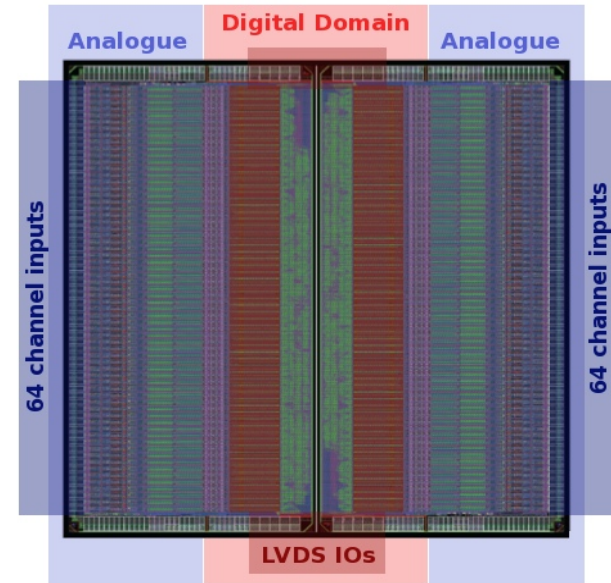


TOFPET: a High-Performance ASIC for Time-of-Flight Applications

Luis Ferramacho

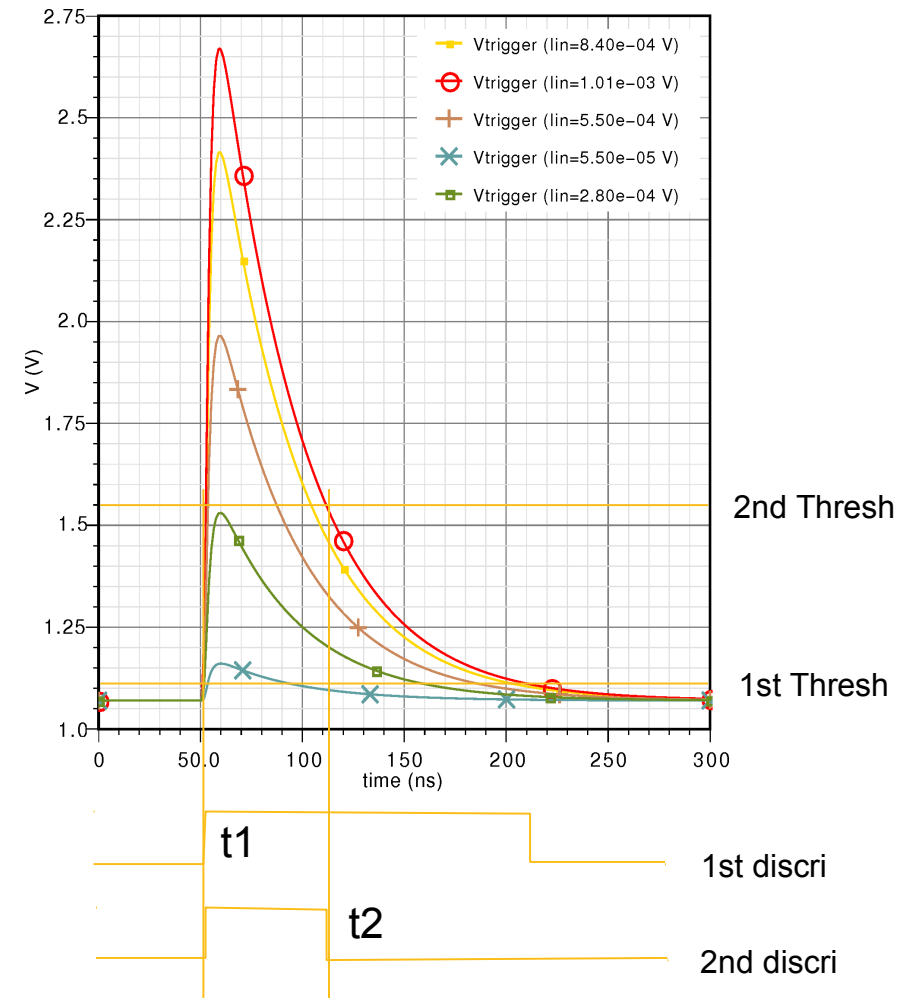
DIRC 2015
13 November 2015

- 2 x 64 channels in 7 x 7 mm²
 - CMOS 130nm
- Frontend + TDC + Digital readout
- Optimum SNR performance for SiPM with capacitance up to 350 pF
- Positive or negative signal polarity
- SNR ($Q_{in} = 200$ fC): 25 dB
- Interpolation TDC
 - Time binning: 50 ps (option 25 ps)
- Optimized for low power
 - 8-11 mW channel
- Digital I/O LVDS
- Output data rate 640 Mb/s
- On-chip calibration circuitry



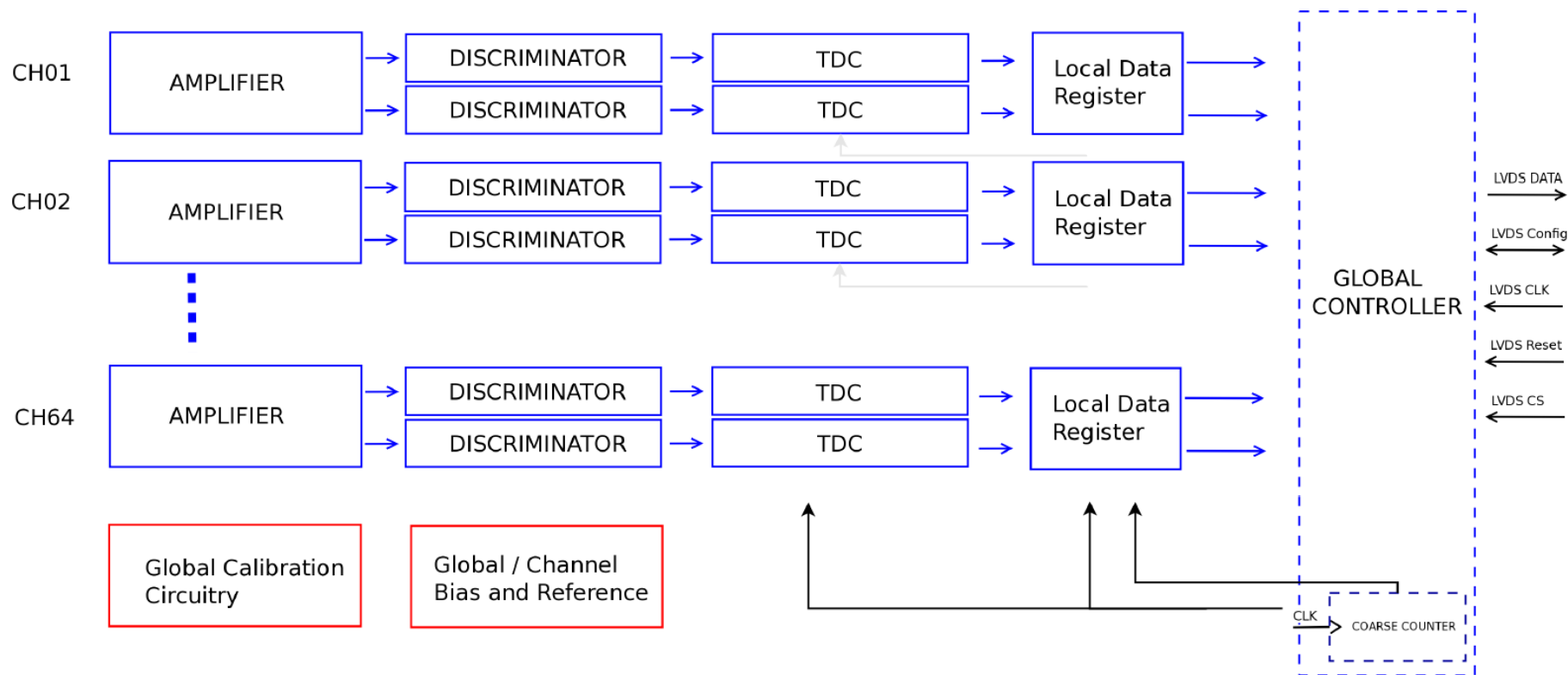
Time and amplitude measurement

- Threshold for time measurement adjustable in the range 0.5-15 p.e.
- Time-over-Threshold (ToT) with second discriminator
- Second discriminator used for trigger
- TDCs generate the time stamps t_1 and t_2



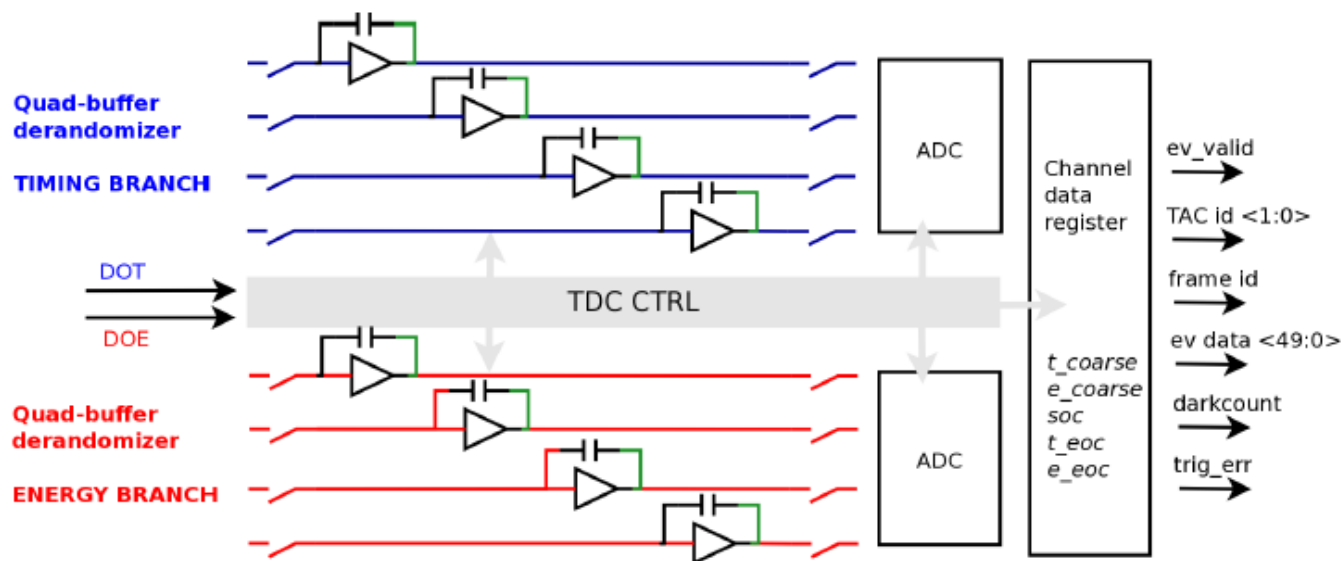
Overall chip architecture

- The TOFPET ASIC consists of a 64-channel analogue block, calibration circuitry, golden-references and bias generators and a global controller.
- Two transimpedance amplifier stages per channel: for time and energy measurement (trigger, shaped signals)

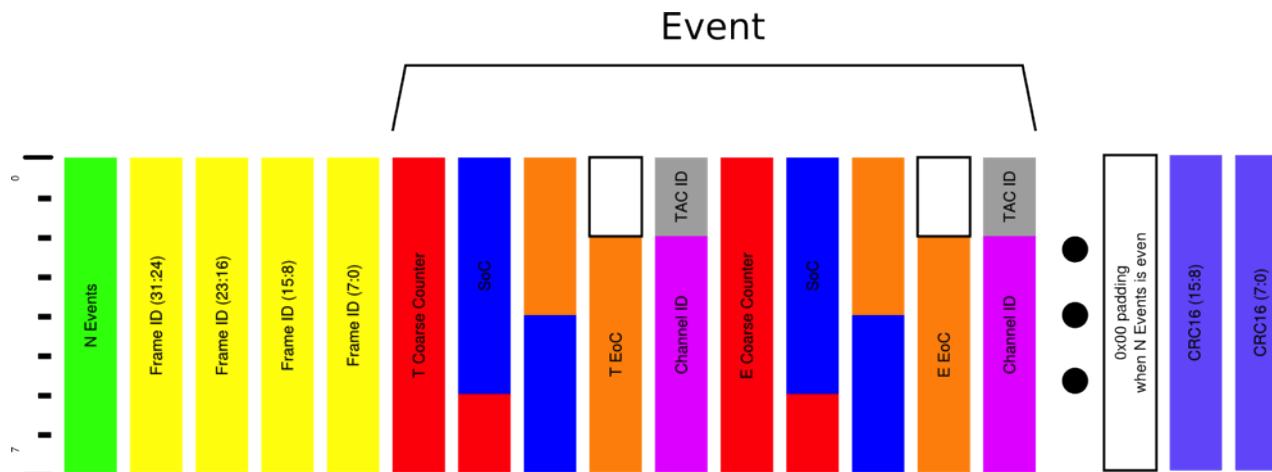


Time-to-digital converters

- **TDC with 25ps/50ps time binning** - based on analogue interpolators
- TDC Control: switching, hit validation, buffer allocation, data reg.
- Four TACs and data FIFOs per channel allow rate per channel of 160 kHz with negligible deadtime
- Time stamp: 10-bit master clock count + 10-bit fine time counter



- **The ASICs transmits data in frames**, each frame consisting of the events captured in a 1024 clock period (6.4 μ s frames).
- Up to 48 events per frame can be captured, each event including time counters and channel ID.
- **Max output rate is 6 M events/s**



- Innovative scheme for **dark count rejection** without triggering the TDC
- For SiPM characterization, **a dark count meter per channel is available.**
- Each channel has an embedded counter, incremented each time a signal triggers the low threshold but not the high threshold.

Summary of ToFPET chip specs

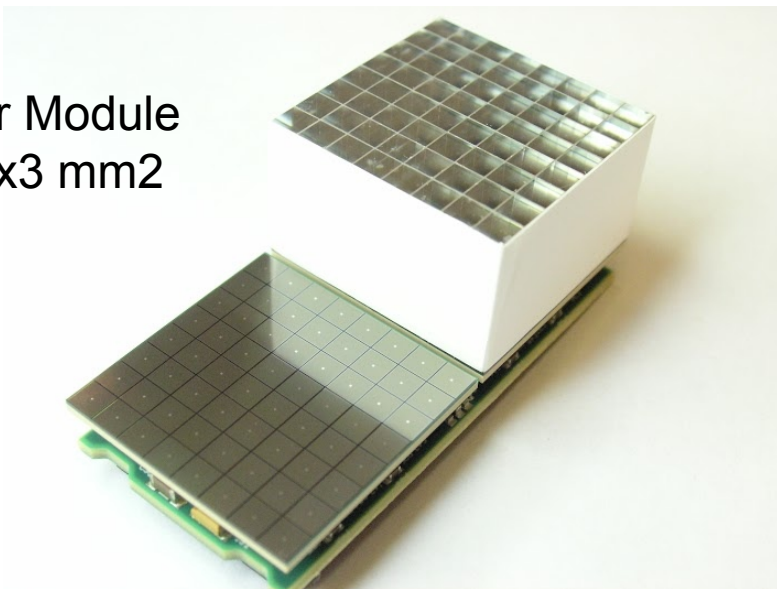
- Signal conditioning and discrimination circuitry and two high-performance TDCs for each of the 64 independent channels.
- TDC time binning: 50 ps (option 25 ps)
- Intrinsic time resolution 21 ps r.m.s.
- Charge measurement with time-over-threshold
- Dynamic range: 300 pC
- SNR ($Q_{in} = 200$ fC): 25 dB
- Coarse Gain: G_0 , $G_0/2$, $G_0/4$
- SiPM family supported: positive or negative signal polarity
- On-chip Calibration Circuitry: internal pulse generator, programmable 6-bit amplitude
- Max Channel Hit rate: 160 kHz
- Max Output Data Rate: 320 Mb/s (640 Mb/s with double-data-rate)
- Fully digital output, 2 data LVDS links DDR compatible
- Operation frequency 80-160 MHz
- Power per Channel: 8-11 mW
- SiPM HV fine biasing: range 500 mV

TOFPET ELECTRONICS

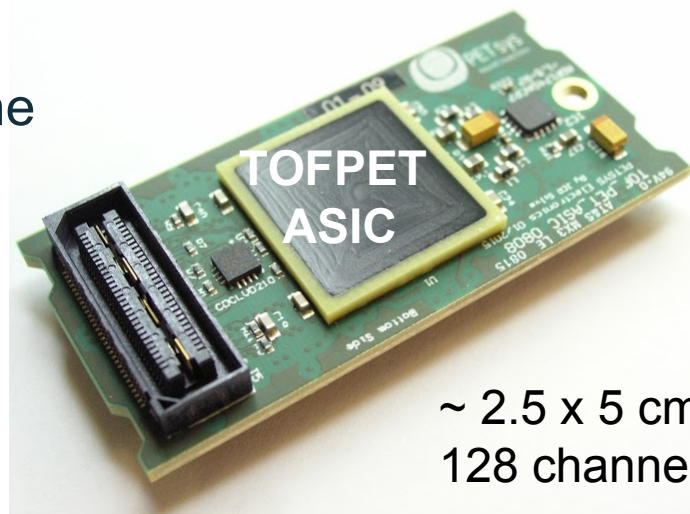
TOFPET Frontend Board

Our new, SiPM based, front end PET detector based on the TOFPET ASIC allows building the **most compact PET detector ever**.

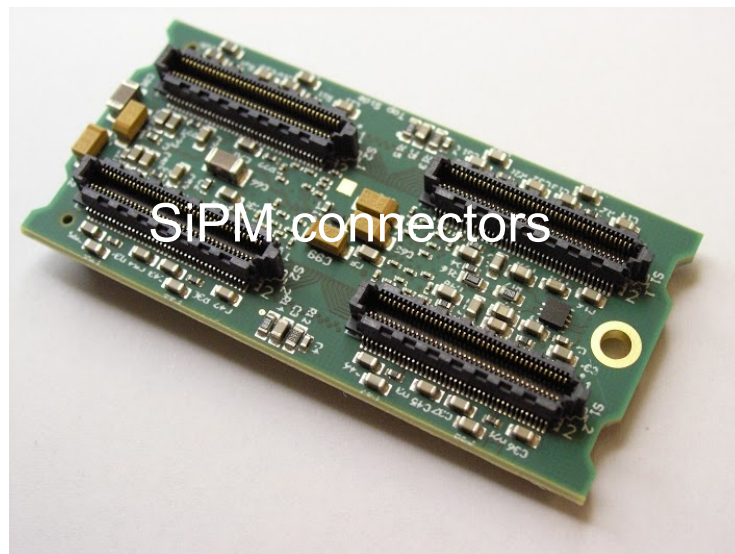
Detector Module
LYSO 3x3 mm²



Directly compatible with Hamamatsu
8x8 MPPC arrays

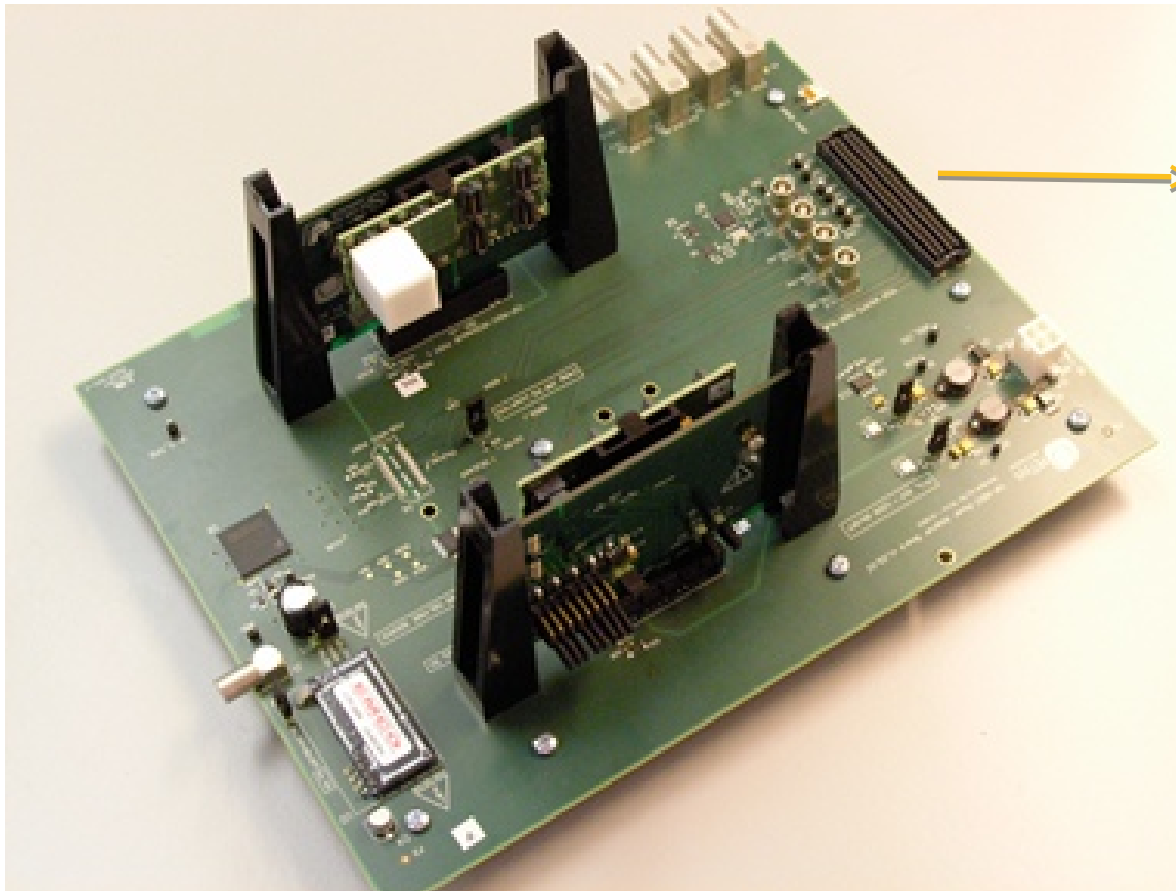


~ 2.5 x 5 cm
128 channels



TOFPET Evaluation Kit

Two frontend boards and power adapter board
Mezzanines with crystal matrices are placed face-to-face



Connector to Virtex
development kit and DAQ

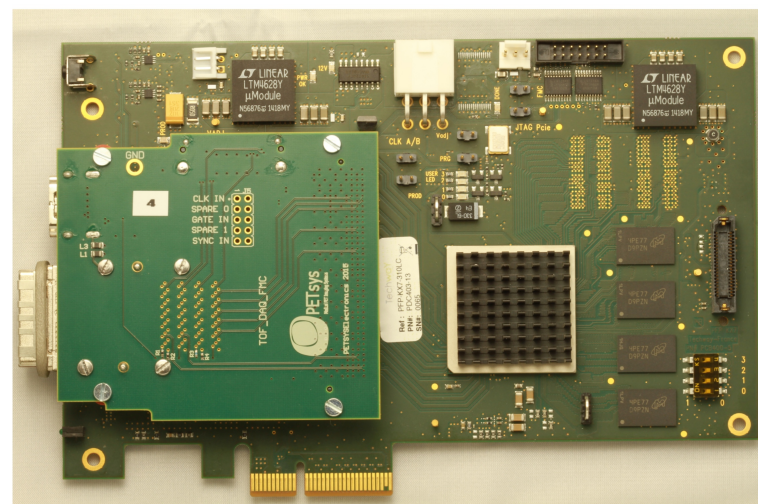
FEB/D Board:

- Data concentration and filtering based on Kintex 7
- Motherboard serving 1024 independent channels
- Data readout and configuration of 8 frontend boards
 - board-to-board or cable connection
- Output data serial links (1.6 Gbit/s) or high-speed optical links (2x8 Gbit/s)
- Daisy chaining of data and configuration links
- On board DC-DC converters (24 V external supply)
- On board SiPM bias voltage regulation (64 lines)

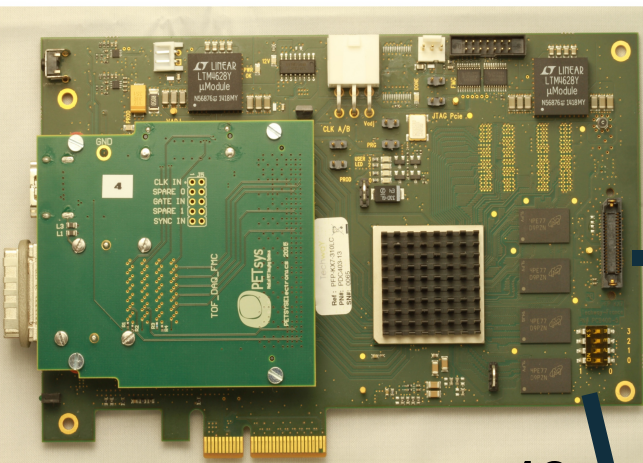


DAQ Board:

- 12 data links (electrical or optical) with total bandwidth 96 Gb/s
- Clock and synchronization signals
- Coincidence trigger in Kintex 7



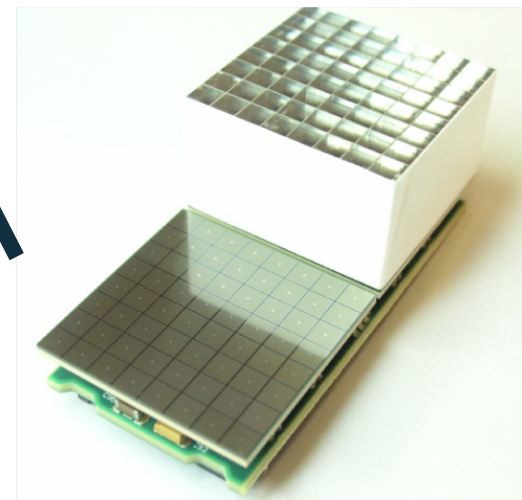
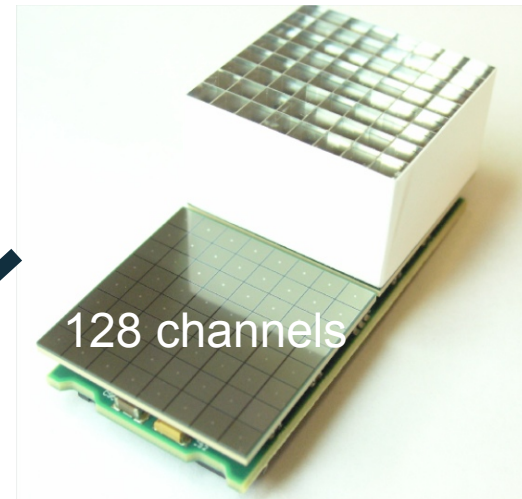
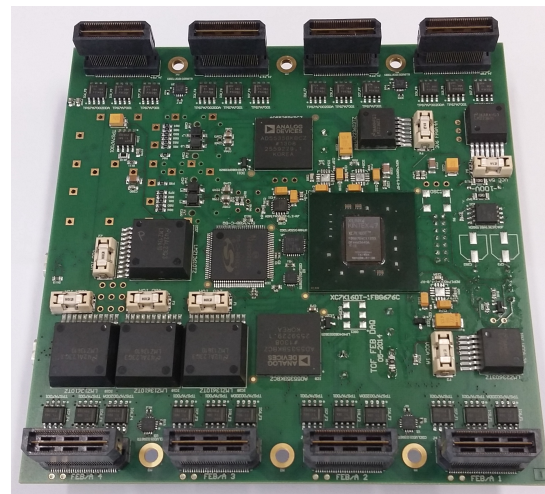
Allows building a PET scanner with many 10'000 channels



x 12



x 8



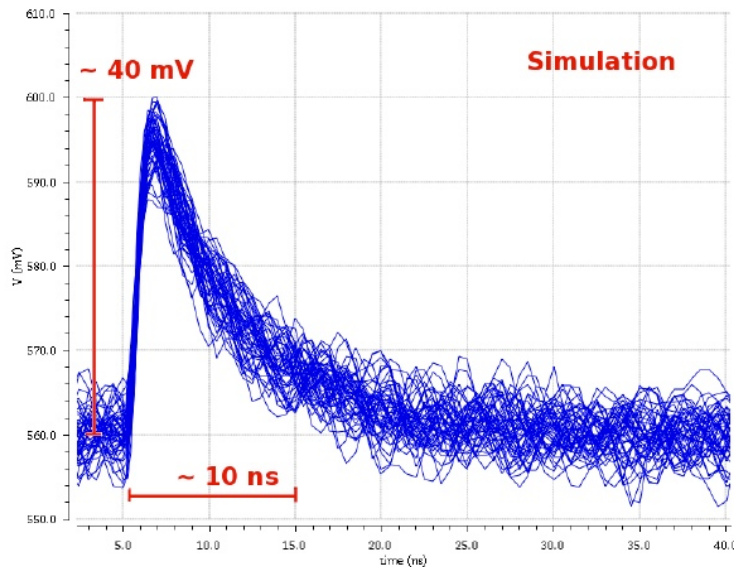
FEB/D daisy chaining
allows to extend the total
number of channels

TOFPET PERFORMANCE

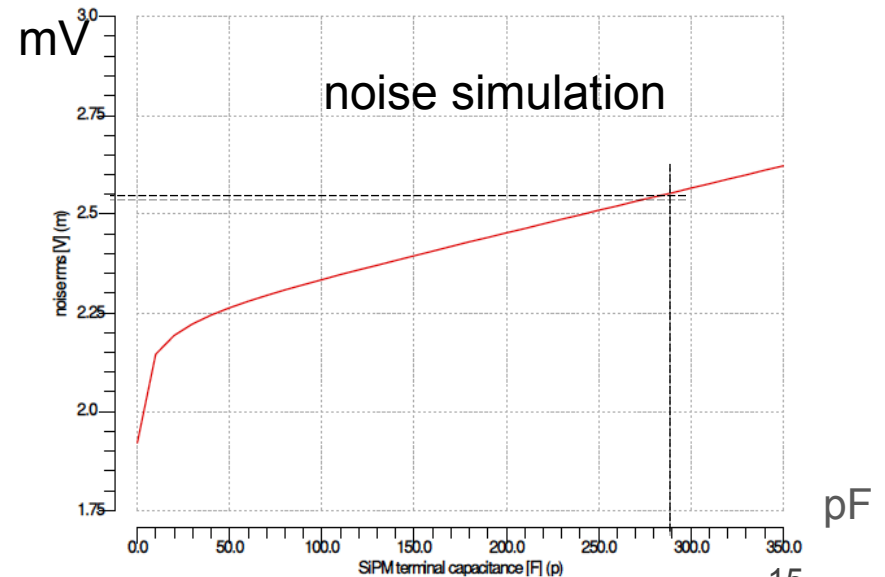
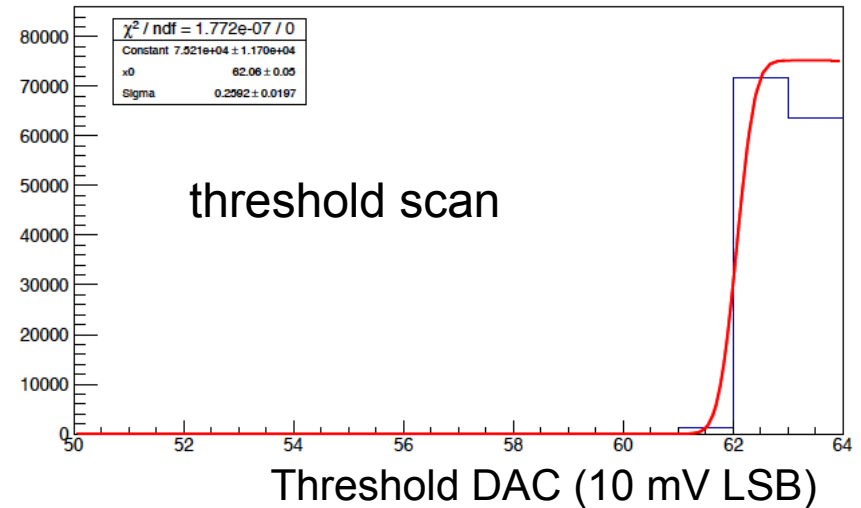
Single photon pulse and noise

Low-noise frontend

- Single photo-electron pulse amplitude is 40 mV
- Measured noise is 2.6 mV

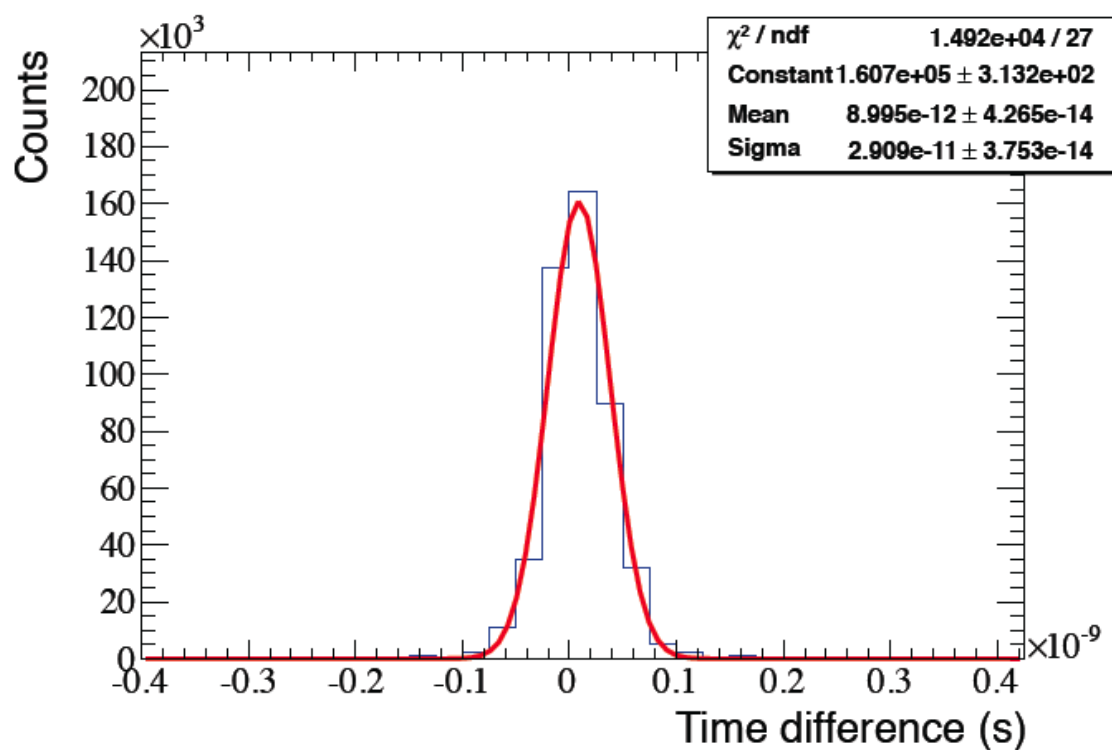


Noise counts - channel 2



Intrinsic time resolution

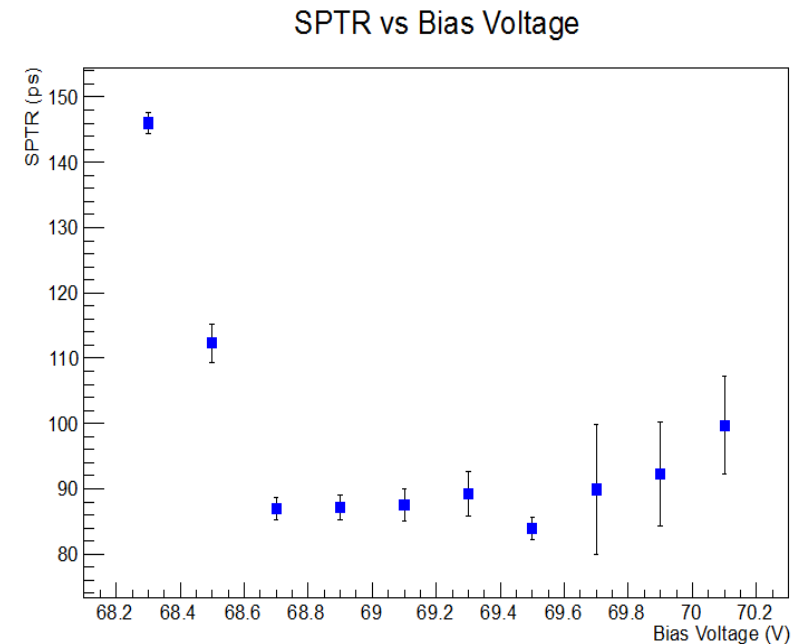
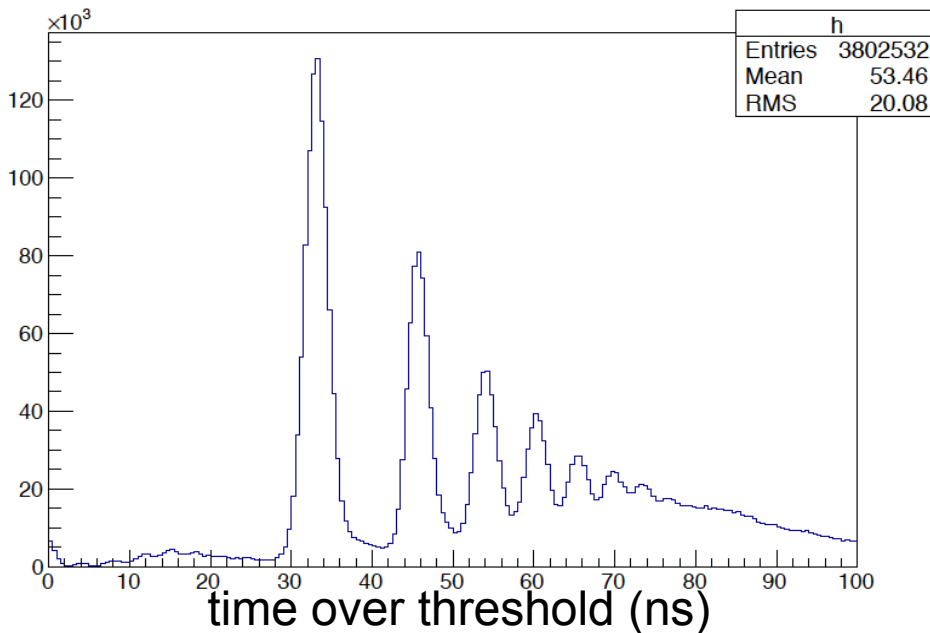
Distribution of the time difference between two channels triggered simultaneously by test pulse



Channel resolution

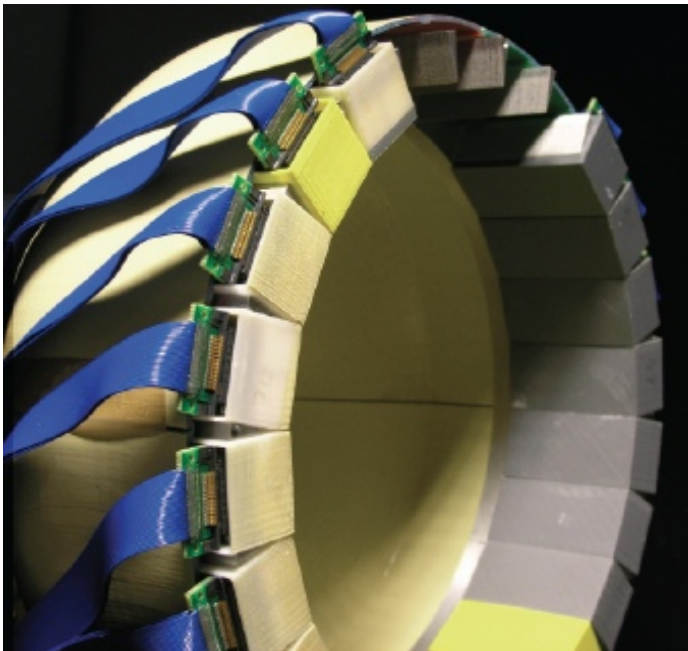
$\sigma = 21 \text{ ps r.m.s.}$

Single photon time resolution Measurements with PiLAS 420 nm laser light



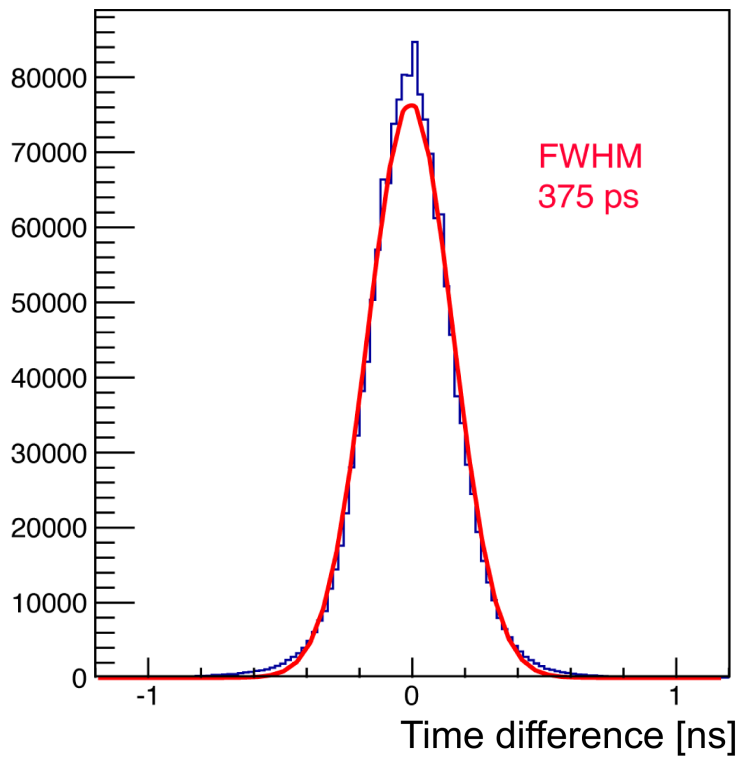
TOFPET demonstrator ring

- PET Scanner demonstrator ring
 - inner diameter of 230mm
 - presently 2/3 equipped
- 16 Detector Modules
- 2048 SiPM channels

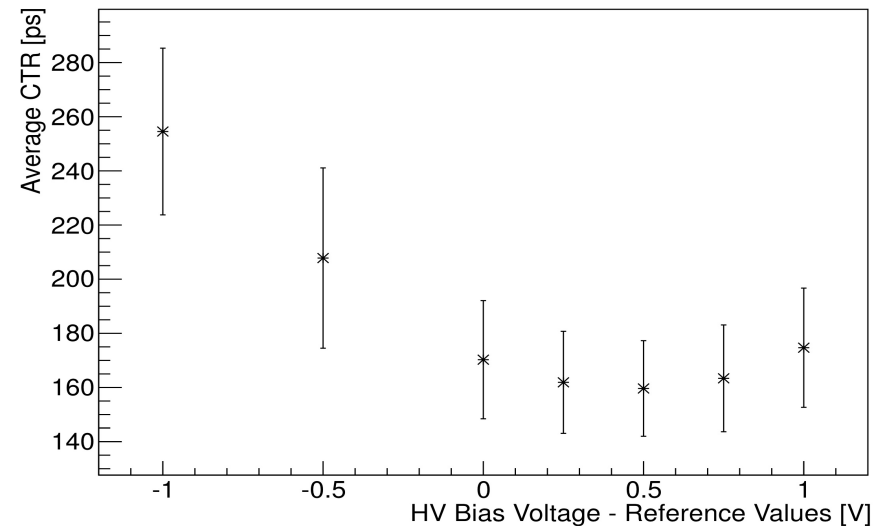


TOFPET demonstrator: timing performance

Coincidence time difference
(All Coincidence events within photopeak)

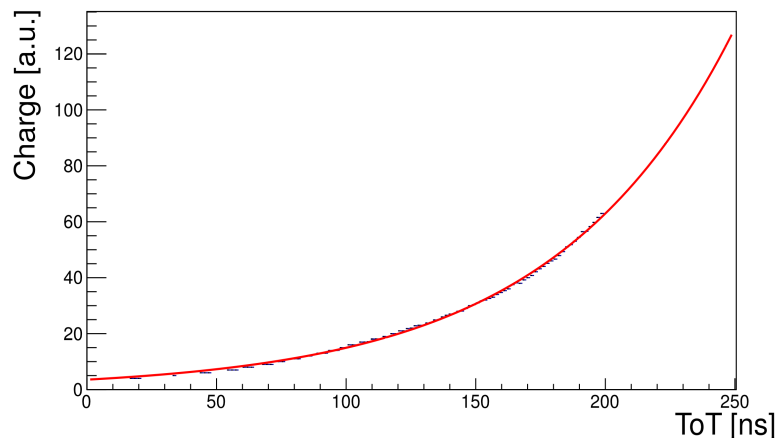


CTR HV Scan

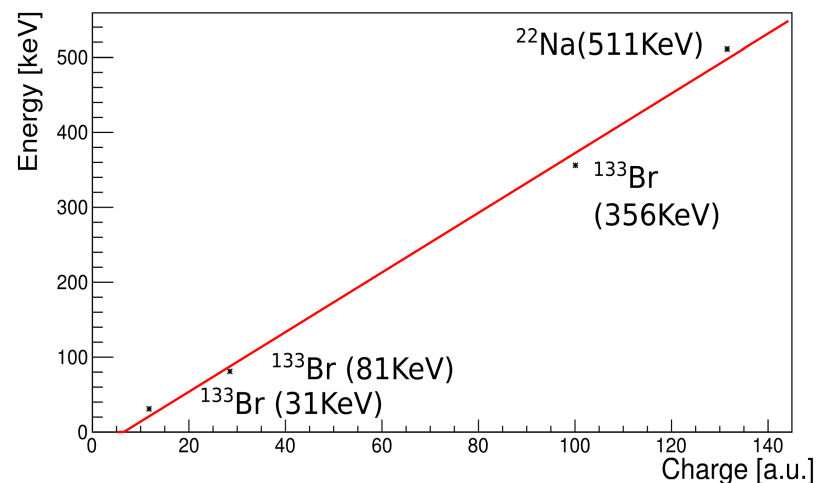


TOFPET demonstrator: Energy resolution

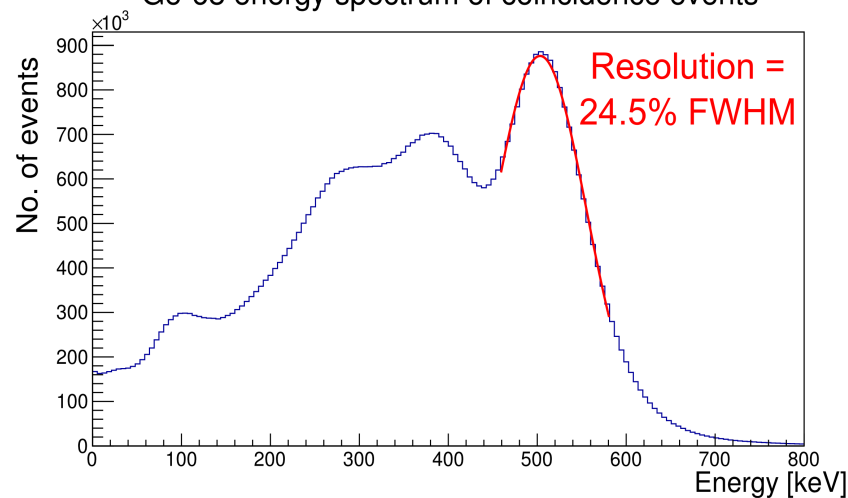
Input charge vs ToT characteristic curve



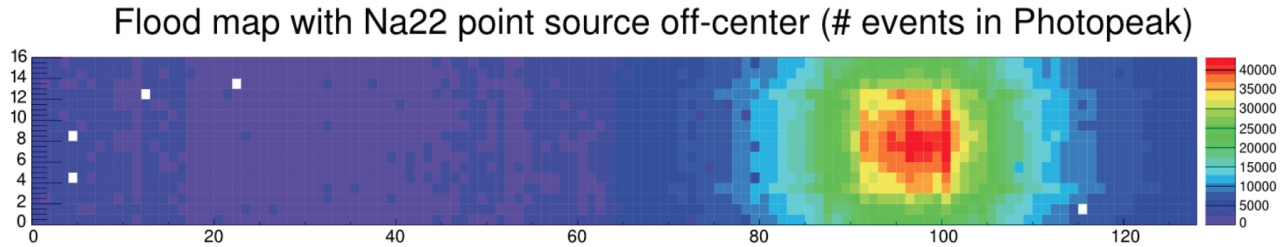
Energy scale correction



Ge-68 energy spectrum of coincidence events

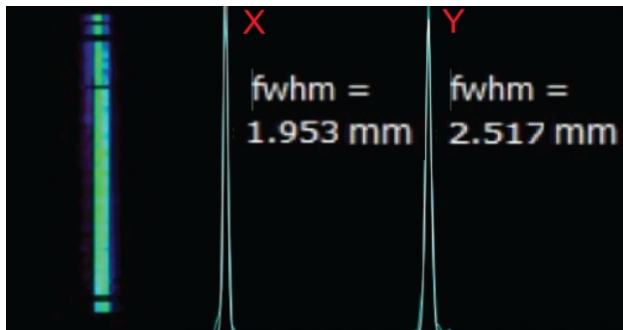


TOFPET demonstrator: Imaging

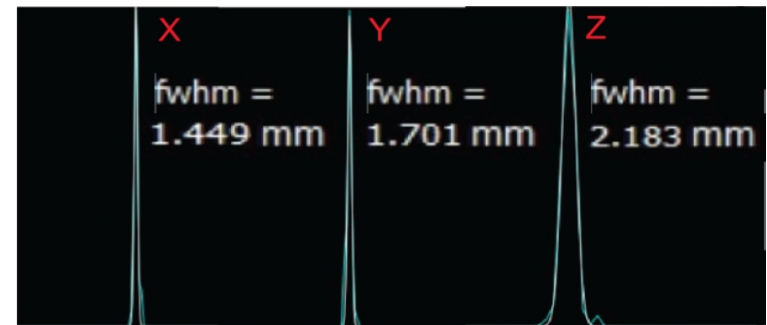


Reconstructed Spatial Resolutions

Ge68 Line source (1.5 mm diameter)



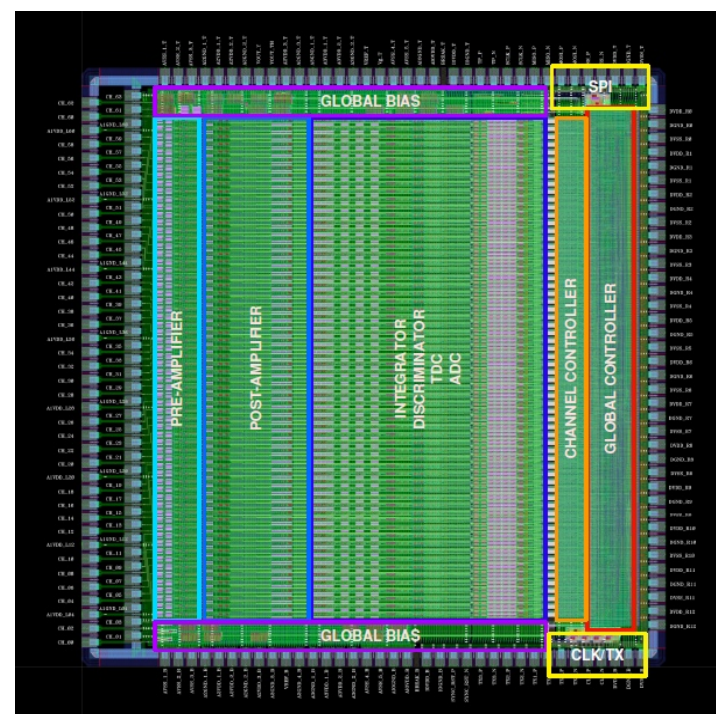
Na22 Point source (1 mm radius)



TOFPET2

- New version of TOFPET chip
 - I/O remains the same (but twice output links)
- Improved timing measurement
 - optimized for SiPM capacitance 320 pF
 - Aiming at PET CTR of 200 ps
- Linear pre-amplifier in the range 0-1500 pC
 - compatible with high gain SiPMs
- Linear charge integrator in the full dynamic range
 - ToT remains an option
- Event rate up to 600 kHz per channel
 - suitable for PET modules with light sharing
- Reduced power consumption
 - 5-8 mW/channel
- Silicon options:
 - low gain, low capacitance SiPMs
 - high gain, high capacitance SiPMs
- Submitted for fabrication

Newest version of the TOFPET ASIC



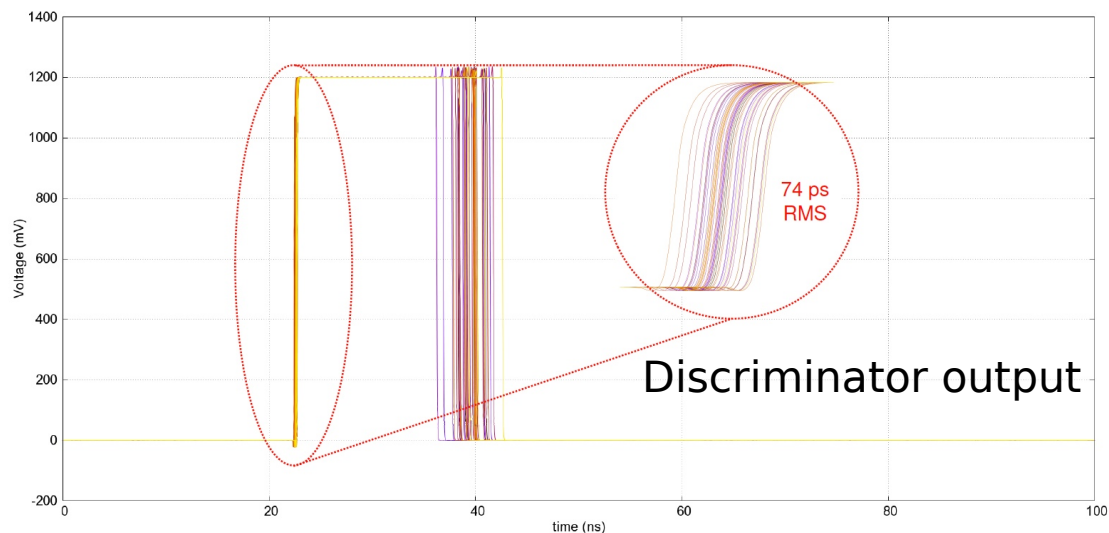
CMOS 110 nm
Die size 5x5 mm²

TOFPET2: full chip simulation

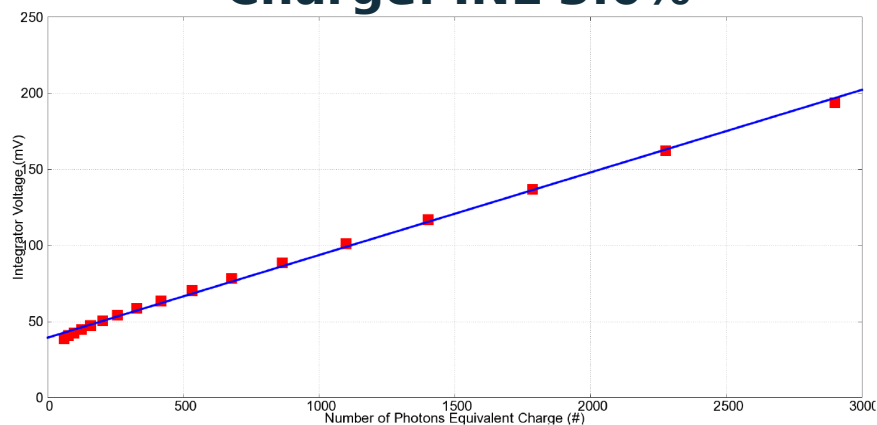
Single-Photon Time Resolution:

$\sigma = 39$ ps RMS
(G: 3.5×10^6)

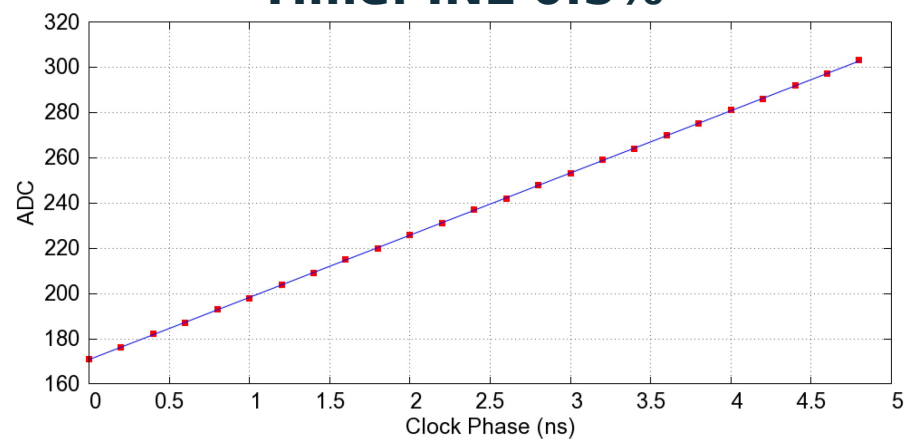
$\sigma = 74$ ps RMS
(G: 1.2×10^6)



Charge: INL 3.0%



Time: INL 0.5%



TOFPET2 design specs

- Signal amplification and discrimination for each of 64 independent channels.
- Dual branch quad-buffered analogue interpolation TDCs for each channel. The first branch is used for timing measurement. The second branch can either be used for time-over-threshold (ToT) or charge measurement (ADC).
- Quad-buffered charge integration for each channel.
- Dynamic range: 1500 pC.
- SNR ($Q_{in} = 200$ fC): 25 dB.
- TDC time binning: 50 ps (option 25 ps).
- Gain adjustment per channel: 1, 1/2, 1/4, 1/8.
- SiPM family supported: positive or negative signal polarity (terminal capacitance up to 320 pF guarantees SNR as above stated).
- On-chip calibration circuitry: internal pulse generator with programmable amplitude.
- Max channel hit rate: 600 kHz.
- Rejects dark counts without triggering, allowing to handle in excess of 1 MHz of dark counts.
- Configurable timing, trigger and ToT thresholds.
- Fully digital output, 4 LVDS data links DDR compatible.
- Low latency trigger data (channels above threshold)
- Max output data rate: 3.2 Gb/s.
- Operation frequency: 200 MHz.
- Power per channel: 5-8 mW.

For more information visit **www.petsyselectronics.com**
or send email to **info@petsyselectronics.com**

Thank you for your attention