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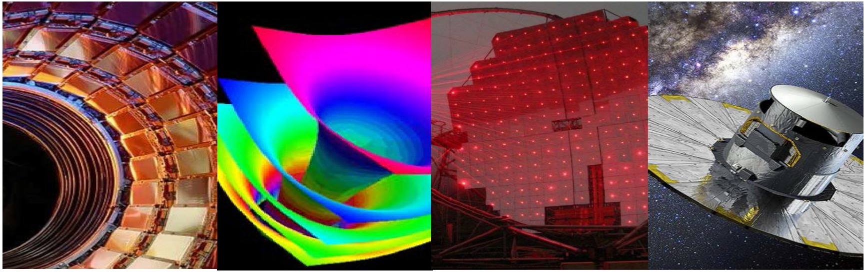

Towards scalable sub-100 ps ToF-PET systems with the FastIC ASIC

D. Guberman, J. M. Fernandez-Tenllado, D. Gascon, S. Gómez, R. Manera, A. Mariscal, J. Mauricio, S. Portero, A. Sanmukh, A. Sanuy, J. Silva, J. Alozy, E. Auffray, R. Ballabriga, M. Campbell, N. Kratochwil, M. Piller, G. Arino-Estrada, S. Majewski, G. Borghi, A. Gola, R. Pestotnik, G. El Fakhri.

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Portorož, 5 September 2022

Universitat de Barcelona

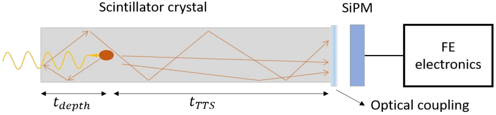
Outline

1. ASICs and front-end electronics in ToF-PET.
2. FastIC basics
3. FastIC performance
4. Future developments

Front-End electronics in ToF-PET scanners

Time resolution of a **ToF-PET** system depends on:

- Scintillators
- Photodetectors
- **Readout electronics + DAQ**



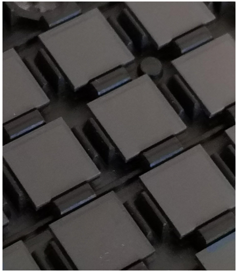
$$t_{jitter} = t_{depth} + t_{scint.} + t_{TTS} + t_{SPTR} + t_{elec.}$$

- FE electronics: **High bandwidth** and **low electronic** noise help reducing the electronic jitter but…
- **Power consumption**, **compactness** and **cost** are relevant when aiming to build a **scanner** with several thousand pixels
- **ASICs** offer a **scalable** solution: large-scale production, versatile, on-chip digitization
  Some Examples: NINO, Weeroc series, FlexToT family, TOFPET2 (PETsys), **FastIC**.

FastIC: towards scalable sub-100 ps ToF-PET scanners

FastIC goal is to optimize the performance of ToF-PET modules with a technology that can be easily scaled to full-body scanners…

- 8 input channels (e.g. SiPMs) per chip ➔ Output as binary pulses
  - ➔ Can be easily acquired with a TDC (e.g., in an FPGA)
- Compact electronics allows to mount a few ASICs in the same board
  - ➔ Allows for mass production of compact modules of ~16 (32) SiPMs.
- Typical power consumption: ~11.5/mW channel

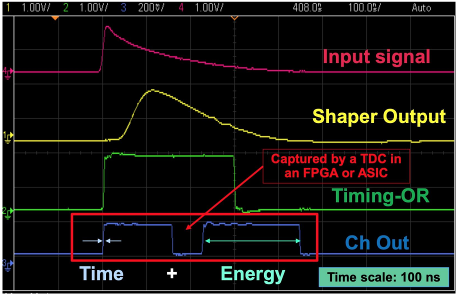


… while aiming to achieve sub-100 ps Coincidence Time Resolution (CTR)

Joint work of ICCUB and R. Ballabriga et al. (CERN Microelectronics group)

FastIC basics

- FastIC can readout up to 8 photodetectors (e.g. SiPMs)
- It outputs the **arrival time** and **energy** of each channel as **two consecutive binary pulses.**

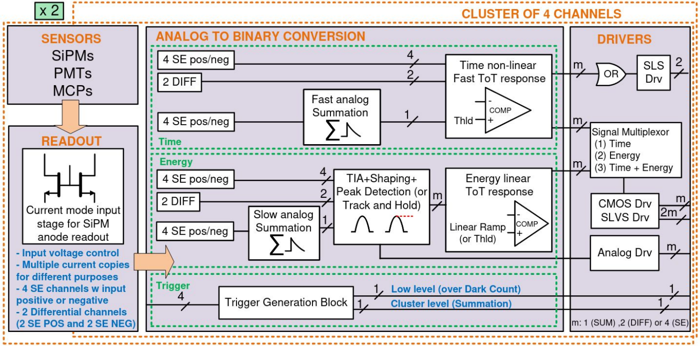


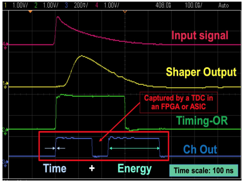
- **Time** is encoded in the **rising edge** of the **first pulse**.
- **Width** of **second pulse** gives the **Energy**[1]
- An additional binary pulse with the **trigger signal** is also output (**Fast-OR**)

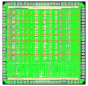
[1] Based on HRFlexToT architecture: *Sanchez, D., et. al. HRFlexToT: A High Dynamic Range ASIC for Time-of-Flight Positron Emission Tomography, 2021, IEEE TRPMS, https://doi.org/10.1109/TRPMS.2021.3066426*

FastIC ASIC Architecture

- **8 Inputs** for 8 single ended (SE) or 4 differential (DIFF) channels.
- **OUTPUT: Arrival time** per channel **and Fast OR** between all of them.
- **OUTPUT: Energy** per channel, as a Linear Time over Threshold with high dynamic range.







65nm - 2 x 2 mm^2

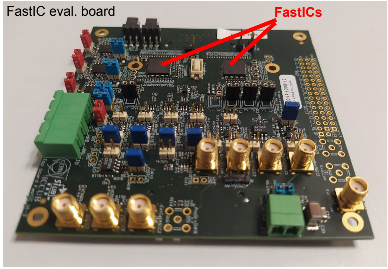
- Designed to work with different sensors (SiPMs, PMTs, MCPs) with different polarities.
- Possibility to perform an **analog summation** of **up to 4 SE channels**.
- Individual triggers/cluster trigger can be modified
- **Power consumption:** SE 12 mW/ch, SUM 29 mW/ch.
- 3 Output modes: SLVS, CMOS, Analog.

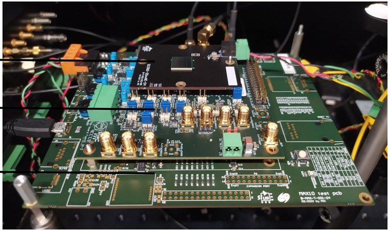
Joint work with R. Ballabriga et al. (CERN Microelectronics group)

Evaluation board

- FastIC evaluation board
  - (Almost) Plug-and-play
  - Holds 2 ASICs
  - Can readout up to 16 channels
  - Dedicated input for pulse injection
  - Allows to probe intermediate analog stages

- FPGA board
  - Programs the ASICs
  - Controls the acquisition
  - 50 ps bin TDC implemented (being tested)





Joint work with R. Ballabriga et al. (CERN Microelectronics group)

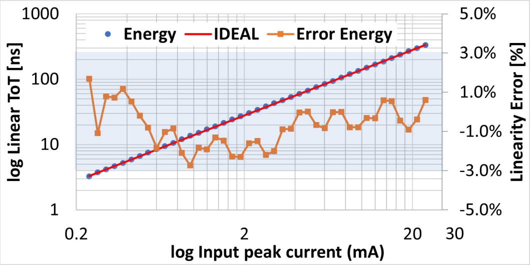
FastIC Performance

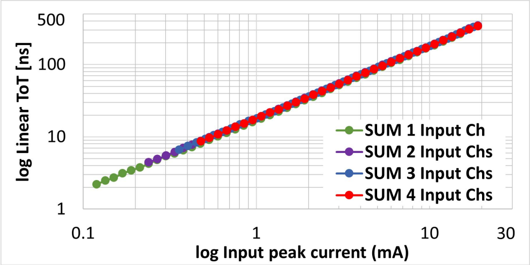
- *Linearity and Dynamic Range*
- *Single-Photon Time Resolution (SPTR)*
- *Energy Resolution with a LSO crystal*
- *Coincidence Time Resolution (CTR) with LSO crystals*

Linearity of the Energy and dynamic range

- Saturation is reached at input currents of +25 mA, -20 mA →Typical Dynamic range ~ a few thousand phe
- Linearity error is below 3% over the whole dynamic range.
- Summation is also linear.

➔ FastIC is suitable for standard PET radiators

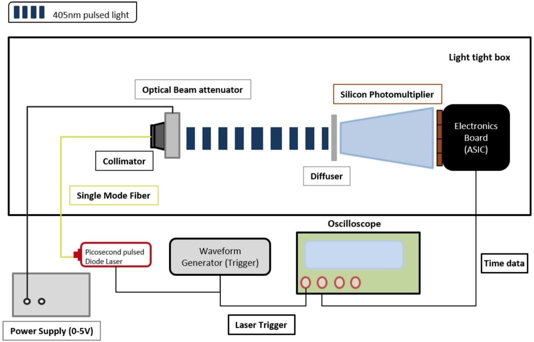


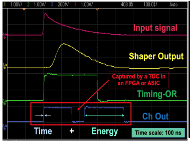


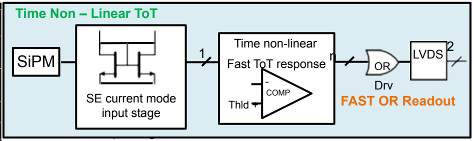
Measurements performed injecting an electrical signal in the FastIC input

Single Photon Time Resolution (SPTR) experimental Setup

- Pulsed Diode Laser (A.L.S. PiL040X) at 405 nm (jitter < 3 ps, pulse width < 45 ps).
- A **single SiPM** is enabled at the FastIC input. We look at the **Fast-OR (trigger) output** (non-linear ToT)
- FastIC output is readout by an Agilent MSO 9404A 4 GHz oscilloscope (20 GS/s)
- We measure the time **arrival time** and pulse **width** of the Fast-OR signal.



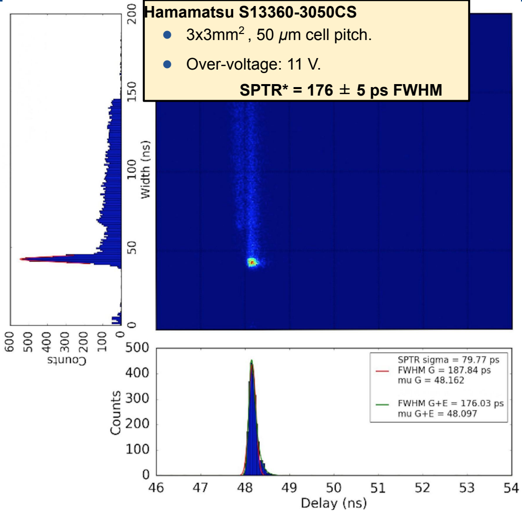




SPTR results

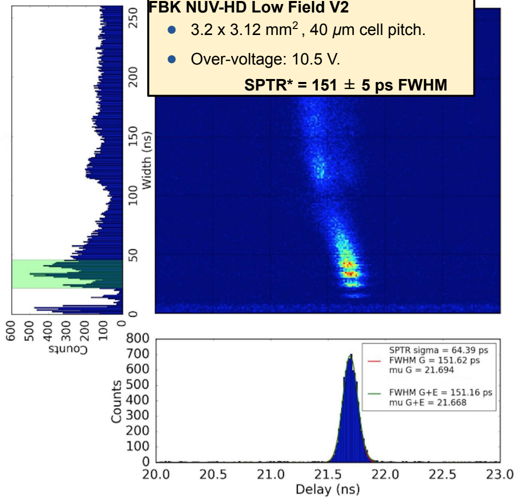
Hamamatsu S13360-3050CS
- $3x3mm^2$, 50 μm cell pitch.
- Over-voltage: 11 V.

SPTR* = 176 ± 5 ps FWHM



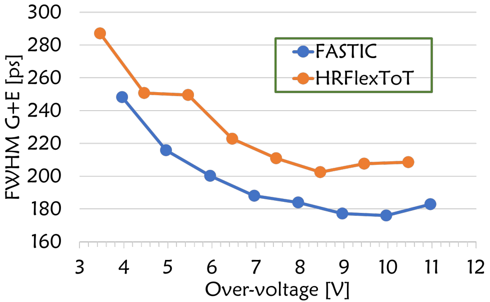
FBK NUV-HD Low Field V2
- $3.2 \times 3.12\ mm^2$, 40 μm cell pitch.
- Over-voltage: 10.5 V.

SPTR* = 151 ± 5 ps FWHM



***SPTR of the full system (SiPM+ASIC+laser jitter)**

Comparison with HRFlexToT (SPTR)



FastIC best: **176 ± 5 ps FWHM**

HRFlexToT best: **202 ± 6 ps FWHM**

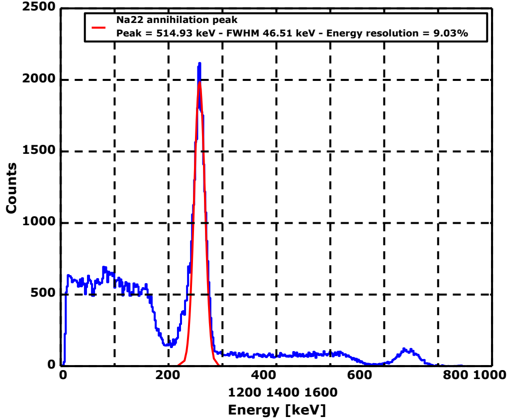
Both measurements with Hamamatsu S13360-3050CS (3x3 mm^2 50 μm cell pitch.)

VERY Preliminary Energy resolution

- TDC implemented in the FPGA is used as DAQ
- Hamamatsu S13360-3050PE SiPM (3 x 3 mm^2, operated at 3V over-voltage)
- **Crystal**: LYSO:Ce:02%Ca, **3.13 x 3.13 x 20 mm^2**

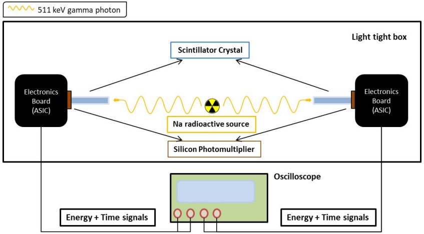
  LY=39.2 ph/keV. Decay Time=32.6 ns.

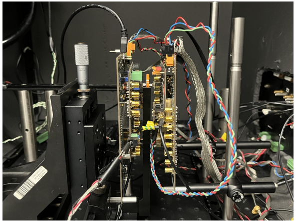
Energy resolution @ 511 keV ~ 9%



Coincidence Time Resolution (CTR) experimental setup

- Radioactive source: ^{22}Na, 330 kBq (2018).
- Agilent MSO 9404A 4 GHz oscilloscope (20 GS/s).
- Meltmount for optical coupling
- Temperature stabilization at 16°C.
- Threshold set at ~0.5 phe in all channels.
- Oscilloscope coincidence window: 25 ns



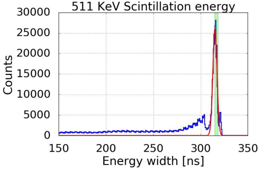


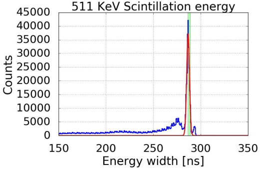
CTR results

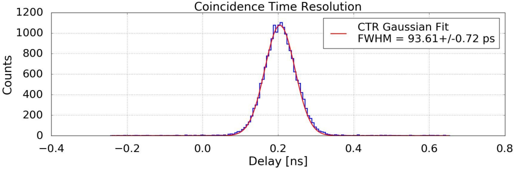
Crystal: LSO:Ce:02%Ca, **2 x 2 x 3 mm^3**

Hamamatsu S13360-3050PE/VE

- 3x3mm^2 , 50 μm cell pitch
- Over-voltage: 8 V.



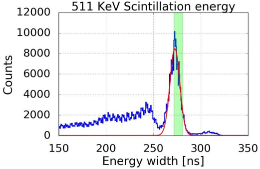


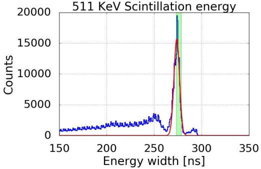


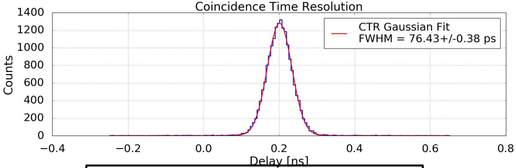
CTR = 93 ± 3 ps FWHM

FBK NUV-HD Low Field V2

- 3.2 x 3.12 mm^2 , 40 μm cell pitch.
- Over-voltage: 6.1 V.







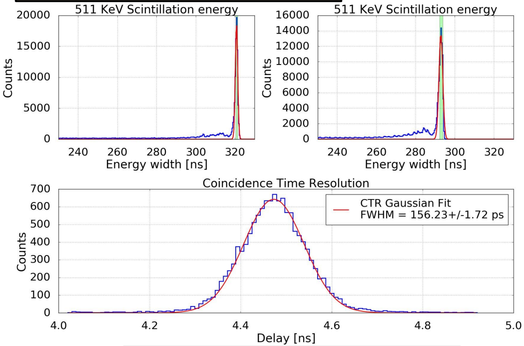
CTR = 76 ± 2 ps FWHM

CTR results

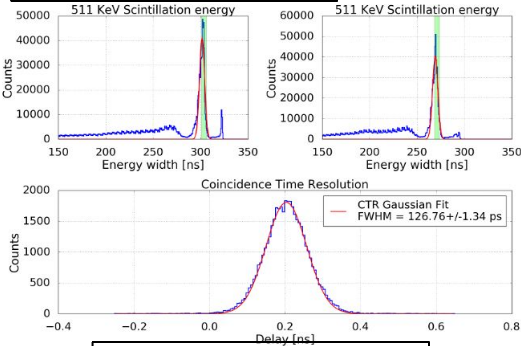
Crystal: LSO:Ce:02%Ca, **3.13 x 3.13 x 20 mm^3**

Hamamatsu S13360-3050PE/VE
- 3x3mm^2 , 50 μm cell pitch
- Over-voltage: 9 V.

FBK NUV-HD Low Field V2
- 3.2 x 3.12 mm^2 , 40 μm cell pitch.
- Over-voltage: 7.1 V.



CTR = 156 ± 4 ps FWHM



CTR = 126 ± 4 ps FWHM

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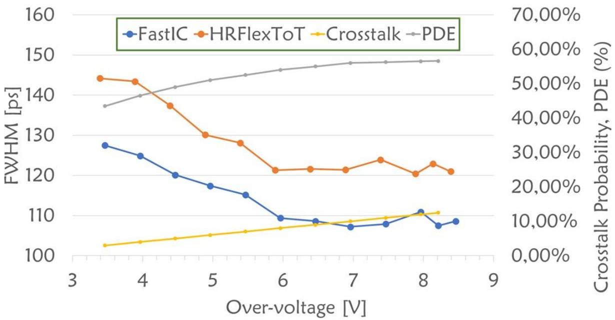
FastIC vs HRFlexTot: CTR

- **Crystal**: LSO:Ce:02%Ca, **2 x 2 x 5 mm²**
- Hamamatsu S13360-3050CS SiPM (3 x 3 mm²)

FastIC best: **104 ± 3 ps FWHM**

HRFlexToT best: **117 ± 3 ps FWHM**



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Comparison with other fast-timing ASICs

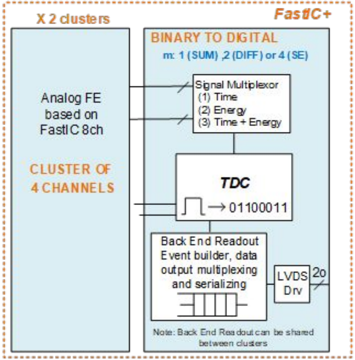
ASIC	LSO size [mm^3]	SiPM	CTR (FWHM) [ps]	Input channels	Output mode	Power consumption [mW/ch]
NINO [1, 2]	2x2x3	FBK NUV-HD	73 ± 2	8	Binary (non-linear ToT)	~27
Petiroc2A [3]	2x2x5	FBK NUV-HD	~86 (analog) ~127 (digital)	32	Digital	~6
PETsys TOFPET2 [4]	2x2x3	Broadcom AFBR-S4N33C013	118 ± 5	64	Digital	~8
HRFlexToT [5]	2x2x5	Hamamatsu S13360-3050CS	117 ± 3	16	Binary (Time +Energy)	~4
FastIC	2x2x3	FBK NUV-HD	76 ± 3	8	Binary (Time +Energy)	~12
FastIC+/+32	**-**	**-**	**?**	**8/32**	**Digital**	**~10**

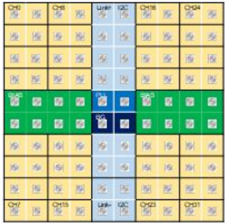
Thanks to N. Kratochwill for collecting most of the data needed to build this table

[1] F. Anghinolfi et al. 2004, NIM-A, 533, 183–187
[2] Stefan Gundacker et al 2019 Phys. Med. Biol. 64 055012
[3] Ahmad et al 2018, IEEE NSS/MIC CR
[4] Nadig et al.: A comprehensive study on the timing limits of the TOFPET2 ASIC and on approaches for improvements, IEEE TRPMS 2022
[5] Sanchez, D., et. al. HRFlexToT: A High Dynamic Range ASIC for Time-of-Flight Positron Emission Tomography, 2021, IEEE TRPMS

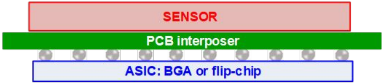
Next Generation FastIC

- **FastIC+ (+32): 8 (32) input channels** and will include a **TDC** with **25 ps bins**
- **GOAL:** Signal processing, digitization of time and energy and Gbit/s serialization with ~ 10 mW/ch.
- **Pixelated structure:** 2.5 D (BGA, flip-chip, etc) or 3D integrated in order to minimize interconnect parasitic to achieve best timing[4].





FASTIC+32



Joint work with R. Ballabriga et al. (CERN Microelectronics group)

[4] J. M. Fernández-Tenllado, et al., "Optimal design of single-photon sensor front-end electronics for fast-timing applications," IEEE NSS/MIC 2019,doi: 10.1109/NSS/MIC42101.2019.9059805.

Conclusions

- FastIC is proposed as an ASIC for large ToF-PET scanners with sub-100 ps CTR
- FastIC provides a competitive performance with relatively low power consumption
- Allows for the development of compact modules that could be easily scaled to large numbers.
- Best **CTR ~76 ps FWHM** with a **2x2x3 mm^3 LSO:Ce:02%Ca** crystal + FBK SiPM (~126 ps FWHM with a **3.13x3.13x20 mm^3** crystal).
- Currently testing a TDC in our FPGA board
- **New ASIC version** under development will **include a TDC** on chip (~25 ps time bin)
- Not only ToF-PET: FastIC suitable for other fast-timing applications!

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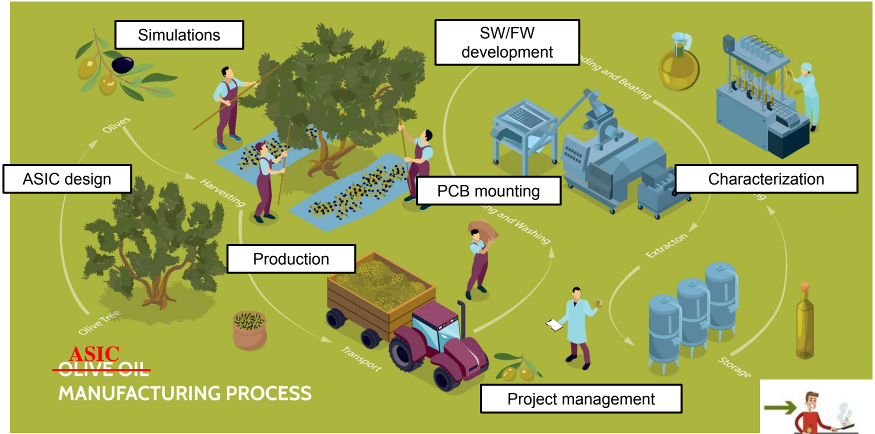
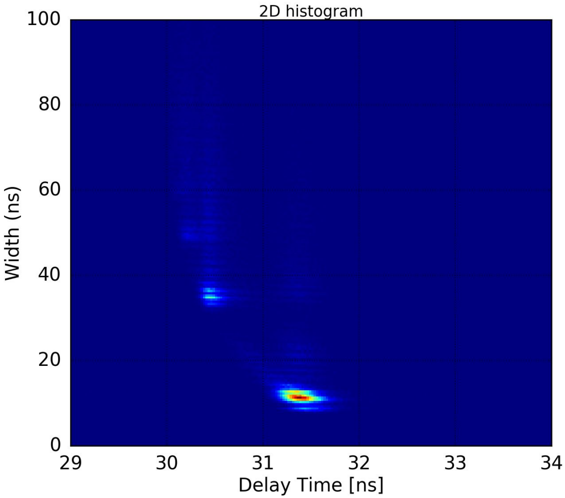


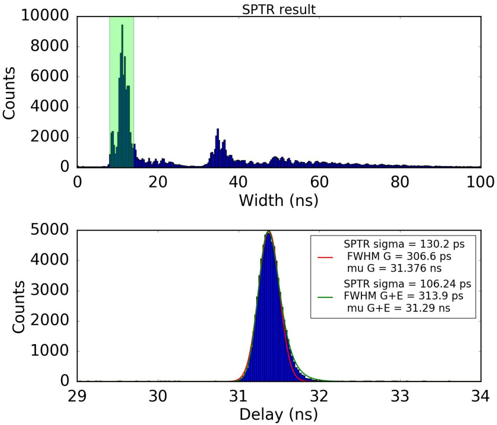
Special thanks to S. Gómez and A. Mariscal for preparing most of the slides and plots shown in this presentation

Image credits: Vecteezy

BACK UP

Example of an SPTR measurement





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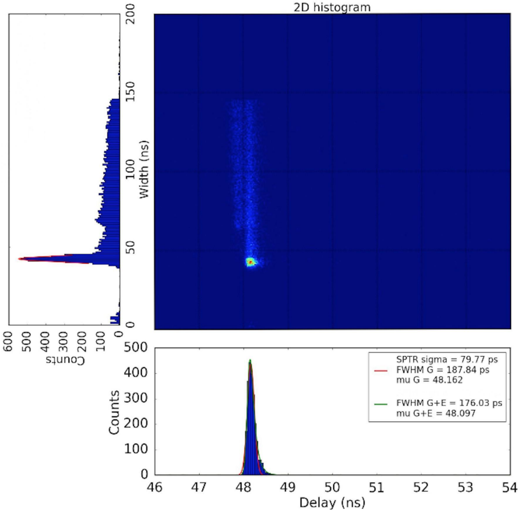
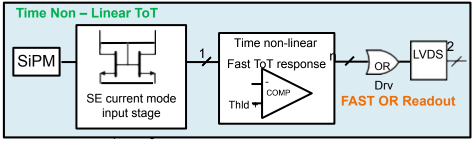
Example of an SPTR measurement

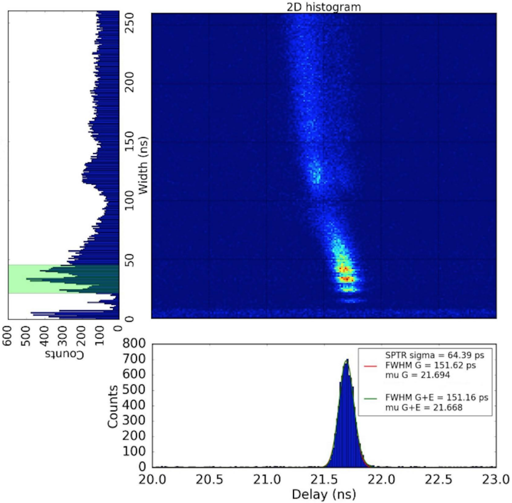
SiPM: HPK S13360-3050CS (3x3 mm^2 50 μm cell pitch.)

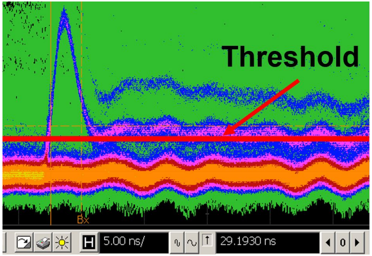




- The threshold of the comparator is set at ~0.5 phe
- We measure the pulse width and arrival time (delay) of the Fast-OR signal
- Single-phe events are identified in the Width vs Delay plot.

FBK SiPM ringing



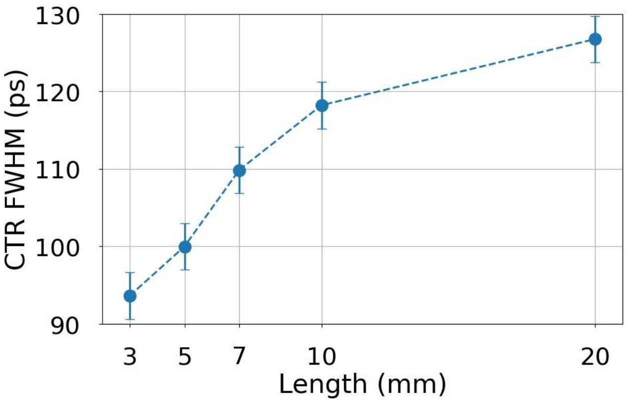


Baseline fluctuations + ringing on signal tail cause this non-uniform width distribution for the 1st PE.

Performance vs crystal length

- **SiPM** : FBK NUV-HD LF V2.
- **Crystal:** LYSO:Ce:02%Ca

  Area = 3.13x3.13 mm^2.
- Degradation of the CTR as the crystal length increase, as expected[3].



[3] Gundacker, S. et al. Time resolution deterioration with increasing crystal length in a TOF-PET system. 2014, NIMA

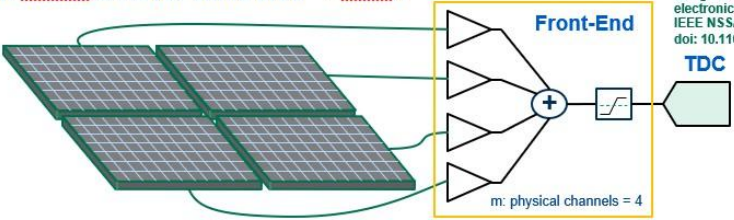
- Different LYSO crystals of 20 mm length were measured from different manufacturers.
- **SiPM: HPK S13360-3050PE**.
- **Reference crystal: LSO:Ce:0.2%Ca**. 2x2x3 mm^3. DTR FWHM = 66 ± 4 ps.

Crystal (Manufacturer)	Size [mm^3]	CTR measured FWHM [± 3 ps]	Light Yield [phe/keV]	Decay Time [ns]
LYSO:Ce:Ca 0.2% (CP)	3.13x3.13x20	120	45	40
LYSO:Ce (EPIC)	3x3x20	125	29	42
LYSO:Ce (Saint-Gobain)	3x3x20	120	33.2	36

- Additionally, crystals with section sizes similar to the SiPM section are more difficult to couple, which results in a possible loss of light.

- **Segment SiPMs to cover same area → Cdet/4**

J. M. Fernández-Tenllado, et alt, "Optimal design of single-photon sensor front-end electronics for fast-timing applications," IEEE NSS/MIC 2019, doi: 10.1109/NSS/MIC42101.2019.9059805.



- Segmentation: Cover same area with m smaller sensors.
  - Potential improvement of the slew-rate by a factor of m (i.e $SR \propto m \frac{Q_{det}}{C_{det}}$)
  - Series noise contribution is approximately constant w.r.t. segmentation
    - (i.e. $\sigma_n \sim \sqrt{m} \cdot \sigma_{n,smallDet} \sim \sqrt{m} \cdot \frac{\sigma_{n\,largeDet}}{\sqrt{m}}$)

Potential reduction of σ_t by a factor m

Too simplistic, see [3]:

Sum of m uncorrelated contributions

The series noise is proportional to the detector capacitance, which reduces a factor *sqrt(m)*