Sub-100 ps Coincidente Time Resolution for ToF-PET detectors using FastIC

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Introduction

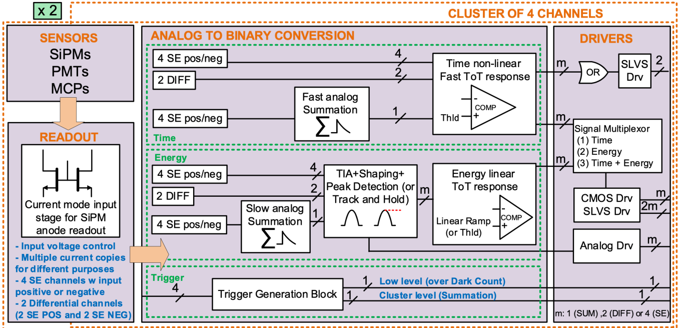
- **FastIC**: **multipurpose front-end readout** for **NEG/POS polarity detectors with intrinsic gain** (SiPM, PMT, MCP). It was **jointly developed by UB and CERN.**
- **Objective**: **Evaluate the FastIC for PET applications** as well as the **new SiPM technology developed by Fondazione Bruno Kessler (FBK)**.

FastIC architecture

FastIC current mode ASIC.

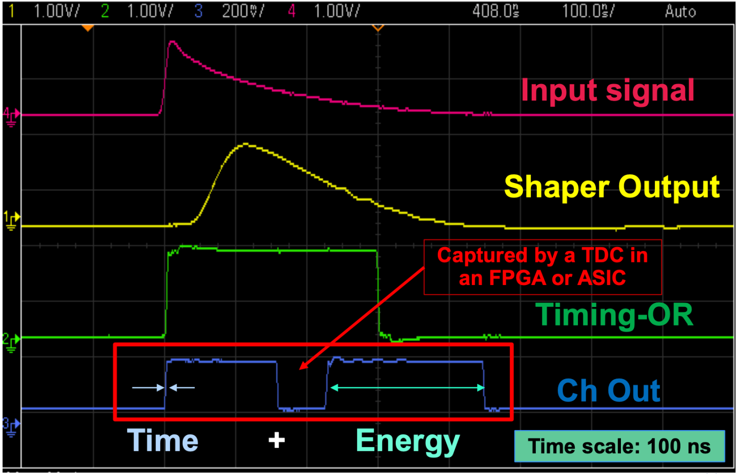
- 8 Inputs:
  - 8 Single Ended (POS/NEG)
  - 4 differential
  - Summation (POS/NEG) in 2 clusters of 4 channels
- Power consumption ≈ 12 mW/ch.

- 3 Output modes:
  1. SLVS
  2. CMOS
  3. Analog
- Arrival time per channel and Fast OR between all of them.
- Energy: Linear Time over Threshold with high dynamic range.



Time + Energy readout

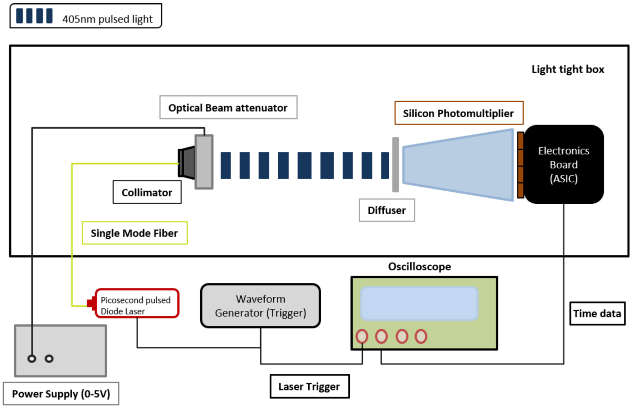
- Outputs the **TIME** and **ENERGY** of each channel as two binary pulses



SPTR: Set-up

The setup is as follows:

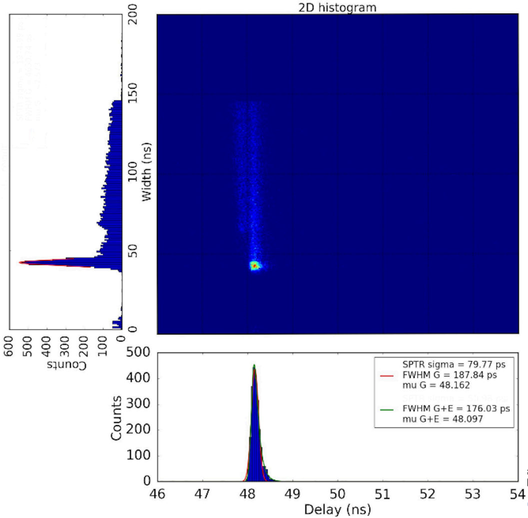
- Advanced Laser Diode Systems A.L.S. GmbH (PiL040X) at 405 nm and a tuned intensity level of 50%, jitter $<$ 3 ps and $<$ 45 ps pulse width .
- Agilent MSO 9404A 4 GHz oscilloscope (20 GS/s).
- **Sensor: HPK S13360-3050CS / FBK NUV-HD LF v2**
- Liquid Crystal attenuator used for the achievement of the single photon regime.
- Several measurements are performed to identify the optimal threshold and overvoltage.



SPRT Results: Hamamatsu SiPM

- Sensor: **HPK S13360-3050CS**. 3x3 mm^2. 50 μm cell pitch.
- Breakdown voltage $\approx$ 53 V
- Overvoltage= 11 V
- PDE of 58% at OV = 11 V
- Intensity light at single photon regime.
- 8k selected events.

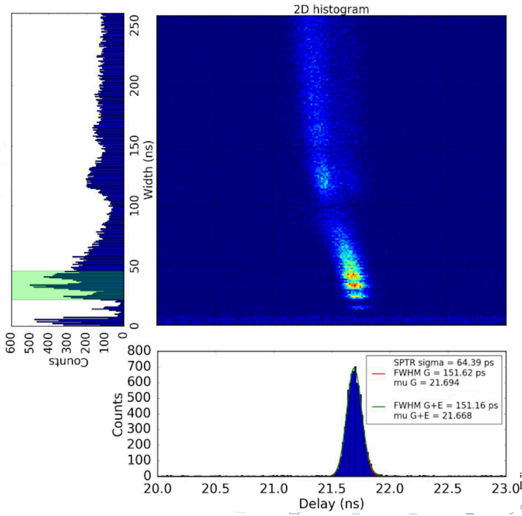
SPTR= 176 $\pm$ 5 ps FWHM



SPRT Results: FBK SiPM

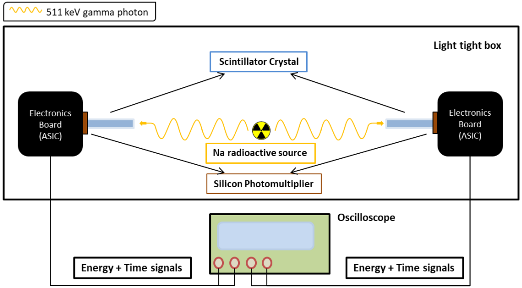
- Sensor:**FBK NUV-HD Low Field V2**. 3.12x3.2 mm^2. 40 μm cell pitch.
- Breakdown Voltage $\approx$ 32 V
- Overvoltage= 10.5 V
- Intensity light at single photon regime.
- 8k selected events.
- Different width peaks for the same photo-electron, due to ringings in the SiPM signal.

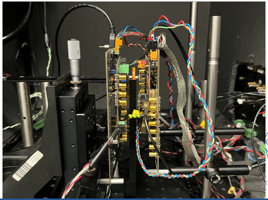
SPTR= 151 $\pm$ 5 ps FWHM



CTR: Set-up

- The setup is as follows:
  - Radioactive source: **NA** 22,330 KBq 2018.
  - Agilent MSO 9404A 4 GHz oscilloscope (20 GS/s).
  - **Inorganic scintillator crystals/ Cherenkov Radiators**.
  - **Sensor: HPK S13360-3050PE / FBK NUV-HD LF v2.**
  - Optical coupling: **Meltmount. Refraction index of 1.52**
  - The measurements are set with the trigger in the energy channels and **selecting only the events in coincidence** within a **time windows of 25 ns**.
  - Temperature stabilization at 16°C.
- Procedure:
  1. Threshold scan to set the **mínimum threshold to 4 LSBs above the noise level**.
  2. **Photon count** to perform a stair case plot with Dark count signal to **identify the threshold levels**.
  3. The **optimal threshold** is selected at a **level lower than the peak current of one SPAD signal** and **above noise**.

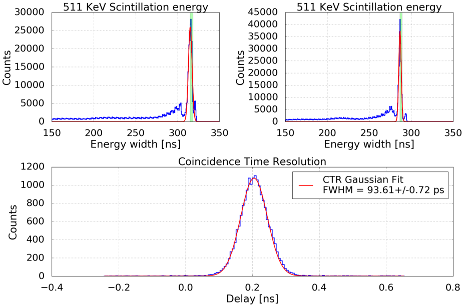




Timing comparison between HPK and FBK

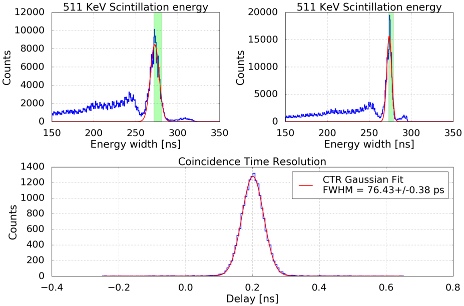
- **Crystal: LSO:Ce:02%Ca 2x2x3 mm^2**. LY=39.2 ph/keV. τ_d=32.6 ns

- **Sensor: HPK S13360-3050PE**. 3x3 mm^2.
- SiPM: OV = 8 V



CTR = 94 ± 3 ps FWHM

- **Sensor: FBK NUV-HD LF V2**. 3.12x3.2 mm^2.
- SiPM: OV = 6.1 V

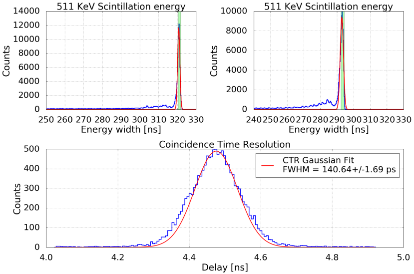


CTR = 76 ± 2 ps FWHM

Timing comparison between HPK and FBK

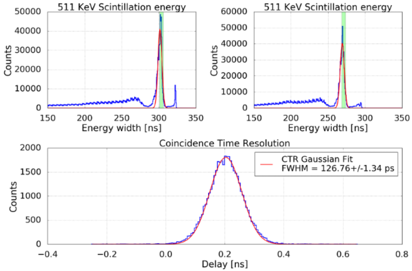
- **Crystal: LYSO:Ce:02%Ca 3.13x3.13x20 mm^2**. LY=45 ph/keV. τ_d=40 ns

- **Sensor: HPK S13360-3050PE**. 3x3 mm^2.
- SiPM: OV = 9 V



CTR = 140 ± 4 ps FWHM

- **Sensor: NUV-HD LF V2**. 3.12x3.2 mm^2.
- SiPM: OV = 7.1 V

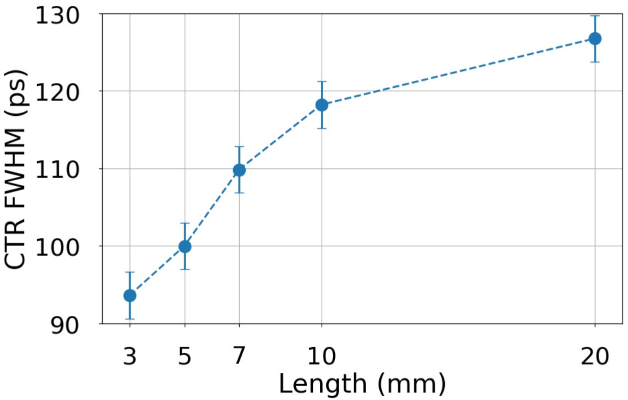


CTR = 126 ± 4 ps FWHM

- **Depth of Interaction (DOI), photon travel spread and light transfer efficiency have a bigger effect on the timing performance as crystal length increases.**

Timing evaluation of LYSO crystals with different lengths

- Measurement of crystals with **different lengths**.
- **Sensor FBK NUV-HD LF V2**.
- LYSO:Ce:02%Ca crystal of **section of 3.13x3.13 mm^2**.
- **Degradation of the CTR as the crystal length increase**. This is in accordance with results published in [1].
- Effects as DOI and optical photon travel spread have a larger impact in the CTR as the crystal length increases [1].
- Additionally, the light transfer efficiency is smaller for larger crystals which also degrades the CTR [1].



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

Timing evaluation of several LYSO crystals

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

Crystal (Manufacturer)	Size [mm^3]	CTR FWHM [± 3 ps]	LY [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

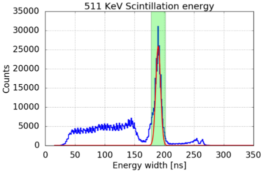
- **LYSO:Ce from Saint-Gobain has better performance than LYSO:Ce from EPIC** which is in accordance with the specifications from both manufacturers.
- **LYSO:Ce Saint-Gobain has a similar performance than LYSO:Ce: 0.2%Ca, but this can be due to the difference in crystal section sizes**.
- Additionally, crystals with section sizes similar to the SiPM section are more difficult to couple, which results in a possible loss of light.

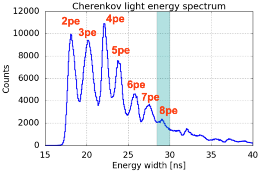
Preliminary results: Cherenkov Radiatior

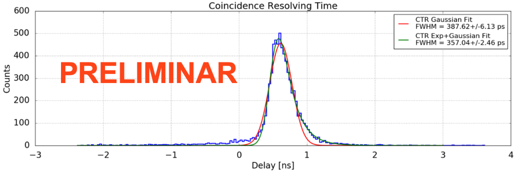
- **Cherenkov radiators** produce few photons with **ultrafast time** response having a high energy resolution.
- Set-up:
  - **Sensor**: **HPK S13360-3050CS**.
  - **Reference Crystal**: **LSO:Ce:0.2%Ca 2x2x5 mm^3** with a Detector Time Reference of ≈ 76 ps FWHM, i.e., a CTR of ≈ 107 ps FWHM
  - **Cherenkov Radiator**: **TlCl 3x3x5 mm^2**
- Measurements done in collaboration with G. Ariño-Estrada from UC Davis.

CTR ≈ 357 ± 5 ps FWHM

- Similar result as obtained by G.Ariño-Estrada [2], but using a **readout electronic scalable for scanner**.







[2] Arino-Estradaet. al. Study of Cherenkov Light Emission in the Semiconductors TlBr and TlCl for TOF-PET. IEEE TRPMS.

Conclusions

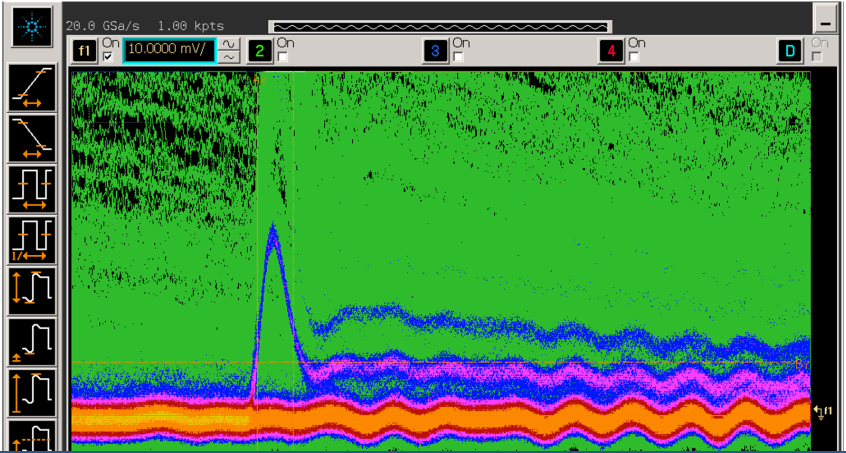
- The versatile **FastIC** can measure **Scintillation** light as well as **Chenrekov** light.
- A **CTR of 76 ps FWHM** is obtained by using a **LSO:Ce:02%Ca** crystal of **2x2x3 mm**^{3} coupled to the FBK new technology, **NUV-HD LF V2**. For HPK we obtained a CTR of 94 ps FWHM.
- Using a **LYSO:Ce:02%Ca** crystal of **3.13x3.13x20 mm**^{3} coupled to FBK SiPM, a **CTR of 126 ps FWHM** was obtained, whereas a CTR **140 ps FWHM** were obtained using the **Hamamatsu sensor**.
- **LYSO:Ce:02%Ca** from **CP** crystal **performs similarly** to **LYSO:Ce from Saint-Gobain**. **Both** crystals **outperform the EPIC** LYSO:Ce crystal.
- Preliminary results on **TlCl Cherenkov** crystal shows that **FastIC coupled to Hamamatsu sensor** have **similar performance** to results in the **literature**.
- In the following months, the **summation feature** will be used to evaluate the timing performance of the FastIC. An **improved time performance** is expected [3].
- Additionally, **FastIC** will be evaluated with different **SiPM arrays**.
- A **new version** of the ASIC is under development including a **TDC with $\approx$ 25 ps time bin** and **without adding power consumption** to the readout.

[3] Sánchez, D. et al. Multimodal Simulation of Large Area Silicon Photomultipliers for Time Resolution Optimization. 2021, NIMA A.

BACK UP

FBK ringings

- Sensor: FBK NUV-HD LF V2
- One fired-SPAD.
- OV = 10 V



- Sensor: **HPK S14160-3060HS**. 3x3 mm^2. 50 μm cell pitch. Breakdown voltage 38 V.
- Crystal: LSO:Ce:Ca 0.2% 2x2x3 mm^3
- FastIC: Threshold at first level of the 1st photon

CTR= 95 $\pm$ 5 ps FWHM