TREDI 2025 – 4-6 Feb 2025 - Trento, Italy

Timing-optimized FBK Silicon Photomultipliers for a modular ToF-PET scanner: the PETVision

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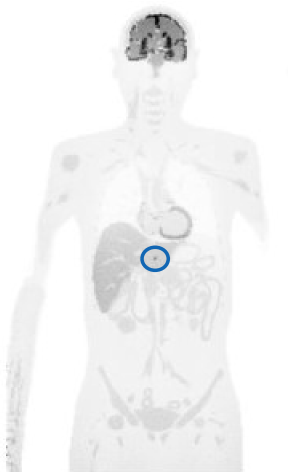
Timing-optimized FBK SiPMs for PETVision
Outline

- **The PETVision project**
  - Project overview, research context, motivations and goals.
- **The PETVision project status**
  - Focus on the photosensor SiPM technology.
- **Coincidence Time Resolution results**
  - CTR with HF readout.
  - CTR with FastIC+ ASIC.
- **Further developments**
- **Conclusion and next steps**

The PETVision project

The PETVision project
Research context

Current leading technology in molecular imaging:
Positron Emission Tomography

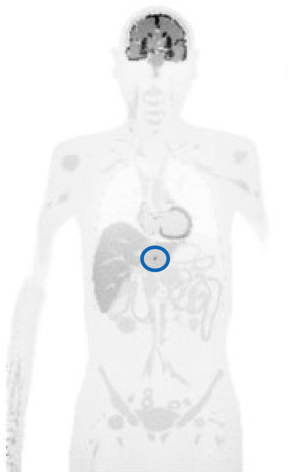


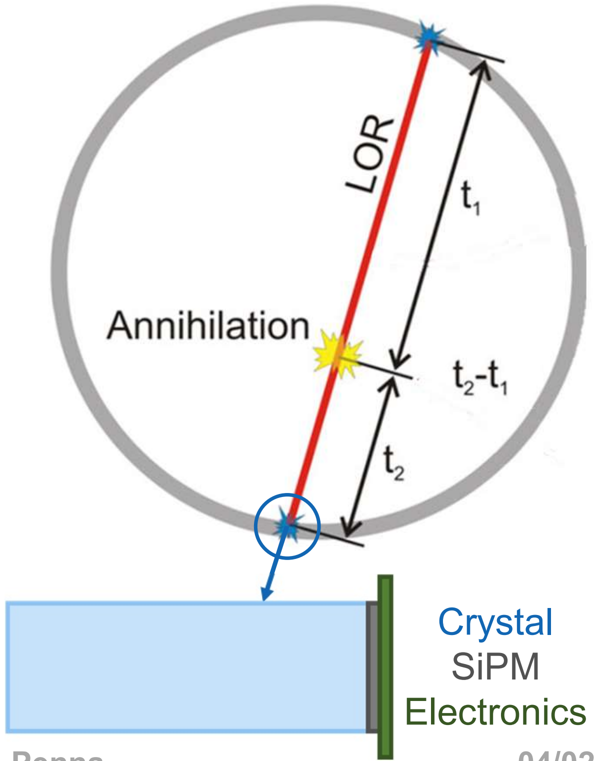
Cancer diagnosis, staging, treatment assessment, drug development…

The PETVision project
Research context

Current leading technology in molecular imaging:
Positron Emission Tomography

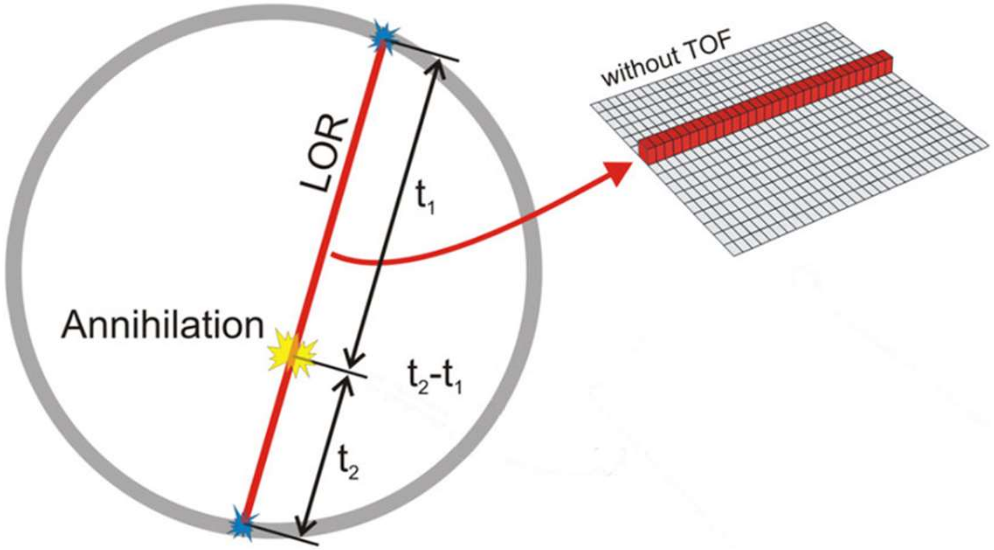
Detection of the **two coincident back-to-back annihilation photons** from a radiotracer





Cancer diagnosis, staging, treatment assessment, drug development…

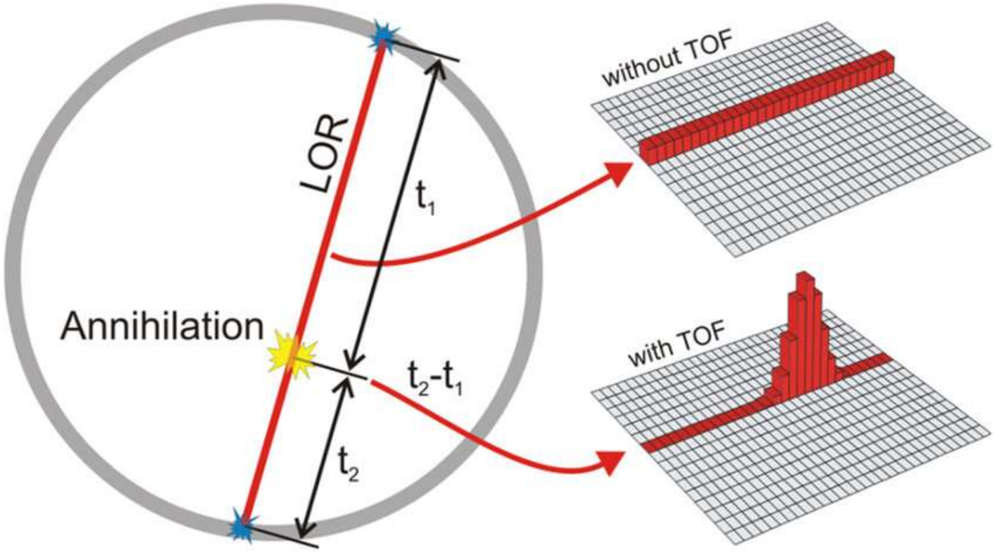
The PETVision project
Motivations



PET **without Time-of-Flight** information

- Uniform probability along the Line Of Response (LOR)
- Long imaging times
  - Long patient radiation exposure

The PETVision project
Motivations



The key parameter is the **Coincidence Time Resolution (CTR)**

PET **without Time-of-Flight** information

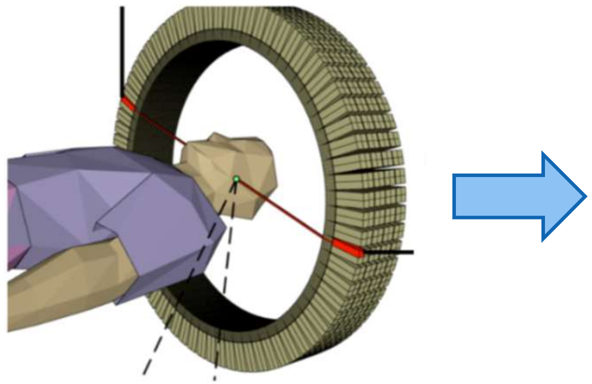
- Uniform probability along the Line Of Response (LOR)
- Long imaging times
  - Long patient radiation exposure

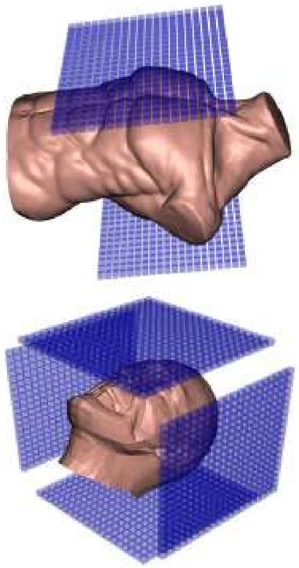
PET **with Time-of-Flight** information

- Exploit the time of arrival difference between the two 511keV photons
- Reduce background
- Increase the SNR
- Reduce dose exposure

The PETVision project
The goal

Develop highly sensitive, state-of-the-art, modular and cost-accessible ToF-PET scanner



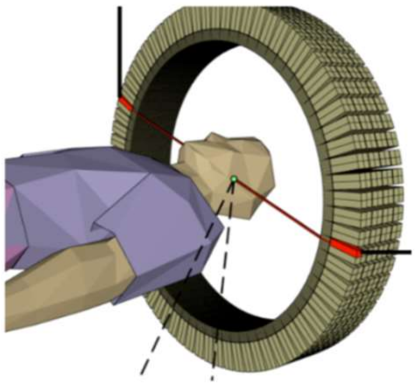


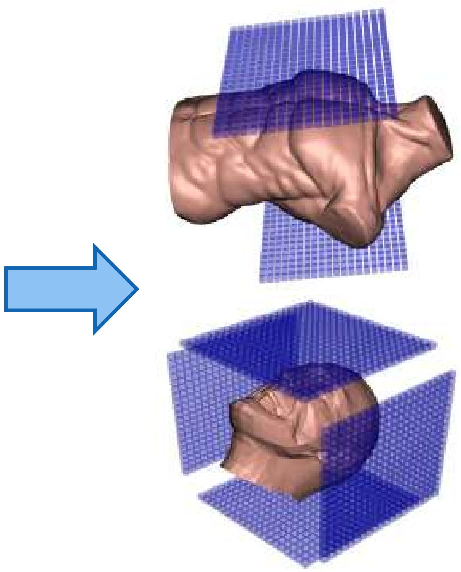
Two planar and opposite detector panels

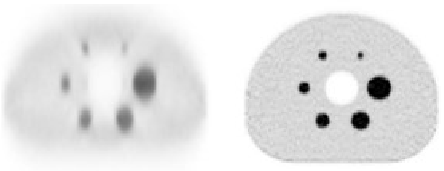
- **High performance**
  Next-generation ToF capability (sub-100ps CTR)
- **Portable**
  Compact ToF-PET scanner
- **Flexible**
  Adjustable FOV and sensitivity
- **Modular**
  Combining multiple panels for multi-organ/total-body PET scanner
- **Accessible**
  Reduced manufacturing cost and complexity thanks to reduced panel area and volume production of components

The PETVision project
The goal

Develop highly sensitive, state-of-the-art, modular and cost-accessible ToF-PET scanner







500ps 70ps

Two planar and opposite detector panels

- **High performance**
  Next-generation ToF capability (sub-100ps CTR)
- **Portable**
  Compact ToF-PET scanner
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- **Modular**
  Combining multiple panels for multi-organ/total-body PET scanner
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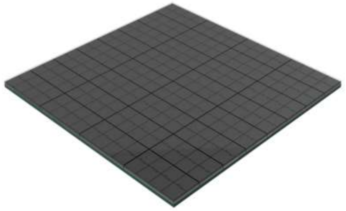
Coincidence Time Resolution of ~75ps

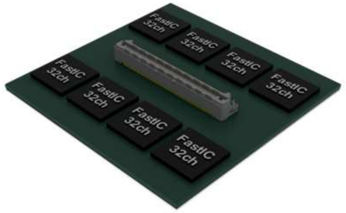
PETVision project status

The PETVision project
Timeline and status

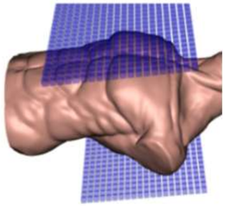
Year 2 → **Year 3** → **Year 4** → **Year 5** → **Year 6-7**



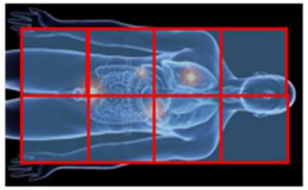
Photodetector: SiPM



ASIC chip and integration



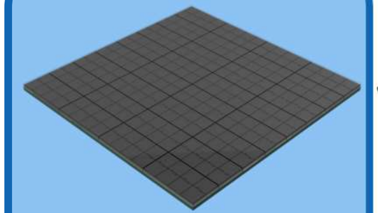
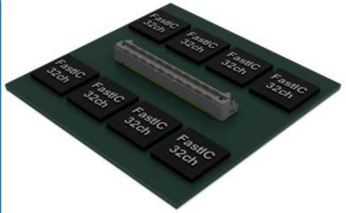
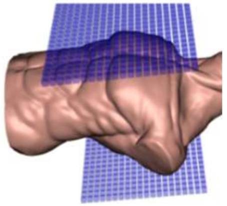
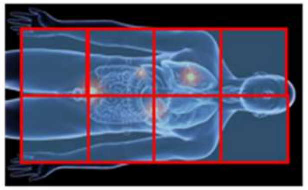
Integration of the prototype



Validation in the hospitals

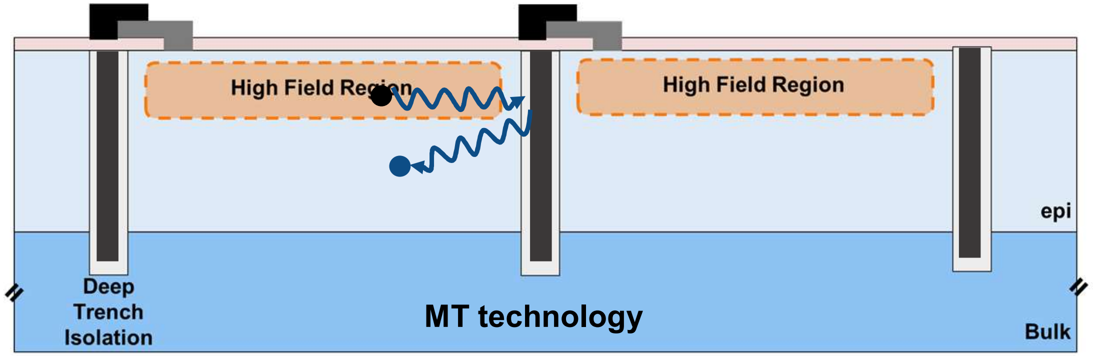
Further developments and exploitation

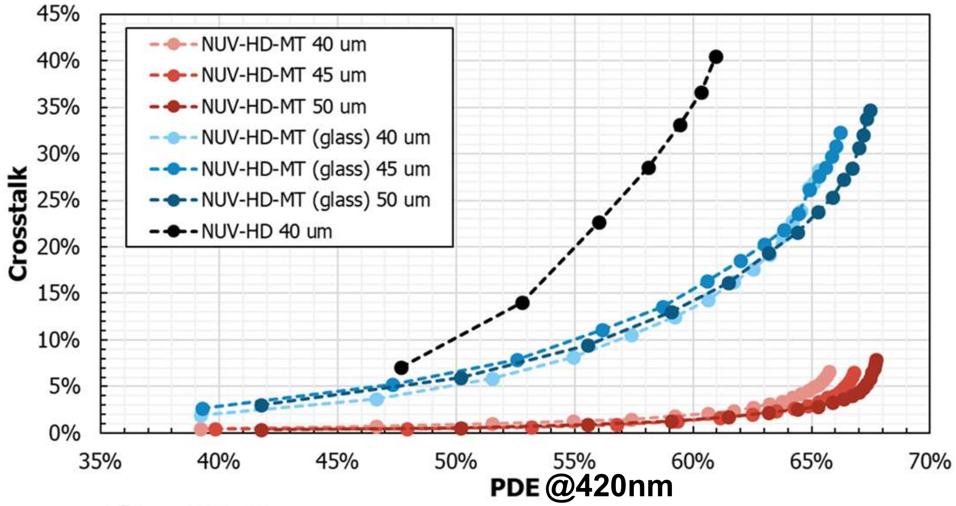
The PETVision project
Timeline and status

Year 2	Year 3	Year 4	Year 5	Year 6-7
 Photodetector: SiPM	 ASIC chip and integration	 Integration of the prototype	 Validation in the hospitals	Further developments and exploitation

Where are we?

The Photodetector
FBK NUV-HD SiPMs with metal-filled trenches (MT)



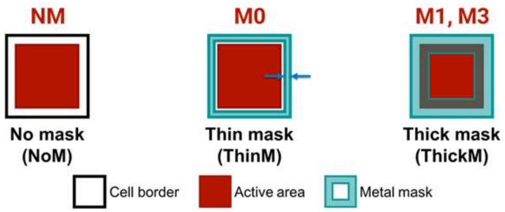


- Metal-filled trenches to **optically isolate adjacent microcells**
  - Significant **reduction** of the **internal crosstalk probability**
  - Significant increase of the maximum operating bias voltage
  - Saturation of avalanche triggering probability (in the NUV)
  - **PDE~65% @420 nm**

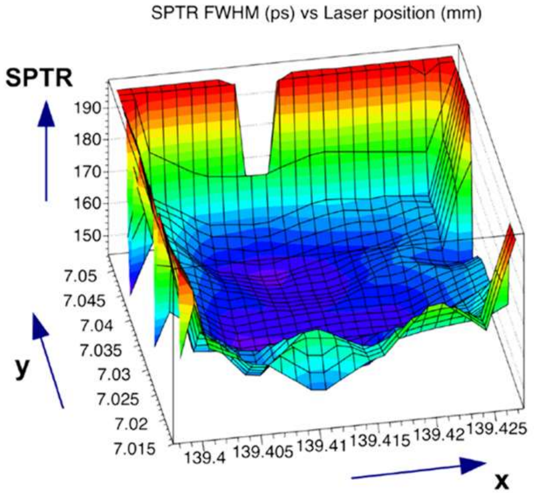
Developed in collaboration with Broadcom

Stefano Merzi et al, “NUV-HD SiPMs with metal-filled trenches”, 2023 JINST 18 P05040
DOI 10.1088/1748-0221/18/05/P05040

The Photodetector
Metal Masked Layout



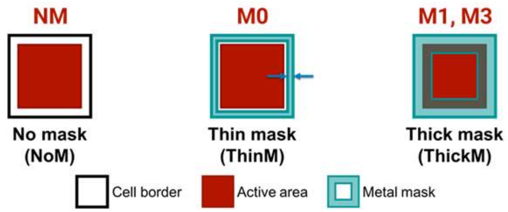
Stefan Gundacker et al, " On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET", 2023 Phys. Med. Biol. 68 165016



Nemallapudi, M. V., et al. "Single photon time resolution of state-of-the-art SiPMs." *Journal of Instrumentation* 11.10 (2016): P10016.

1. Remove the **outer areas** of the SPAD which show **worse SPTR**

The Photodetector
Metal Masked Layout



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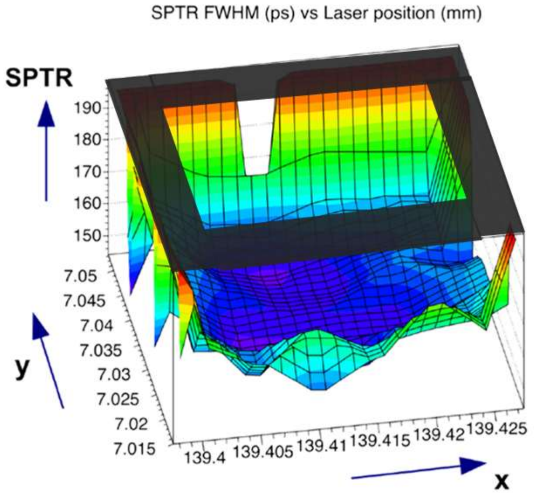

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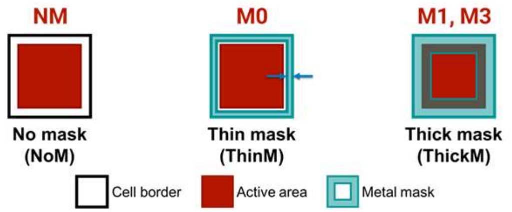
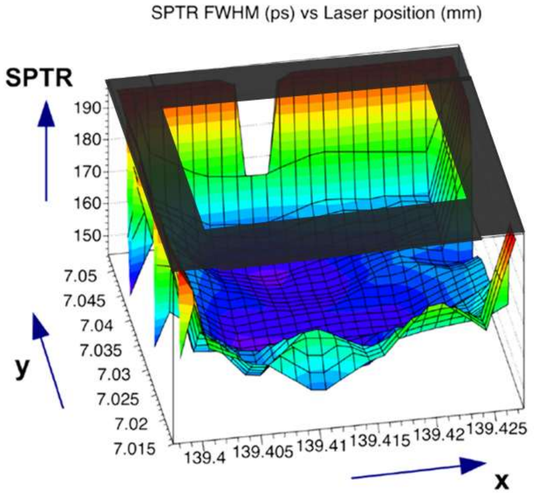
Metal Masked Layout

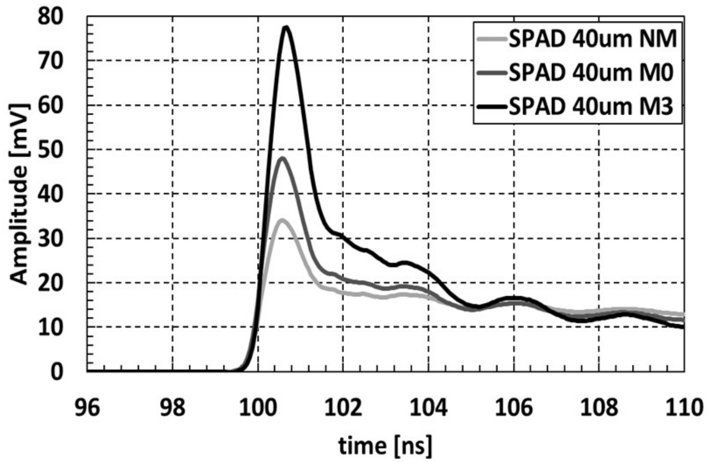


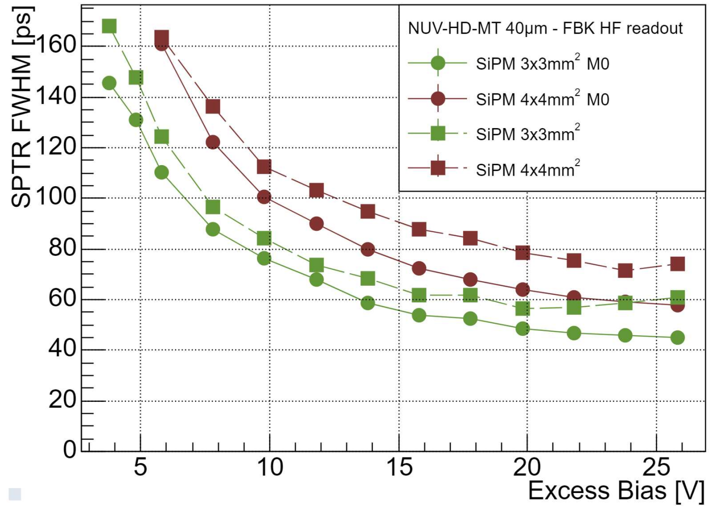
Stefan Gundacker et al, " On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET", 2023 Phys. Med. Biol. 68 165016



Nemallapudi, M. V., et al. "Single photon time resolution of state-of-the-art SiPMs." *Journal of Instrumentation* 11.10 (2016): P10016.

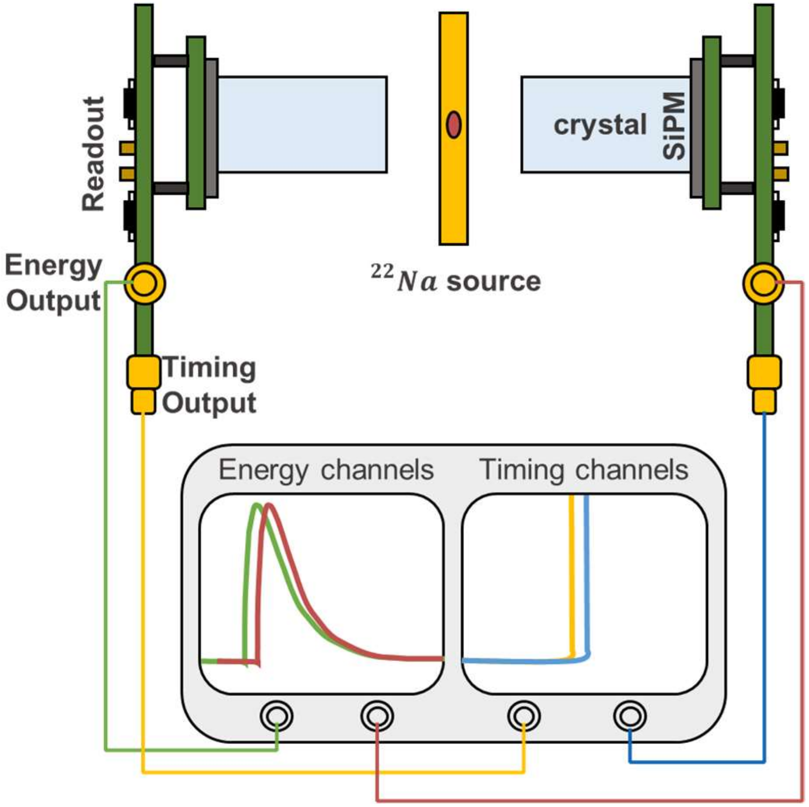
1. Remove the **outer areas** of the SPAD which show **worse SPTR**
2. A **higher capacitive coupling** between anode and readout: increase the fast peak of the single cell response
3. Better **signal extraction / integrity**





Coincidence Time Resolution

Coincidence Time Resolution
Experimental setup



Keysight EXR404A 4GHz 40GS/s

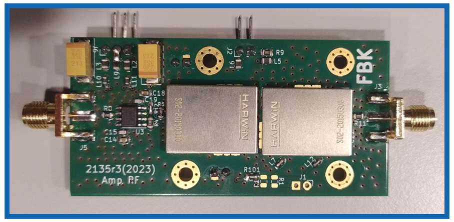
Photodetector

- NUV-HD-MT $3 \times 3\ mm^2$ $40\ \mu m$ M0

Readout Electronics

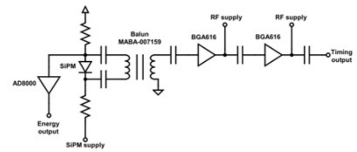
- High Frequency redout developed at FBK*

Crystals



- LYSO:Ce:Ca TAC
  - $2mm \times 2mm \times 3mm$
  - $2mm \times 2mm \times 20mm$
- LSO:Ce:Ca
  - $2mm \times 2mm \times 3mm$
- Teflon wrapped and coupled with meltmount

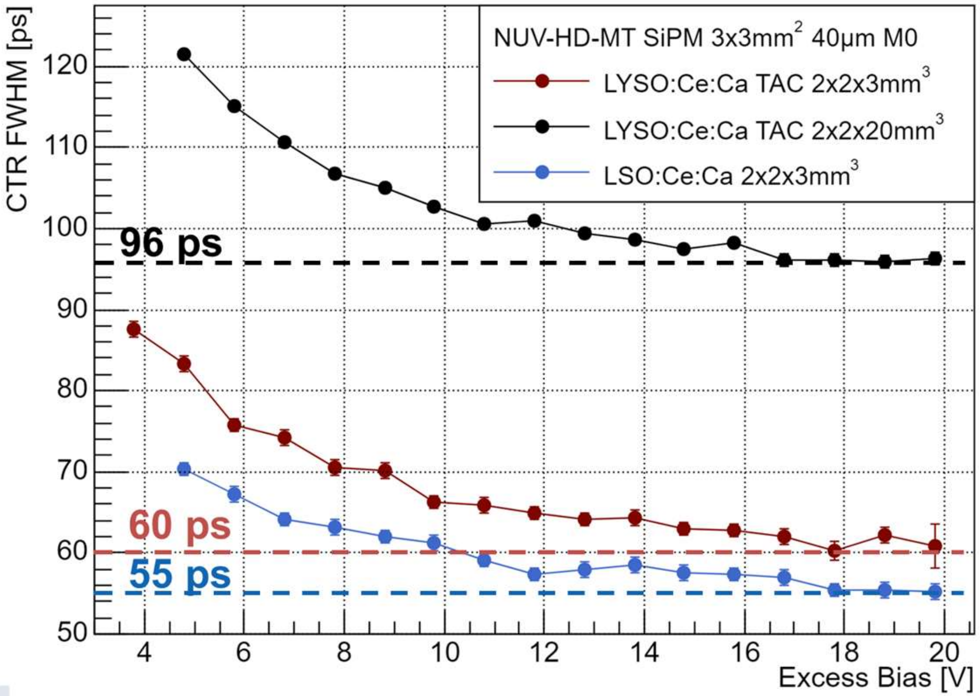
Temperature controlled: 18°C



Performed with G.Terragni - Crystal Clear Collaboration Lab27 at CERN

*Cates et al. "Imptoved SPTR for analog SiPMs with front end readout that reduced the influence of the electronic noise", 2016
*Gundacker et al. "HF SiPM readout advances measured CTR limits in ToF-PET", 2019

Coincidence Time Resolution
Results with High Frequency Electronics



CTR FWHM

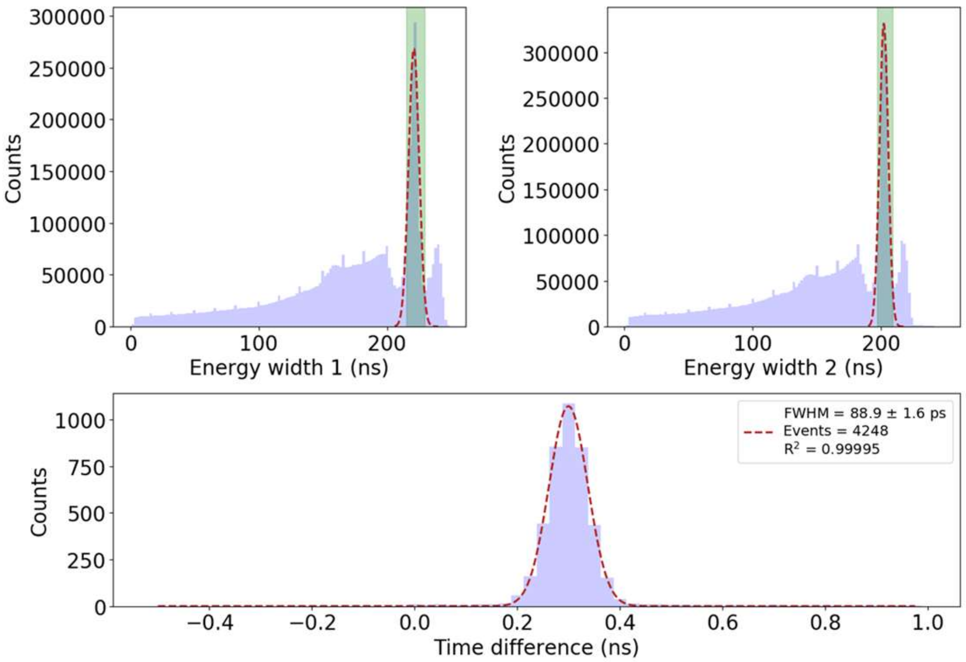
- LYSO:Ce:Ca TAC
  - $2mm \times 2mm \times 3mm$: ~ 60 ps
  - $2mm \times 2mm \times 20mm$: ~ 96 ps
- LSO:Ce:Ca
  - $2mm \times 2mm \times 3mm$: ~ 55 ps

Comparable to the state-of the art measurements:

- *Stefan Gundacker et al, "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET", 2019 Phys. Med. Biol.* ***64*** *055012*

Performed with G.Terragni - Crystal Clear Collaboration Lab27 at CERN

Coincidence Time Resolution
Results with FastIC+



CTR FWHM $= (88.9 \pm 1.6)\ ps$

Photodetector

- NUV-HD-MT $3 \times 3\ mm^2$ $50\ \mu m$ M0

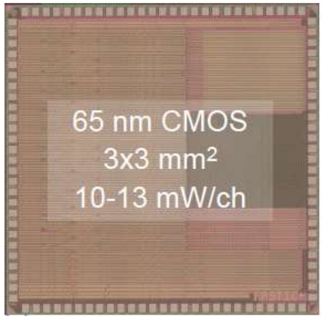
Readout Electronics: FastIC+

- Based on the FastIC (2020)
  - 8 channels
  - Time and Energy channel
- Low power: $\sim 10 - 13\ mW/ch$
- TDC
  - 25ps bin width
- Fully digital output
- 2 different channels of the same ASIC used for the CTR measurement

Crystals

- LYSO:Ce:Ca TAC
  - $2mm \times 2mm \times 3mm$

A. Mariscal-Castilla et al., "Toward Sub-100 ps TOF-PET Systems Employing the FastIC ASIC With Analog SiPMs," in IEEE Transactions on Radiation and Plasma Medical Sciences, vol. 8, no. 7, pp. 718-733, Sept. 2024,



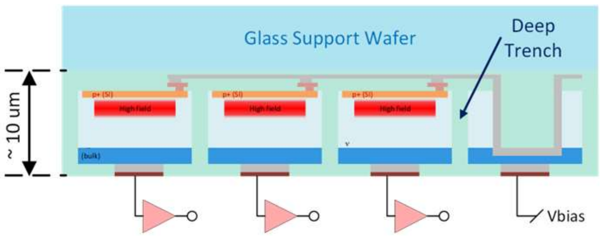
A. Mariscal-Castilla et al., "FastIC+: An Analog Front-End including on-chip TDCs for fast timing detectors" IEEE NSS MIC RTSD Conference, Oct. 2024, Tampa.

Further developments

Further Developments
Petvision Photon Detection Module (PDM) Challenges

Photosensor development

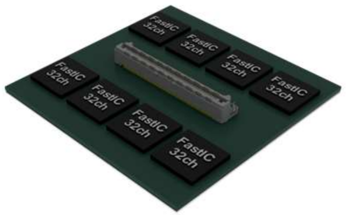
- DTI can be exploited to build a bulk **TSV coincidence with each single SPAD**.
- Common connection of the front to bias the SiPM, by using a TSV.
- Sensor readout from the back.



A. Gola et al., "[FBK roadmap towards the next-generation of 3D-integrated SiPM and SPAD technologies](#)", PD 2024, Vancouver

ASIC development

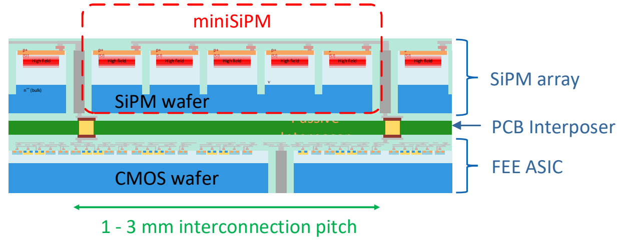
- Different input stage designs to **improve electronics jitter**
- **Optimization** of energy path in terms of **power consumption**
- **New** SAR **ADC development**
  - 12-bit resolution @ 40 MSps with < 1mW/ch



ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

2.5D integration

The Photon Detection Module (PDM) of PETVision will be based on **2.5D integration techniques**.



- Many challenges to be faced
  - Interconnection density and ball size
  - PCB planarity
  - Two-sided reflow
  - Integration of passive components
  - Thermal management

CRS CUSTOM RADIATION SENSORS

The PETVision project
Conclusions and next steps...

PetVision aims to achieve sub-100 ps CTR at system level that has to be scalable and cost-effective.

1. **Timing performance of the photodetector** shows excellent Timing performance
   - The best CTR was achieved with a NUV-HD-MT $3 \times 3\ mm^2$ SiPM $40\ \mu m$ M0, a short LSO crystal and using the HF readout: $\mathbf{CTR \sim 55\ ps\ FWHM}$.
2. The first **sub-100 ps CTR is achieved with ASICs** including on-chip TDCs
   - With a NUV-HD-MT $3 \times 3\ mm^2$ SiPM $50\ \mu m$ M0 and a short LYSO:Ce:Ca crystal: $\mathbf{CTR = (88.9 \pm 1.6)\ ps\ FWHM}$

- PETVision aims to go further by
  - Using improved scintillators
  - Exploiting TSV technology to improve timing of NUV-HD MT SiPMs
  - Developing an optimized ASIC based on FastIC+
  - ASIC and sensor 2.5 D integration and codesign: integrated PDM

Funded by the European Union
European Innovation Council

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