



RESEARCH AND DEVELOPMENT ON TOF-PET TROUGH CHERENKOV EMISSION

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DFA

INFN-CT

SAMOTRACHE

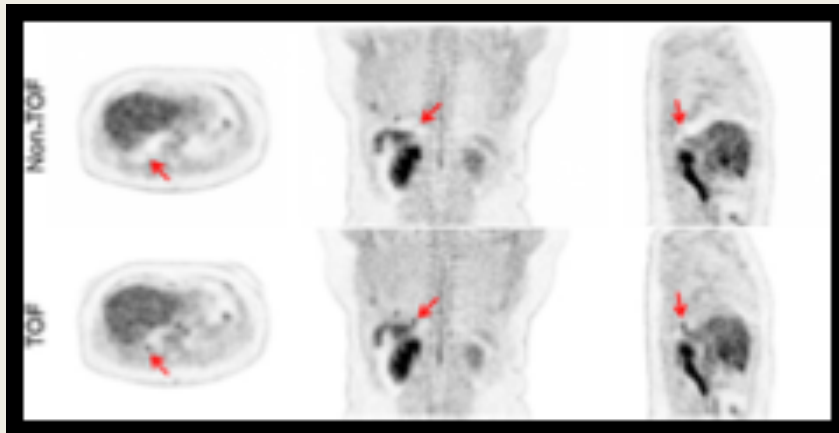
**FATA "FAst Timing Applications for nuclear physics and medical
imaging"**
8-10 Oct 2025

INFN-Sezione di Catania - Dipartimento di Fisica e Astronomia "E. Majorana"

INTRODUCTION

Time-of-Flight PET: A New Frontier

- TOF-PET improves image reconstruction by measuring photon arrival times.
- **Key Advantages:**
 - Improved spatial accuracy:** better localization along the line of response
 - Noise reduction:** clearer and more reliable images
 - Dose optimization:** lower exposure for the patient
 - Diagnostic efficiency:** faster acquisition times



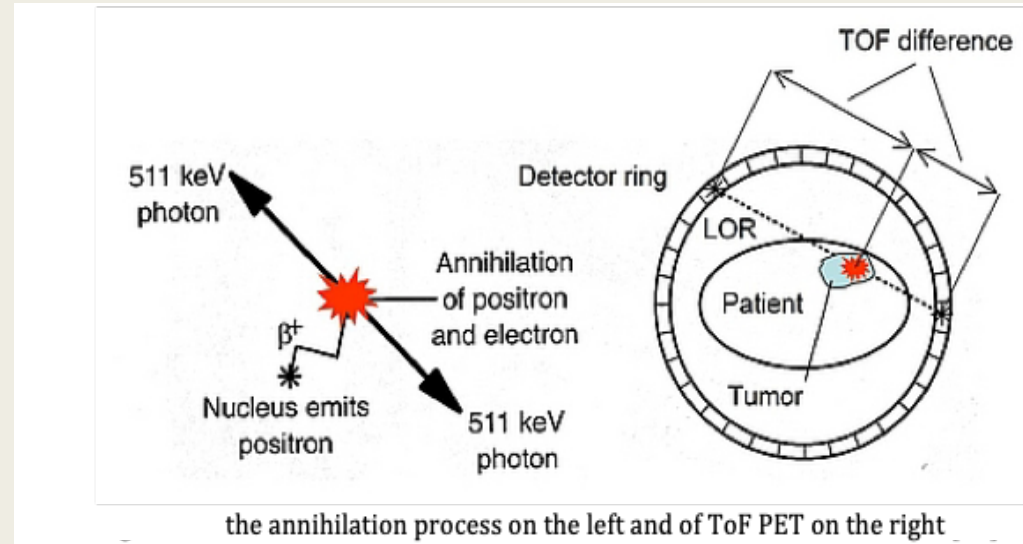
Comparison between conventional PET (NON-TOF) and Time-of-Flight PET (TOF) imaging across axial, coronal, and sagittal views. TOF-PET demonstrates superior contrast and spatial resolution, enabling clearer visualization of lesions and improved diagnostic accuracy.

Conti M., Bendriem B. "The new opportunities for high time resolution clinical TOF PET" *Clinical and Translational Imaging*, Volume 7, pp. 139–147, 2019

What is TOF-PET?

Time-of-Flight Positron Emission Tomography

Is an advanced imaging technique that improves the accuracy of PET scans by incorporating timing information



A positron emitted from a radiotracer annihilates with an electron, producing two 511 keV photons.

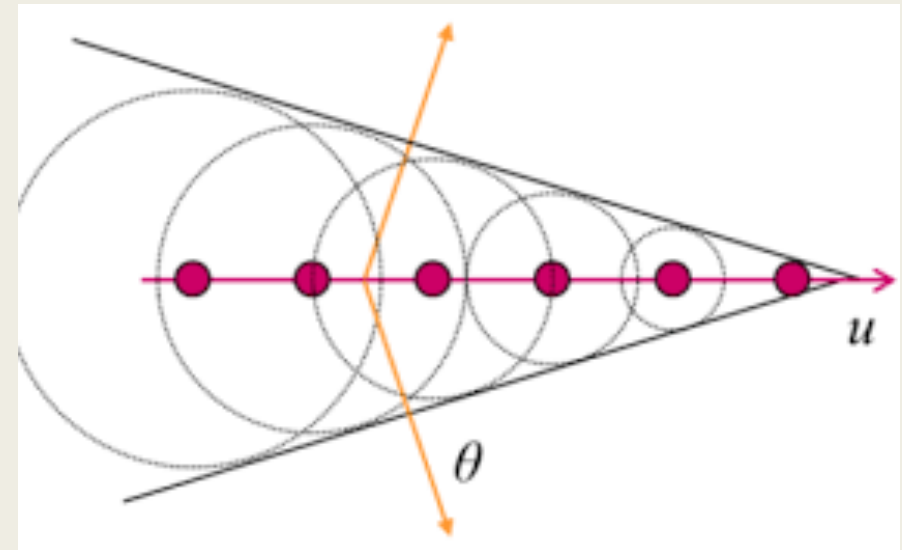
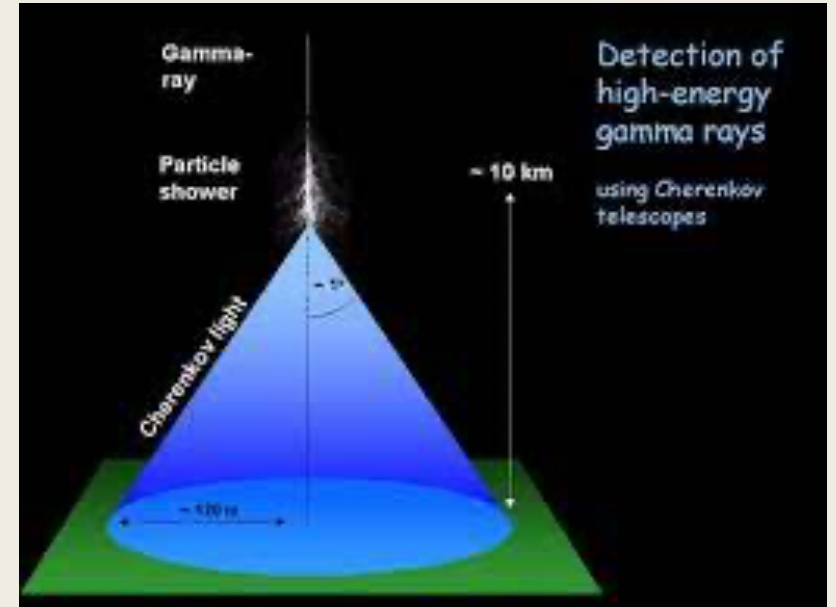
The PET scanner detects these photons using a ring of detectors.

The Time-of-Flight (TOF) measures difference in arrival time between the two photons to reconstruct the Line of Response (LOR), enabling precise localization of metabolic activity .

Cherenkov Radiation

Ultrafast Photon Emission

- Produced by charged particles in transparent medium faster than the speed of light in that medium, producing a cone of light..
- Instantaneous light emission (picosecond scale).
- Spectral range: UV to visible.
- Ideal for high-precision timing.



Radiator Materials

Radiator materials must balance:

- **Fast photon emission**
- **High transparency**
- **Good thermal and mechanical properties**

Material	Emission Type	Timing Characteristics	Application Role
CeBr ₃	Scintillation	Fast decay (~20 ns)	Energy resolution
BaF ₂	Cherenkov + Scint	Dual timing (~0.6 ns / 600 ns)	Timing separation
PbF ₂	Cherenkov only	Prompt emission (<0.1 ns)	Ultrafast timing

The choice of material directly impacts the detector's ability to resolve photon arrival times, which is critical for improving image quality and reducing dose in PET imaging

Why We Use PbF₂ in Cherenkov-Based TOF-PET

Key Advantages of PbF₂:

- **Pure Cherenkov Emission** No scintillation tail → faster timing response
- **High Refractive Index (~1.82)** → Lower Cherenkov threshold velocity → More photons emitted per event → Wider emission cone → better photon collection
- **High Density (7.77 g/cm³)** → Increases interaction probability with 511 keV gamma photons
- **Excellent UV-Visible Transparency** → Efficient photon transmission to SiPMs
- **Good Mechanical and Thermal Properties** → Stable under irradiation and compatible with modular designs

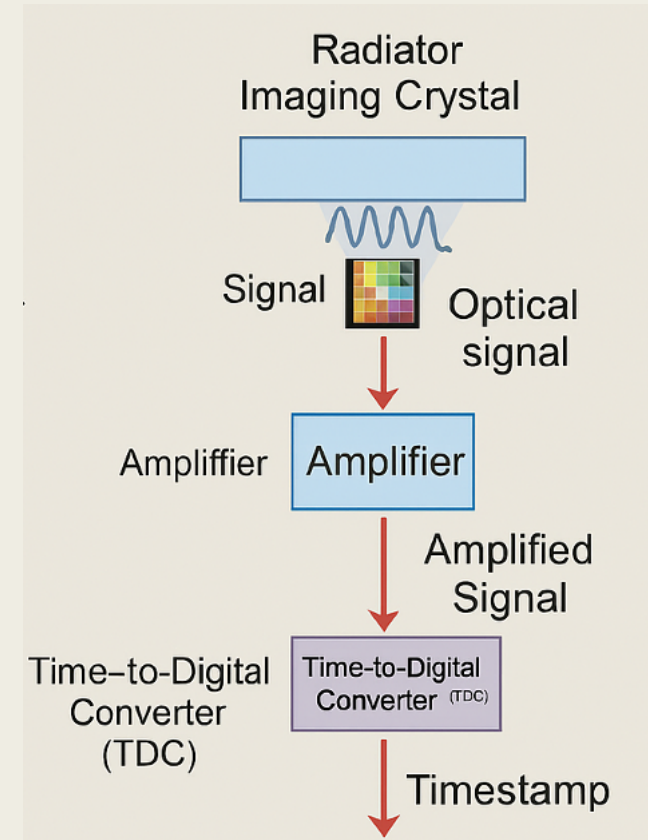
Property	PbF ₂ (Lead Fluoride)	BaF ₂ (Barium Fluoride)	CeBr ₃ (Cerium Bromide)
Emission Type	Pure Cherenkov	Cherenkov + Scintillation	Scintillation only
Refractive Index (n)	~1.82	~1.50	~1.65
Density (g/cm ³)	7.77	4.89	~5.18
Atomic Number (Z)	82	56	35 (Br), 58 (Ce)
Timing Characteristics	Prompt emission (<1 ns)	Dual: fast (~0.6 ns) + slow (~600 ns)	Fast decay (~20 ns)
Photon Yield (511 keV)	~16.5 Cherenkov photons/event	Moderate (Cherenkov + scint.)	High scintillation yield
Transparency Range	UV–Visible	Deep UV–Visible	Visible

Photodetectors and Readout Electronics SiPMs and Timing Electronics in TOF-PET

Silicon Photomultipliers (SiPMs) are compact, solid-state photodetectors optimized for detecting Cherenkov and scintillation light with single-photon sensitivity.

TOF-PET systems use **fast amplifiers** and **Time-to-Digital Converters (TDCs)**) or fast digitizer in order to record the arrival time of the photon, to preserve timing precision.

This **timestamp** is essential for reconstructing the annihilation point along the Line of Response.



Accurate timing extraction is essential for achieving sub-nanosecond resolution

State of the Art

TOF-PET with Cherenkov Light (PbF_2 + SiPM)

PbF_2 is a pure Cherenkov radiator with ultrafast light emission (<1 ns), ideal for TOF-PET.

SiPMs → high photon detection efficiency in the UV-visible range
fast response times below 100 picoseconds,
compatibility with magnetic fields

Latest Experimental Results

- **Cherenkov Photon Yield:** → $\sim 16.5 \pm 3.3$ photons for 511 keV event ($2 \times 2 \times 3$ mm³ PbF_2 crystals)
- **Coincidence Time Resolution (CTR):**
 - ~ 215 ps FWHM with standard SiPM readout
 - ~ 190 ps FWHM with slow-rate-based time walk correction
 - ~ 143 ps FWHM in multilayer simulation setups

Kratochwil et al., *Phys. Med. Biol.*, 2021

Gundacker et al. (2019) – *High-Frequency SiPM Readout Improves TOF-PET Timing Physics in Medicine & Biology*

Experimental Overview

Our goal is to develop and characterize a fast detection module based on PbF_2 crystals and SiPMs, optimized for TOF-PET applications.

Module Components:

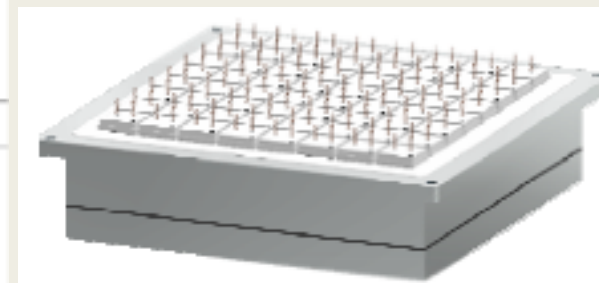
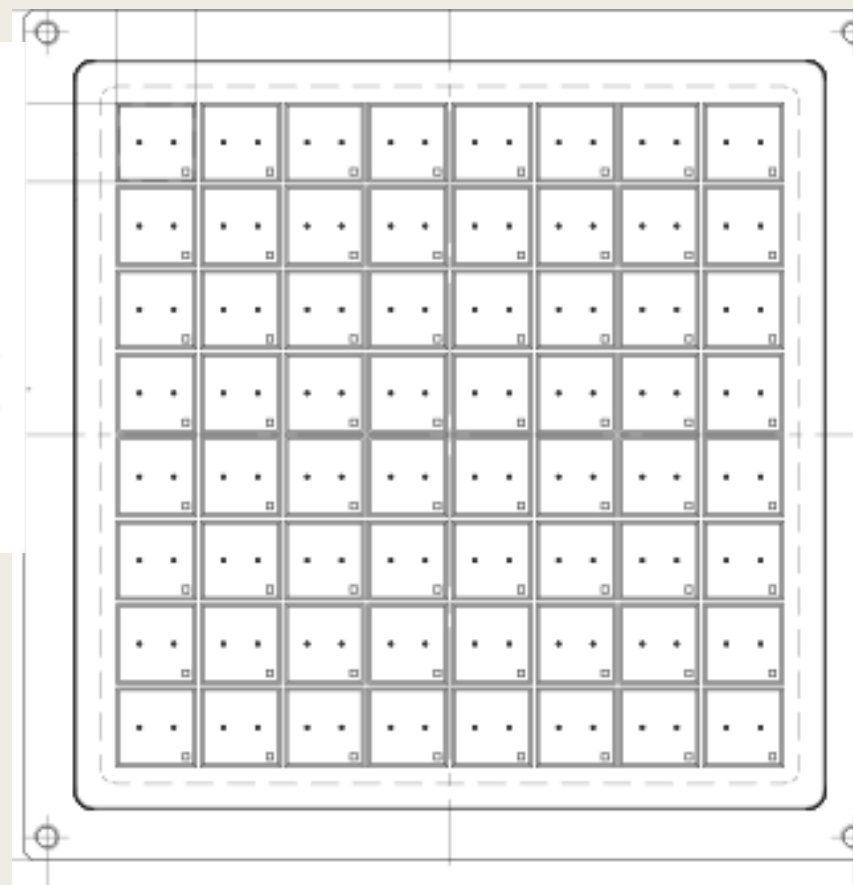
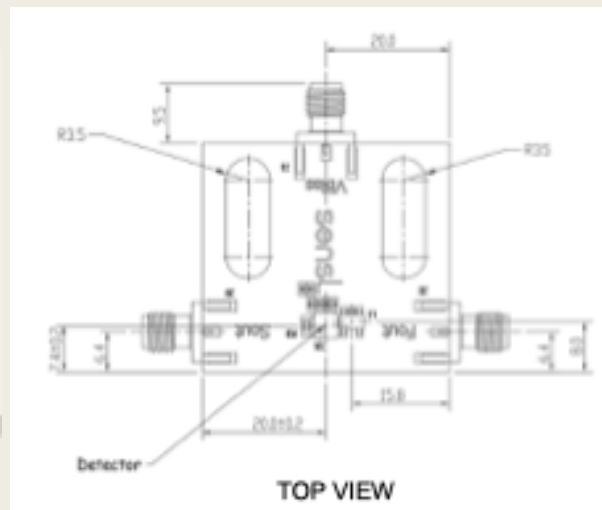
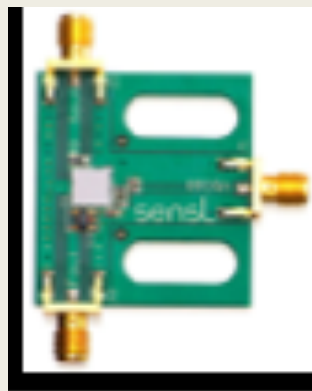
- PbF_2 crystal matrix (8×8)
- MicroFC-SMA SiPMs
- CAEN PSAU 5600 readout electronics
- LeCroy oscilloscope (*WAVERUNNER 9254M* , 2.5 GHz, 40 GS/s)
- Optical coupling and mechanical support

Goals:

- Evaluate timing resolution and photon yield
- Characterize SiPM response with laser and Co-60 source
- Benchmark against current TOF-PET technologies

Detector Configuration

Crystal Matrix Design and Photosensor Coupling



MicroFC-SMA

Output	Function
Vbias	Positive bias input (cathode)
Fout	Fast output
Sout	Standard output (anode)

8x8 PbF₂ crystal matrix,

The mechanical layout ensures stable optical coupling and thermal dissipation

Readout Electronics

CAEN PSAU 5600



CAEN PSAU 5600: compact power and signal unit for SiPMs. Used to power and read out signals from the **PbF₂ + SiPM quad module**

Provides:

- Vbias:** adjustable bias voltage (up to 90 V)
- Fout:** fast output , for timing connected to oscilloscope or timing electronics
- Sout:** standard output, for energy calibration and pulse shape analysis

Its compact design simplifies integration and ensures stable operation across multiple channels.

Advantages:

- Simplifies cabling and signal routing
- Stable bias supply with low noise
- Enables simultaneous timing and energy readout

SiPM Characterization with Laser Source

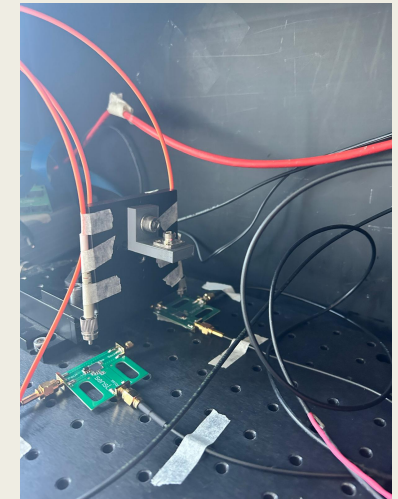
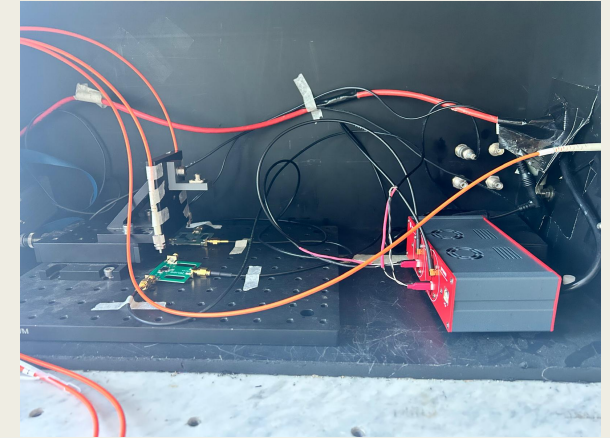
- evaluate key performance parameters of **Silicon Photomultipliers (SiPMs)** before integration into TOF-PET setup
- Ensure optimal bias voltage, gain, timing response, and noise levels

Experimental Setup

- **Pulsed laser source** SP5601 400 nm with adjustable intensity and repetition rate
- **SiPM mounted on CAEN PSAU SP5600** for bias control and signal amplification

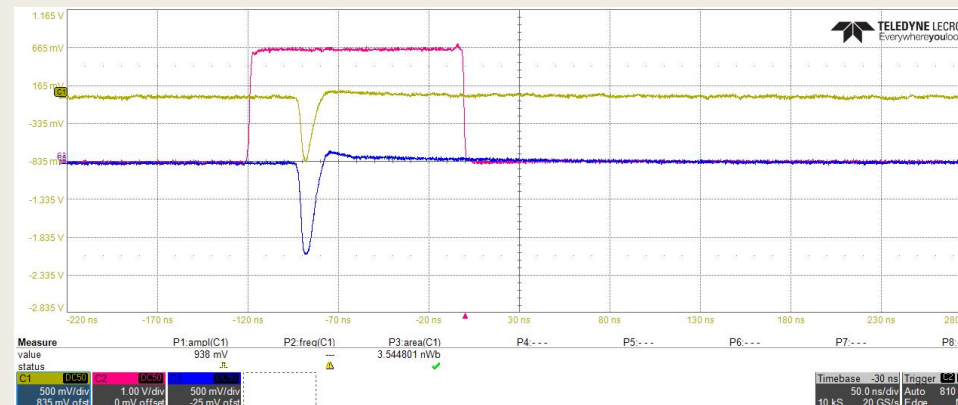
Oscilloscope LeCroy Waverunner 9254M , 2.5 GHz, 40 GS/s, to observe and record output pulses

- **Dark box** to eliminate ambient light and reduce noise



Preliminary Results:

- Stable gain in the 28–32 V range
- The system working



Experimental Validation

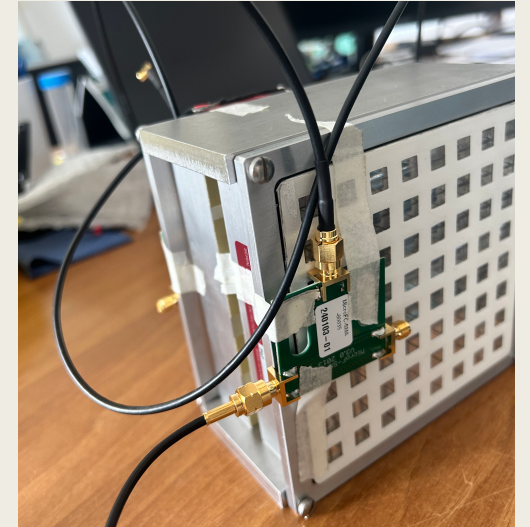
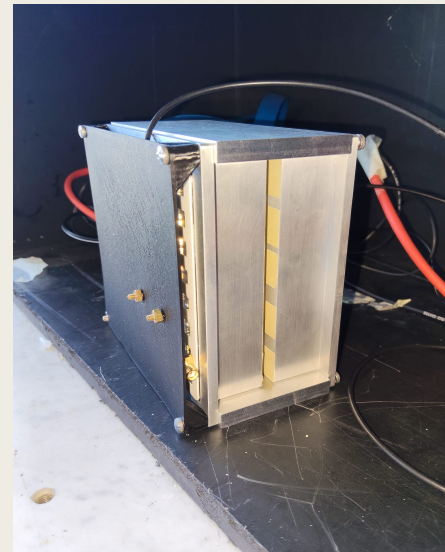
Timing and Energy Response under Gamma Irradiation

Two **PbF₂** matrices coupled to **SiPMs**

Co-60 source emitting coincident gamma photons (1.17 MeV & 1.33 MeV)

Readout via **CAEN PSAU SP5600**

Acquire signals with an oscilloscope



To ensure efficient optical coupling between the PbF₂ crystal and the SiPM, we applied a thin layer of *RTV615 A/B resin* at the interface

Preliminary Experimental Test with PbF_2 matrix

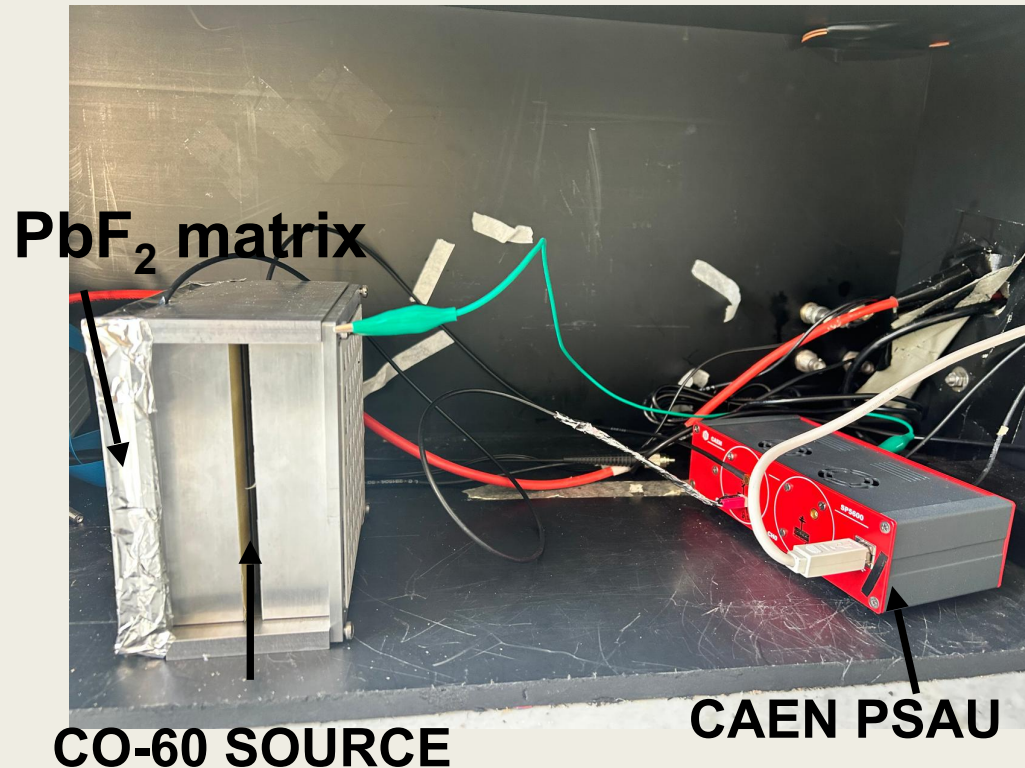
Measurements:

1. Background Activity (No Source):

1. Threshold: **-45 mV**
2. Bias Voltage: **28 V**
3. Gain: **35 dB**
4. Recorded over several hours:
 1. Number of events above threshold
 2. Time interval between consecutive triggers
 3. Charge integral of each event

With Co-60 Source:

- Same acquisition settings
- Increased event rate observed



- **Detection Rate doubled** with the Co-60 source compared to background configuration

Coincidence Measurement for TOF Extraction

- Measure time differences between two SiPMs coupled to PbF_2 crystals
- Validate the system's ability to resolve photon arrival times with sub-nanosecond precision

Experimental Setup:

- Two PbF_2 crystals, each coupled to a dedicated SiPM
- Co-60 or Na-22 source placed equidistant between detectors
- Readout via CAEN PSAU SP5600
- Fast oscilloscope to capture timing information

WORK IN PROGRESS

Goals:

- Extract **Coincidence Time Resolution (CTR)**
- Evaluate timing jitter and synchronization accuracy
- Benchmark standard PET performance against TOF-PET systems



THANKS