Development of the Fast and Efficient Gamma Detector Using Cherenkov Light for TOF-PET

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Positron Emission Tomography (PET)

• Functional 3-D imaging technique in nuclear medicine
  ➢ **Oncology**: small tumors and metastases imaging
  ➢ **Neurology**: exams of neurodegenerative diseases (Alzheimer, Parkinson)
  ➢ ...

• **Principle**:
  ✓ **Radioactive tracer** (ex: FDG) is injected in the patient body and then chemically bounded in tissue
  ✓ $\beta^+$ decay: emission of a **positron**
  ✓ **Annihilation** with an electron of tissue: two 511 keV $\gamma$ are emitted back-to-back
  ✓ Detection in **coincidence**
  ✓ **Image reconstruction**

• Important characteristics of PET detector
  ➢ Efficiency
  ➢ Time resolution
  ➢ Spatial resolution
Time of Flight Technique

Provides information on the localisation of the annihilation vertex on the Line-Of-Response (LOR).

**Goal**: achieve time resolution of 100 ps (FWHM)

→ localisation of 3 cm on the LOR

→ Improvement of the image **signal-to-noise ratio**

\[ \text{gain} = \sqrt{\frac{2 \cdot D}{c \cdot \delta t}} \]

For example,

*With \( D = 20 \text{ cm} \) (organ size)*

* \( \delta t = 100 \text{ ps} \),

*gain in contrast is 3.6*
Time of Flight Technique

Improvement of the signal-to-noise ratio:

→ reducing of the radiation dose received by the patient while keeping the same image quality,

→ or, alternatively, improvement of the image quality without increasing the received dose.

Current PET-scan uses scintillation

\[ \sim 10 \text{ to } 50 \text{ ns} \]

To improve the TOF: using of Cherenkov radiation

fast: \[ \sim 10 \text{ ps} \]

but low yield

→ development of 2 twin projects: CaLIPSO and PECHE
PECHE: towards a new PET technology

→ Construct a Cherenkov detector with high detection efficiency and time resolution

→ **PbF$_2$ crystal (10 mm):**
  * very fast with Cherenkov radiation
  * one of the highest photoelectric fraction: 46 %
  * optical refractive index: 1.82 for $\lambda=400$ nm
  * near perfect optical transparency between 250 nm and infrared wavelengths
  * large density: 7.66 g/cm$^3$

→ **Optical gel (OCF 452):**
  * refractive index: 1.55 (400 nm)
  * transparent up to 300 nm

→ **MicroChannel Plate-PMT (Photonis)**

→ **Preamplifiers 2.5 GHz bandwidth, 30 dB, ZKL-2R5+**

→ **SAMPIC module: Time and Waveform Digital Converter (TWDC) chip**

MCP-PMT Photonis
* **Low Dark Count Rate**
  \[ \approx 100 \text{ Hz/cm}^2 \]
* **Fast**: \[ \text{TTS} \lesssim 100 \text{ ps (FWHM)} \]
* **Good quantum efficiency**
  up to 25%

- Active surface 53 mm x 53 mm
- Windows material: sapphire
- 8 x 8 anodes
- 25 \( \mu \text{m} \) pore diameter

XP85012 Planacon
The SAMPIC module

Signals numerisation with the **SAMPIC** module:

A 32-channel, 10-GSPS Time and Waveform Digital Converter module, developed by IRFU and LAL.

* provides digitized waveform with 64 samples, 1.6 GS/s to 10 GS/s

* extremely good resolution in time: $< 5 \text{ ps (σ)}$

* allows to use on-line the configurable Constant Fraction Discriminator (CFD) algorithms

* acquisition of waveform and/or CFD time

Typical signal with 6.4 GS/s
→ A 511 keV gamma enters the crystal, what probability do I have to detect it?

* gamma-conversion efficiency: 67% for 10 mm crystal
* photoelectric conversion in PbF$_2$: 46%
* optical coupling from crystal to PMT
* quantum efficiency of photocathode: up to 25%

Simulation gives an efficiency of about 30%
Efficiency Measurement Setup

→ Measured with reference YAP detector with « Tag & Probe » method
Efficiency Measurement Results

In order to know when a 511 keV gamma entered on the detector
→ selection of the 511 keV events in the YAP
→ look at the coincidence events in the PbF$_2$

YAP energy spectrum

\[
\text{Eff} = \frac{N \text{ (PbF}_2\text{)}}{N_{\text{YAP}} (E>E_1, E<E_2)}
\]

Eff ~ 28 % (preliminary)

Systematic effects taken into account:
overestimation of the $N_{\text{YAP}}$, due to the presence of Compton scattering from 1.3 MeV Compton

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Simulation of intrinsic dispersion of the optical paths in the crystal

For a single detector: FWHM ~ 40 ps

10 mm thick
MCP-PMT Time Resolution Measurement

Measurement in a single photon mode, in the center of MCP-PMT, laser beam width ~ 25 ps

FWHM = 79 ± 5 ps
Detector Time Resolution Setup

Connection with the SAMPIC module

Detector left
- Pre-amplifiers
- MCP-PMT
- PbF$_2$ crystal

Detector right

Source $^{22}$Na ($\beta^+$)

511 keV $\gamma$

$t_{10/90}$ $\approx$ 700 ps
Towards full-size Detector

* MCP-PMT = 64 anodes
* grouping anodes by 4
* reading the 9 central anodes

**SIMULATION: Number of anode hits per PMT**

![Graph showing number of anode hits per PMT](image-url)
Towards full-size Detector Measurement

**Time Difference between the two detectors in the MCP-PMT center**

For a single detector: \( \text{FWHM} = (150 \pm 10) \text{ ps} \)

\[ \text{FWHM} = 0.211 \text{ ns} \]
\[ \text{FWHM}/2.355 = 0.0894 \text{ ns} \]
\[ \text{FWTM} = 0.758 \text{ ns} \]

Entries: 4226

Work in progress
Towards full-size Detector Measurement

Time Difference between the two detectors in the full MCP-PMT

For a single detector: FWHM = (180 ± 10) ps
Detector Time Resolution Measurement

Time Difference between the detectors with a better light collection: 2 photons per MCP-PMT

For a single detector: \( \text{FWHM} = (138 \pm 10) \text{ ps} \)
First test with PbF\textsubscript{2} crystal Cherenkov detector allows us to reach an efficiency of 28\% in rough agreement with simulations. Main degradation factor is the optical interface between crystal and windows MCP-PMT. We are working on improving it.

In time resolution, we measure for a single detector:
* in the center of the detector 150 ps.
* in all the readable surface 180 ps, after a first work calibration.
We are now working on the optimization on read-out electronics.
→ Twin to PECHE

→ TMBi used as liquid Cherenkov radiator

→ Previous demonstrator:
  Time Resolution of (592 ± 18) ps (FWHM)
  Efficiency of 34.5 %


→ We now focus on **Time Resolution**, in order to reach **150 ps (FWHM)**
Optical Demonstrator CaLIPSO assembly and filling
→ Efficiency measurement as previously : ~ 23 %

→ Time resolution in progress

Thank you for your attention !
Back-Up
Clinical size performance: NECR calculation

NECR = noise equivalent count rate, estimated with GATE-based simulation