Development of the Fast and Efficient Gamma Detector using Cherenkov Light for Positron Emission Tomography

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Overview

I. Positron Emission Tomography and Time of Flight

II. PET Cherenkov Detector : PECHE

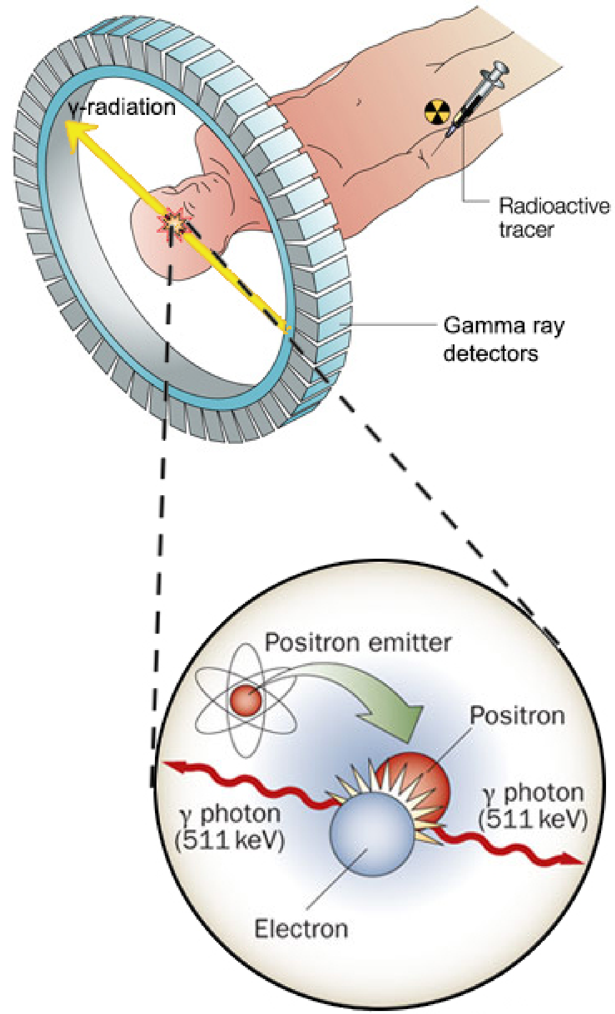
III. Time Resolution

IV. Efficiency

Positron Emission Tomography

- 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
  - ✓ **β+ decay** : emission of a **positron**
  - ✓ **Annihilation** with an electron of tissue : **two 511 keV γ** are emitted back-to-back
  - ✓ Detection in **coincidence**
  - ✓ **Image reconstruction**



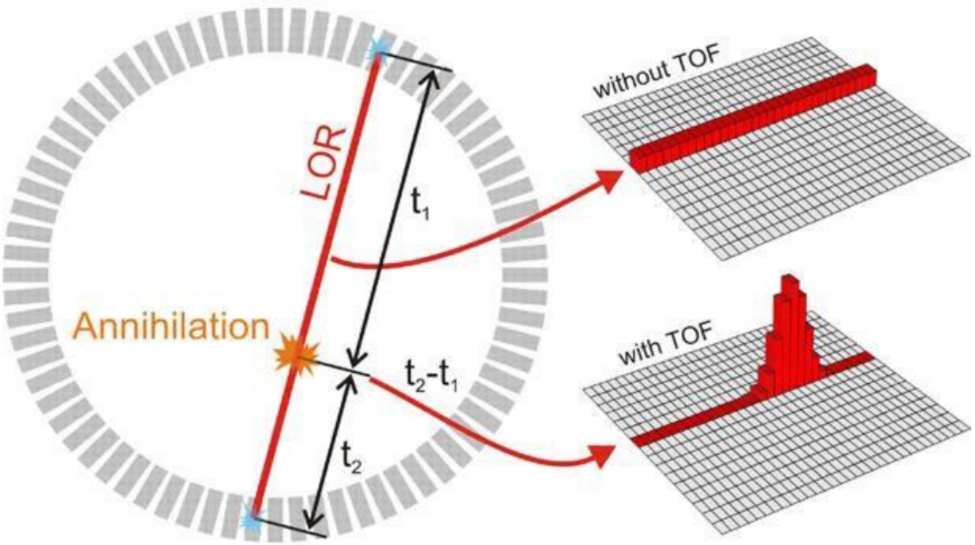
Time of Flight

Time of Flight provides information on the localisation of the annihilation vertex on the line of response (LOR).

Reachs time resolution of 100 ps

=> localization of 3 cm on the LOR

→ Improvement of the signal-to-noise ratio



PECHE and CaLIPSO

Improvement of **time resolution**

= 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 use scintillation

→ slow : ~ 50 ns

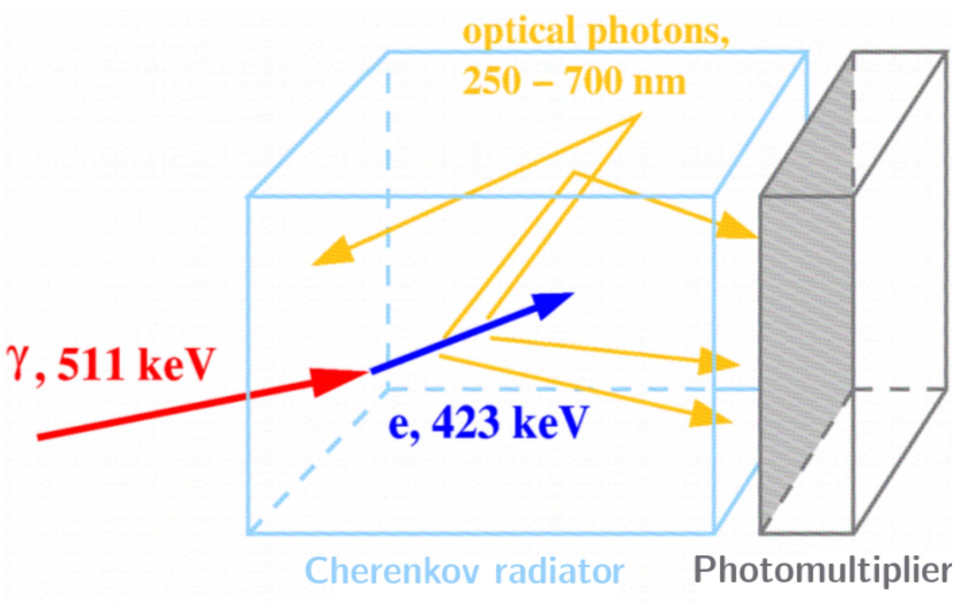
To improve the TOF : using of **Cherenkov radiation**

→ fast : ~ 10 ps

→ development of 2 projects : **CaLIPSO** and **PECHE**

PECHE : towards a new PET technology

Development of a complet detection chain optimized for 511 keV :
Cherenkov radiator - Photomultiplier – Electronic – Acquisition



→ Conversion of the 511 kev γ through **the photoelectric process** or through the Compton effect. The photoelectric effect produces an energetic and relativistic electron.

→ Production of **Cherenkov photons**, detected by the photomultiplier attached to the **Cherenkov** radiator.

PECHE : towards a new technology PET

→ Cherenkov radiator : PbF_2 crystal :

* very fast with Cherenkov radiation
* attenuation length : 9 mm
* one of the highest photoelectric probability

→ MicroChannel Plate-PMT

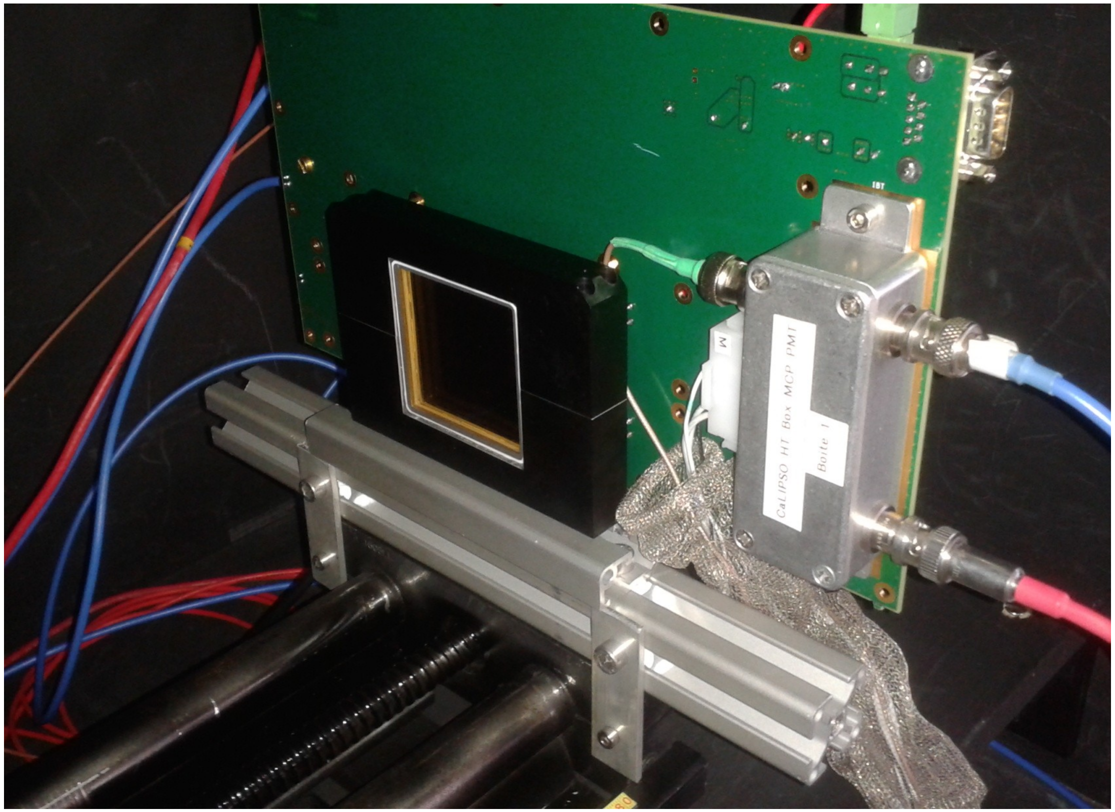
→ Preamplifiers 1.5 GHz bandwidth

→ SAMPIC module :

Time and Waveform Digital Converter (TWDC) chip

PECHE : towards a new technology PET

→ MicroChannel Plate PhotoMultiplier Tube



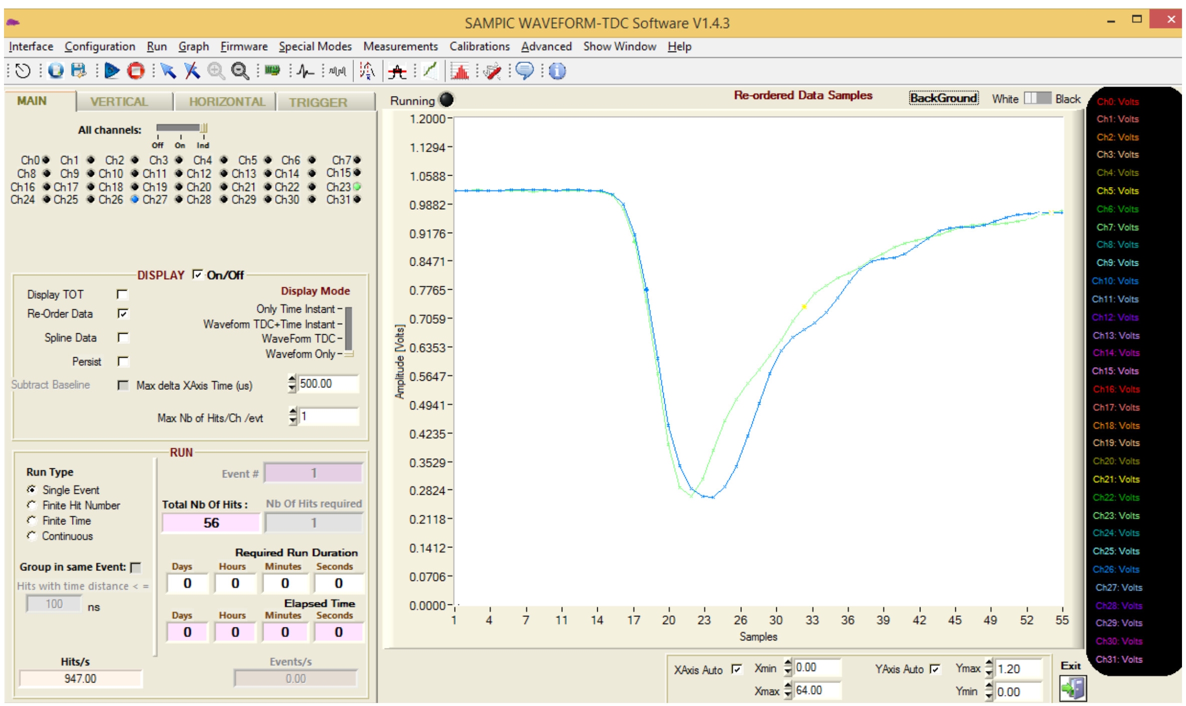
25 μm MCP-PMT Photonis
XP85012 Planacon

* 8x8 anodes
* Low "Dark Count Rate" $\simeq$ 100 Hz/cm^2
* Quantum Efficiency up to 25 %
* Active surface : 53 mm x 53 mm
* Very fast : TTS $\simeq$ 70 ps (FWHM)
* Windows material : sapphire

PECHE : towards a new technology PET

→ SAMPIC module for numerization of signals

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

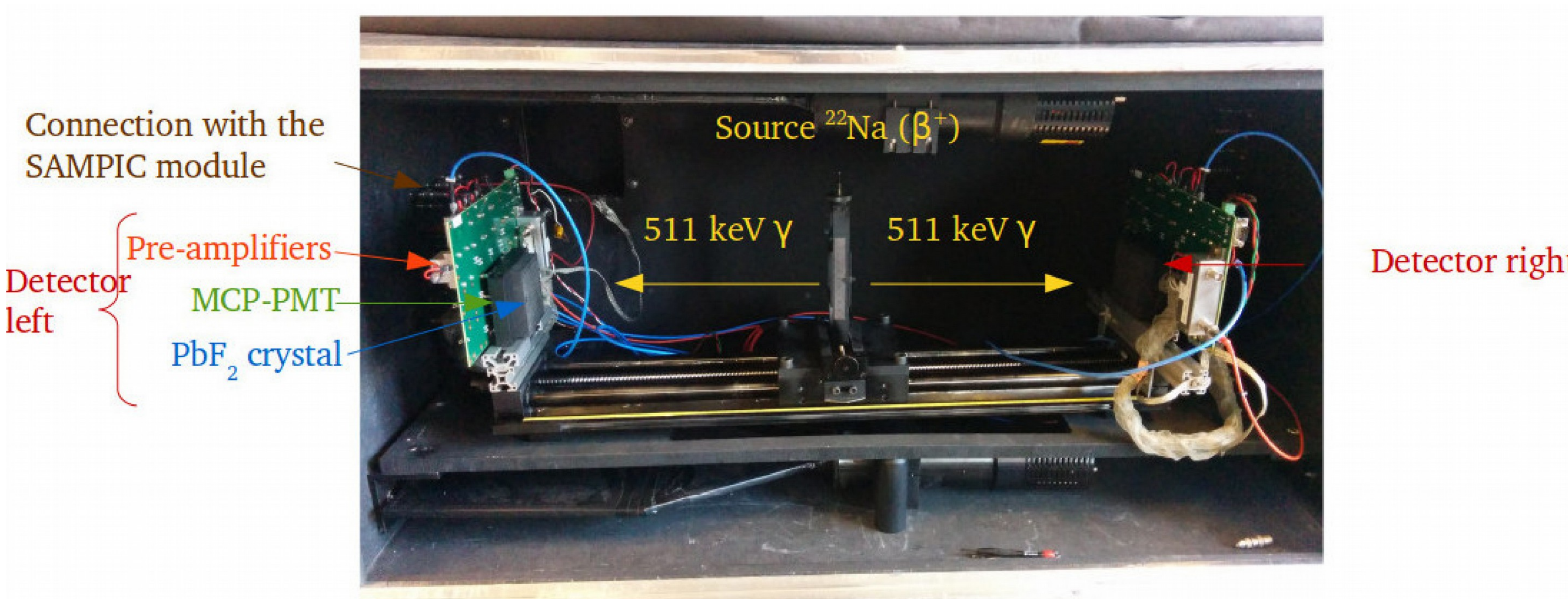


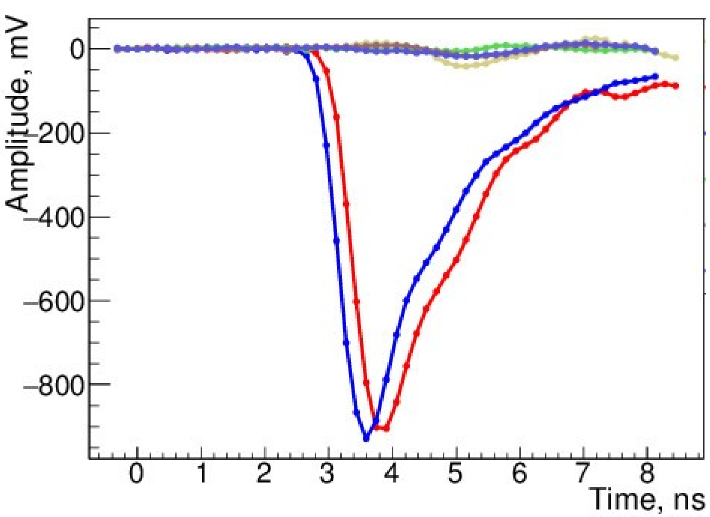
* provides digitized waveform with 64 samples

* extremely good resolution in time : < **5 ps (σ)**

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

Time Resolution





* intrinsic dispersion of the optical paths in the crystal : **30 ps** (FWHM) according to the simulation

→ **negligeable**

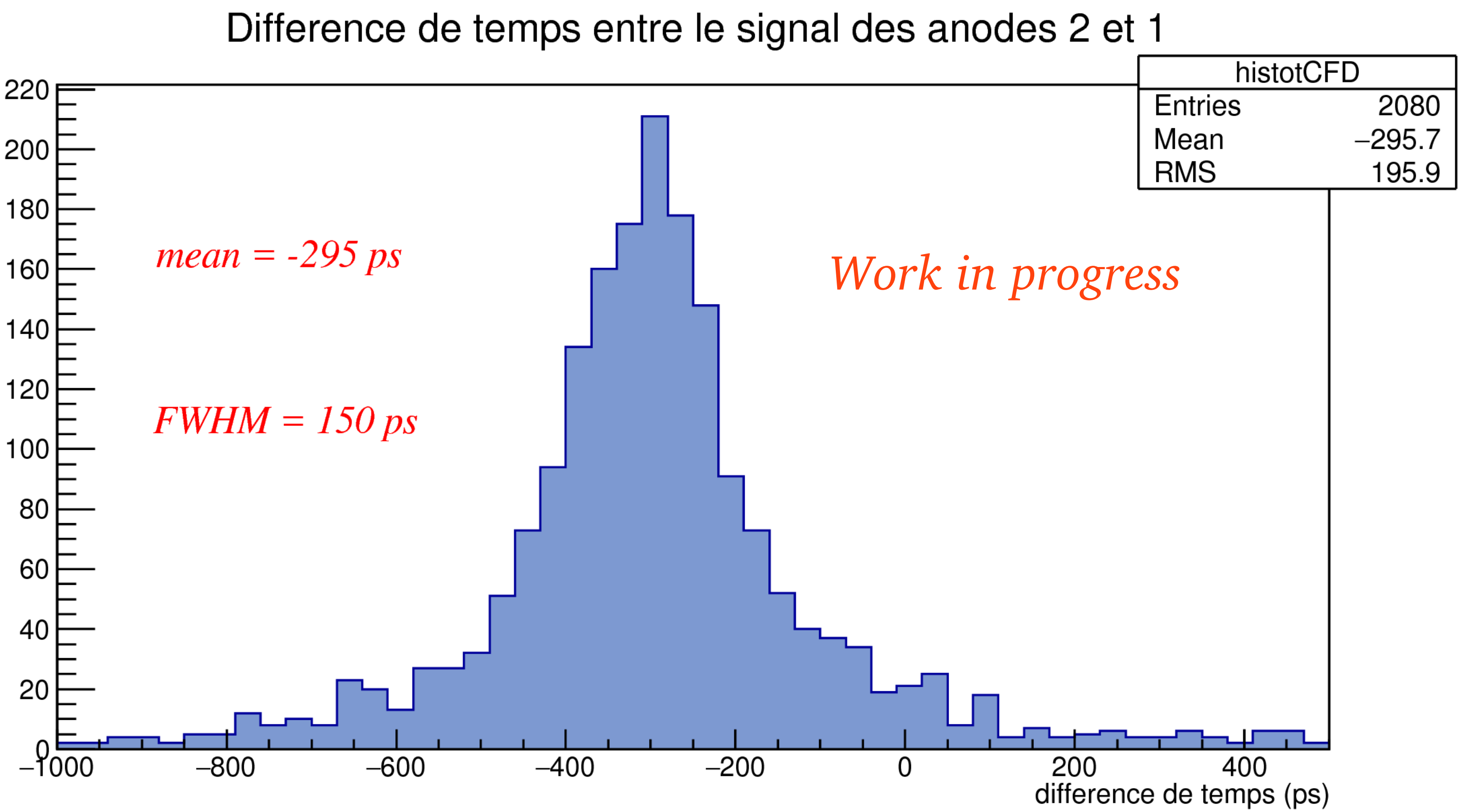
* TTS of MCP-PMT : **70 ps** (FWHM)

→ **main limitation for the time resolution**

→ **Expected ~ 70 ps (FWHM)**

Time Resolution

→ Time difference between two detectors



Resolution for a single detector : ~ 100 ps

Efficiency

→ For one 511 keV gamma arrived on the crystal, which probability I have to detect it ?

* gamma-conversion efficiency

* photoelectric conversion in PbF_2

* production of ~ 20 Cherenkov photons

* optical interface between crystal and MCP-PMT

* quantum efficiency of MCP-PMT

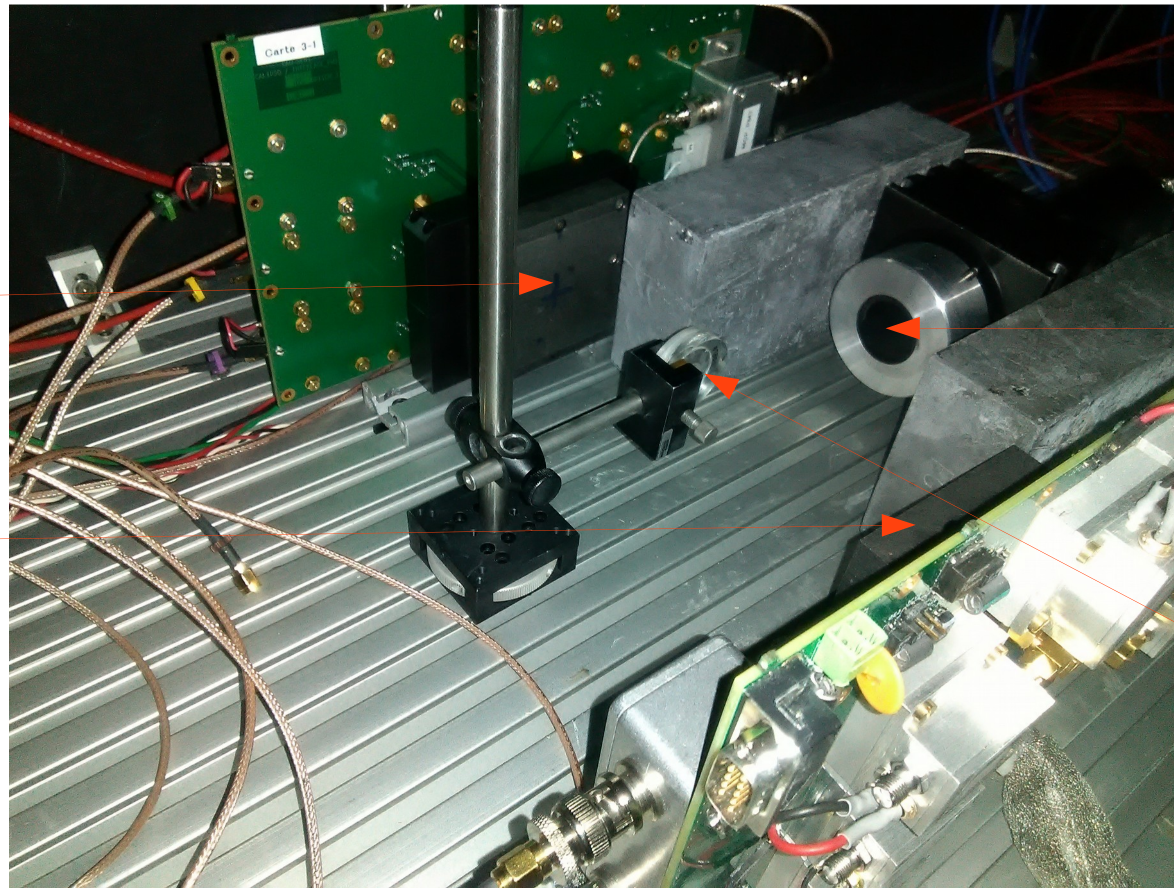
→ I expect ~ 25 %

Efficiency

→ Measured with reference YAP detector with « TAG & PROBE » method

PMT TAG :
γ 511 keV

PMT PROBE :
γ 511 keV



YAP detector :
γ 1.3 MeV

^{22}Na source
(beta emission)

→ I reach 22 %

Efficiency

→ For one 511 keV gamma arrived on the crystal, which probability I have to see its the signal ?

* gamma-conversion efficiency

* photoelectric conversion in PbF_2

* production of ~ 20 Cherenkov photons

* optical interface between crystal and MCP-PMT

* quantum efficiency of MCP-PMT

→ We expect ~ 25 %

Conclusion

→ I obtained the first result on time resolution of 100 ps.
I al working on the optimization of read-out electronics and improvement of the time performance.

→ I demonstrated the possibility to detect a Cherenkov light of 511 keV photon in PbF_2 with the high efficiency of 22 %.

→ I am now working on a demonstrator with a liquid Cherenkov radiator instead of crystal.

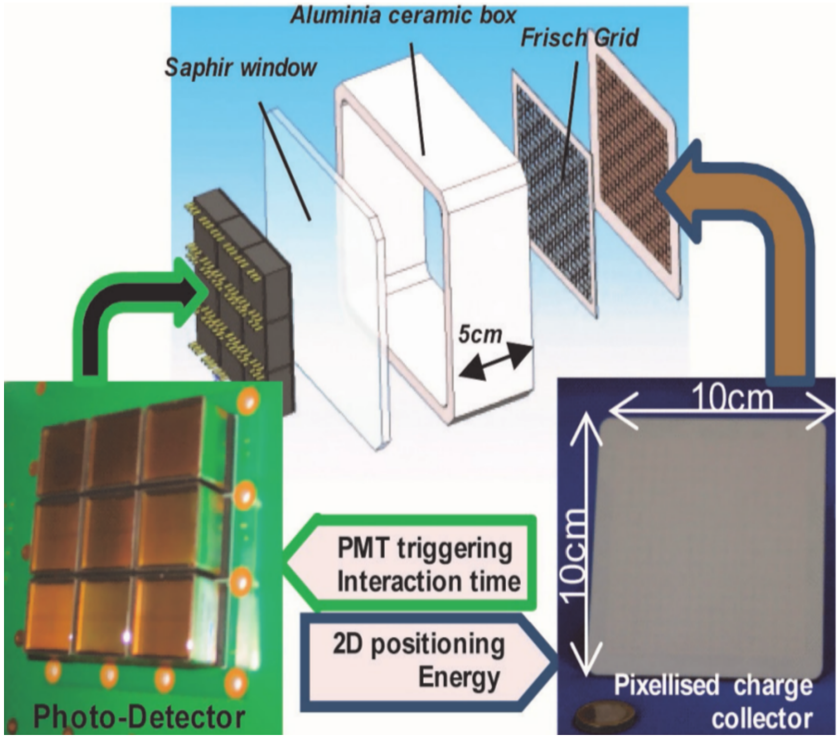
Thank you for your attention !

Back-up – CaLIPSO : brain studies PET scanner

- **Cherenkov** radiator : Trimethyl Bismuth (TMBi), limpid and dielectric liquid, highly efficient (47 %) for photoelectric conversion of 511 keV photons.

- Double detection : **optical signal** and **ionization signal**
  - Cherenkov light detected by micro-channel plate photomultiplier (MCP-PMT)
  - Free electrons induced a charge pulse on a pixelated plane on the other side of the detector

- Expected time resolution : **~ 100 ps** (FWHM)
  3D positionning : **~ 1 mm^3**



Back-up – PET-scans currently used

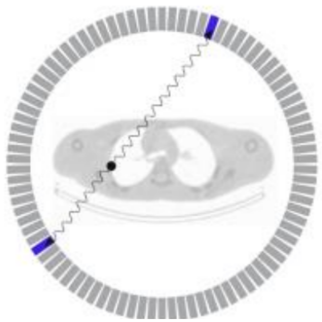
Scintillating crystals : detectors more used in PET. Composed of a scintillating crystal which converts the γ in visible photons, detected by PMT.
NaI, BGO, LSO, LYSO

Semi-conductors : direct conversion of the γ in signal of charge. In the matter, the energy deposited by the γ creates some electron-ion paires, which there number are proportionnal to the deposited energy. These charges are collected to produce the detection signal, and so on can calculate the initial γ energy.
CdTe, CZT

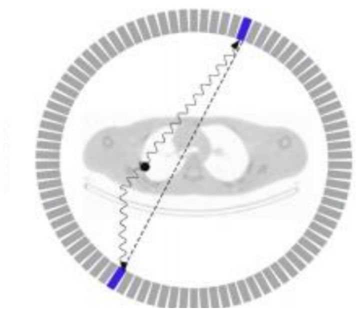
RPC (Resistive plaque chamber) : it is a gas volume between 2 electrodes. Interactions with the photons are in the electrodes and the multiplication is done in the gaz.

(TPC) Time projection chamber with liquid Xenon

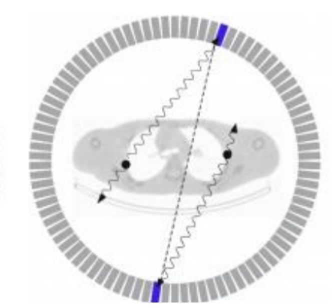
Back-up – Coincidences



True coincidences : They come from the detection of the 2 gammas emitted by **the same annihilation** and which are not interacted in the matter. They are doing **the signal** which we are looking for. Only ~6 % of the decays product true coincidences. So, the detector must be the most efficient.



Diffused coincidences : They come from the detection of 2 gammas emitted by the same annihilation but for which **one of them did one or more Compton diffusion** ine the body patient before to be detected. So, the line of response is false. This phenomen can be reduced measuring the gamma energy, which is so less than 511 keV.



Fortuitous coincidences : They come from the detection of two gammas in the same coincidence windows but which are emitted **by two different annihilations**. The number of these coincidences is proportionnal to the time of the coincidence windows. So, this number can be reduce if we reduce the time of the windows and thus if we have a detector with the best time resolution.

Back-up – Noise Equivalent Count Rate (NECR)