Clear Mind

CEA - Saclay

ClearMind project: development of the TOF-PET detection module with tens-picoseconds time resolution

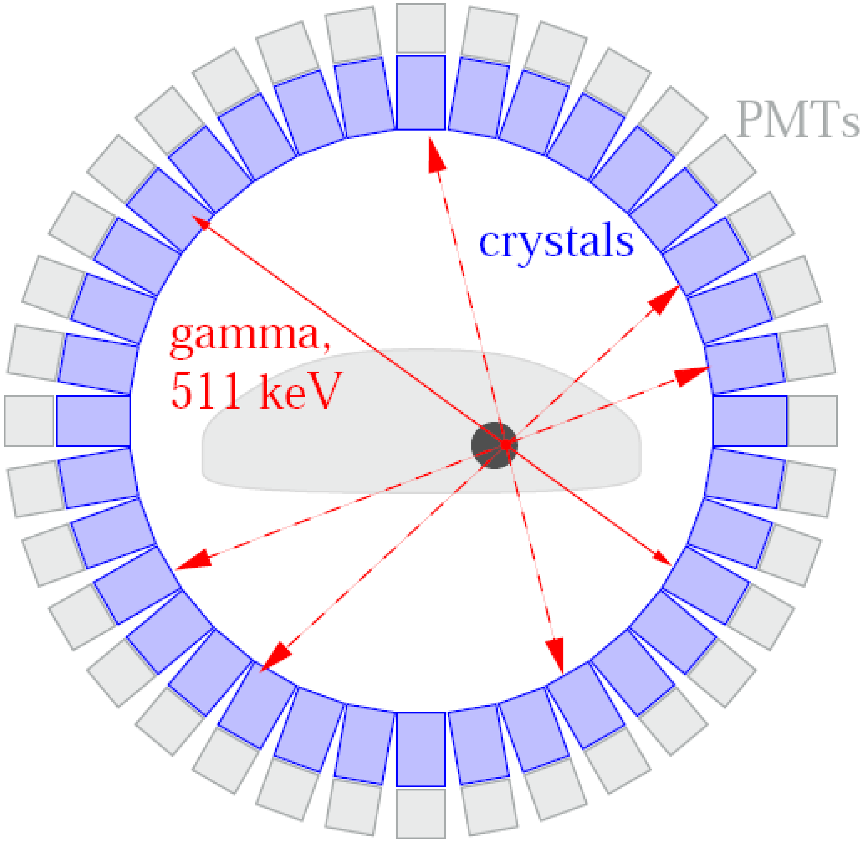
V. Sharyy
for the ClearMind Collaboration

French-Ukrainian Workshop on Instrumentation
September 19, 2020

Positron Emission Tomography

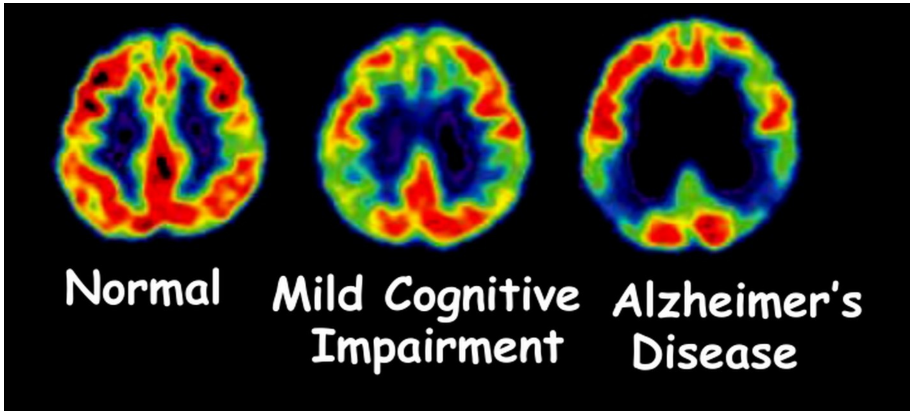
- PET is a nuclear imaging technique used widely in oncology, cardiology and neuropsychiatry.
- Allows to detect at picomol level the the biochemical activity.
- PET scan in a nootshell:
  - Inject one of the radioactive tracer

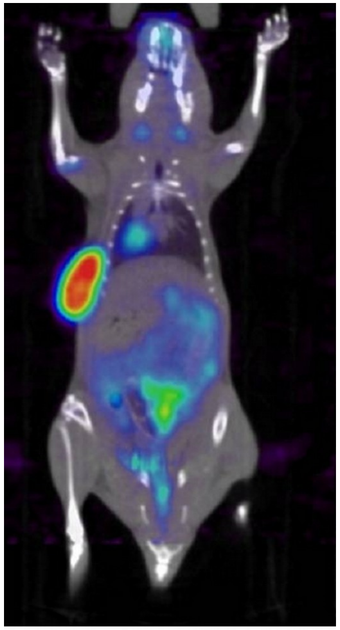
    e.g. ^{18}F-FDG, τ~110 min, ~one hour rest time
  - emits positrons ⇨ annihilation with an electrons ⇨ two 511 back-to-back gamma.
  - Gamma detection in coincidence ⇨ register ~100M lines-of-responce ⇨
  - 3D image reconstruction

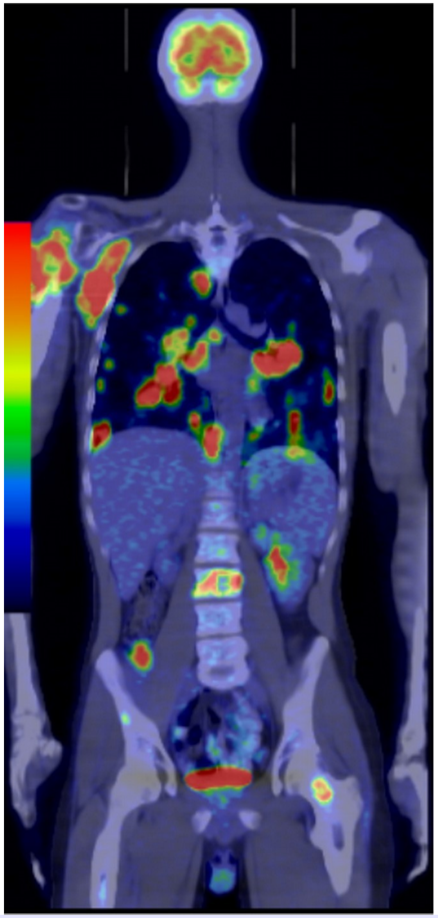


Scanner Types

- Preclinical (small animals)
  - Small aperture
  - High spatial resolution
  - Small sensitivity
- Brain scanner
  - Limited aperture
  - High sensitivity
  - Good spatial resolution
- Whole-body
  - Large aperture
  - High sensitivity
  - Low spatial resolution
  - Full body dose ~ **5 – 15 mSv** (natural radioactivity per year France : 2 mSv)

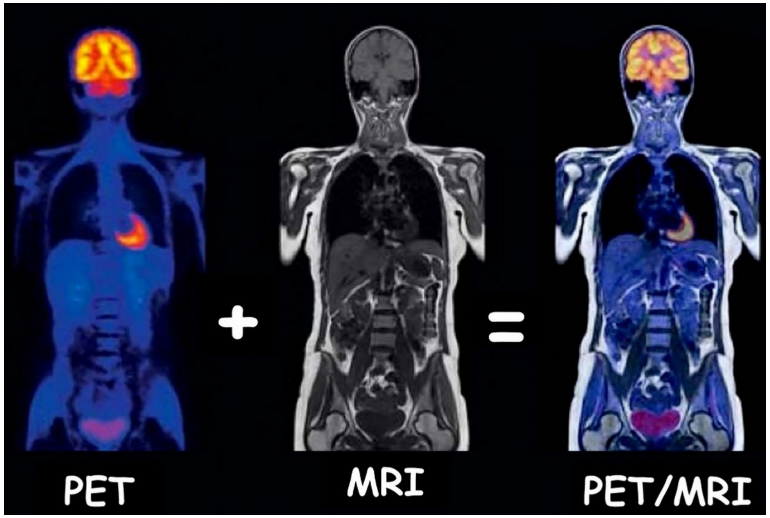




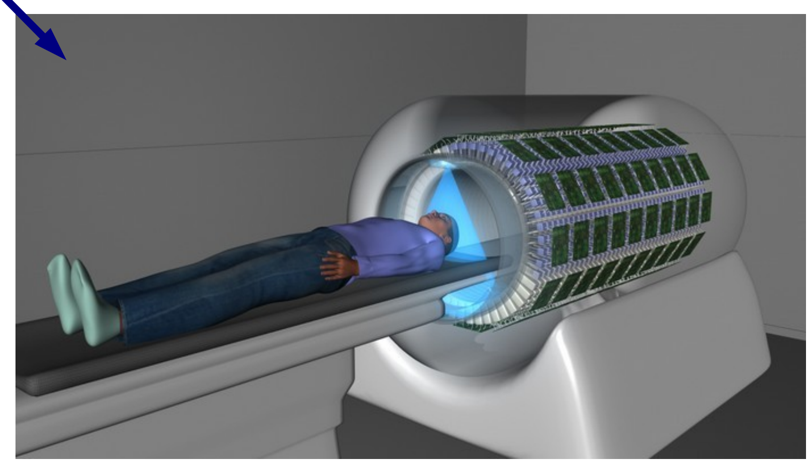


PET Evolution

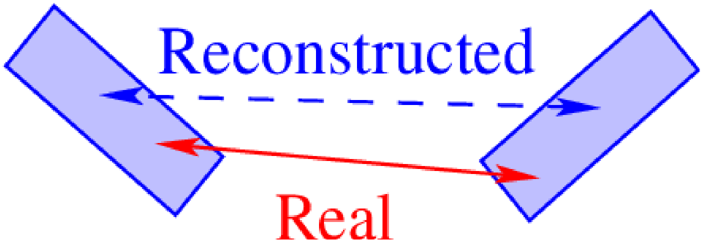
- Combined modalities: CT/PET, MRI/PET



- Improvement sensitivity: total-body PET → 40 fold improvement in sensitivity

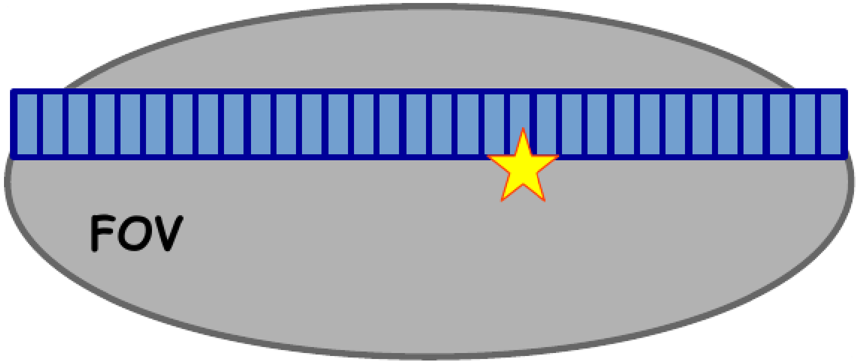


- *Reduce bias: depth-of-interaction reconstruction*

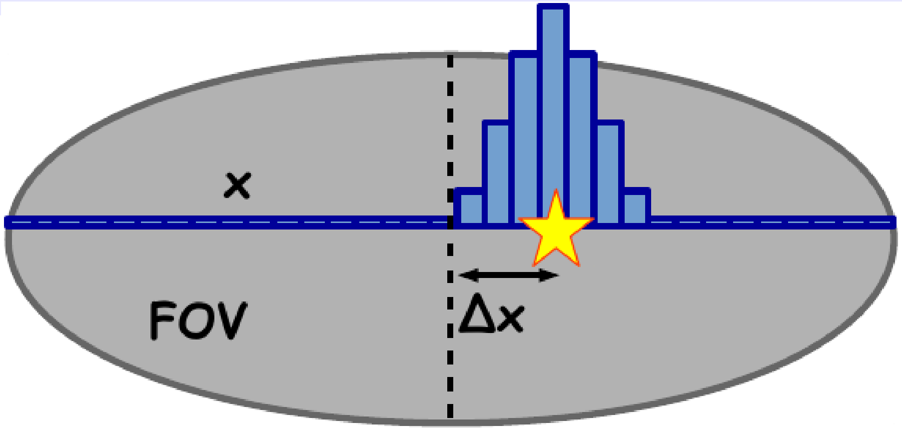


- Time-of-flight technique (TOF) ⇨ see next slides
- New developments in electronics, and gamma-detection

TOF Technique



Conventional PET



TOF PET

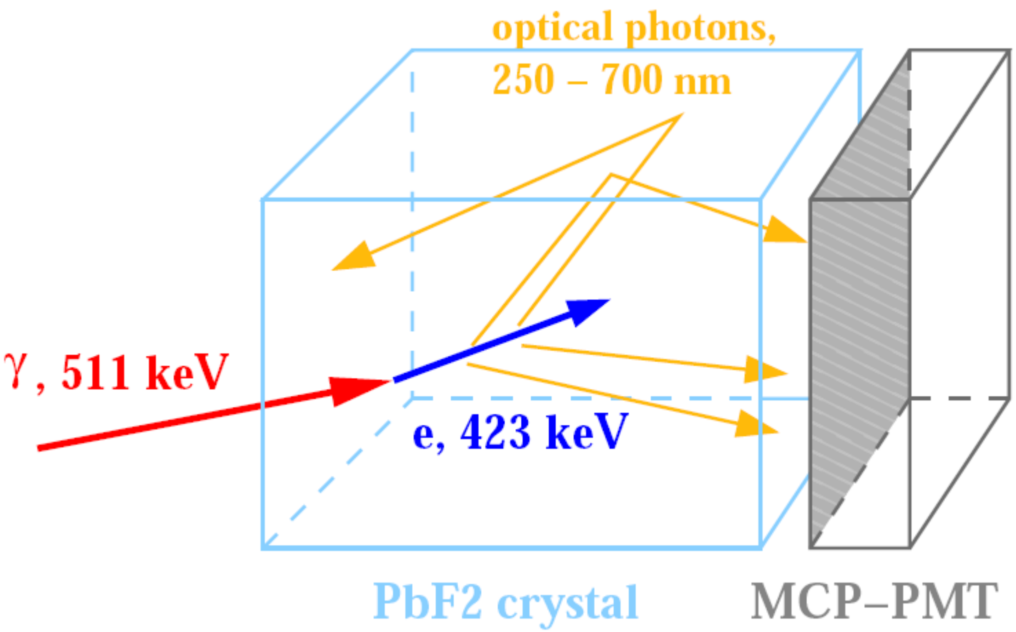
- TOF techniques: measure the difference in time between two photons ⇨ improve S/B
- Contrast of the image directly correlated to the S/B and available statistics.
- TOF gain estimation:

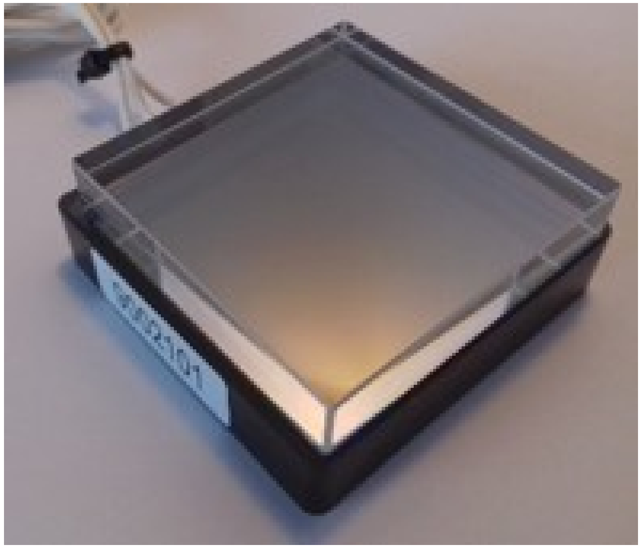
$$G = \frac{S/N_{TOF}}{S/N_{noTOF}} \sim \sqrt{\frac{D}{\delta x}} \sim \sqrt{\frac{D}{c/2\ \delta t}}$$

D=30 cm ⇨ CRT=**150 ps** (FWHM) ⇨ G~2.9 ⇨ **8x lower dose**

Previous Studies: Cherenkov Detection

- **High resolution TOF and high efficiency** for whole-body PET : ***PECHE*** project
  - Non-scintillating crystal, PbF2, as a detection medium
  - Use Cherenkov light for the detection → Radiation time ~ few ps
  - Goal: CRT < 100 ps (FWHM)
  - Use the fastest type of PMT : micro-channel-plate PMT
  - Use the dedicated high-speed digitizing electronics developed by IRFU and LAL, IN2P3

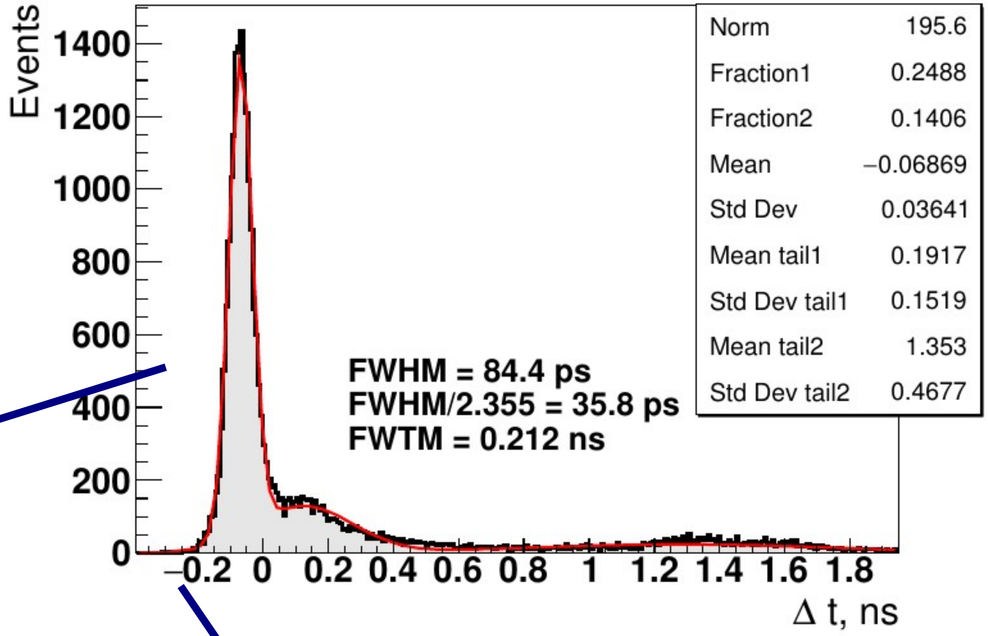




C. Canot et al., *J. Inst. 14 P12001 (2019) arXiv:1909.06107*

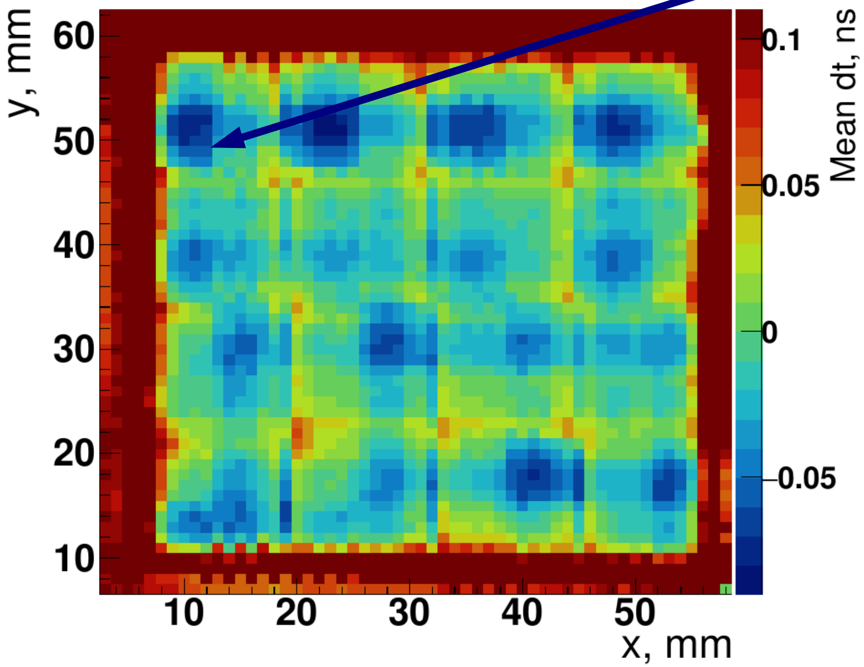
Previous Studies: PMT Readout

- Measure time difference between PMT and pulse laser (20 ps beam duration)
- 1 mm step size
- ~70kHz acquisition speed
- ~2 hours per PMT



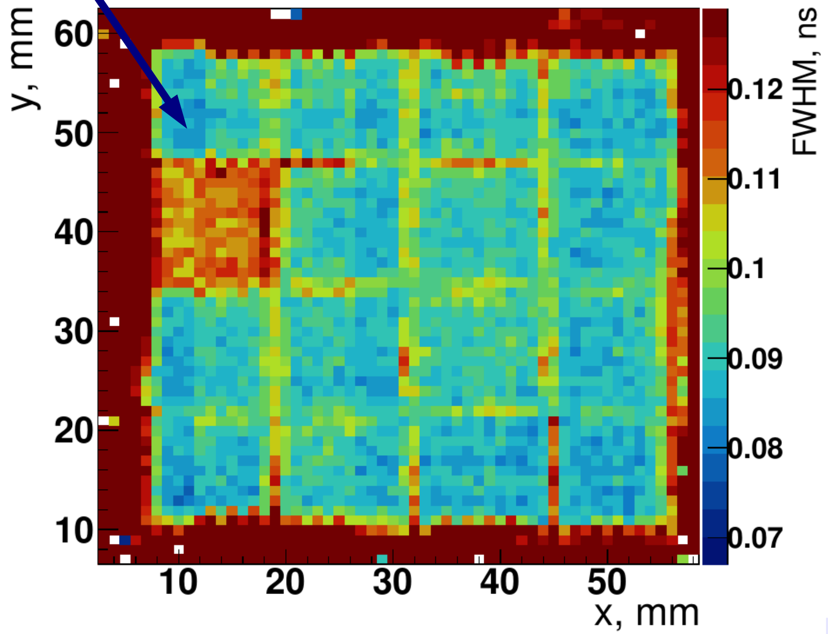
FWHM = 84.4 ps
FWHM/2.355 = 35.8 ps
FWTM = 0.212 ns

Distribution Mean

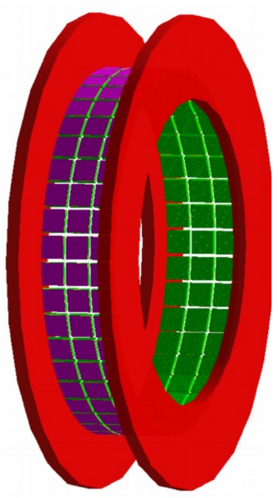


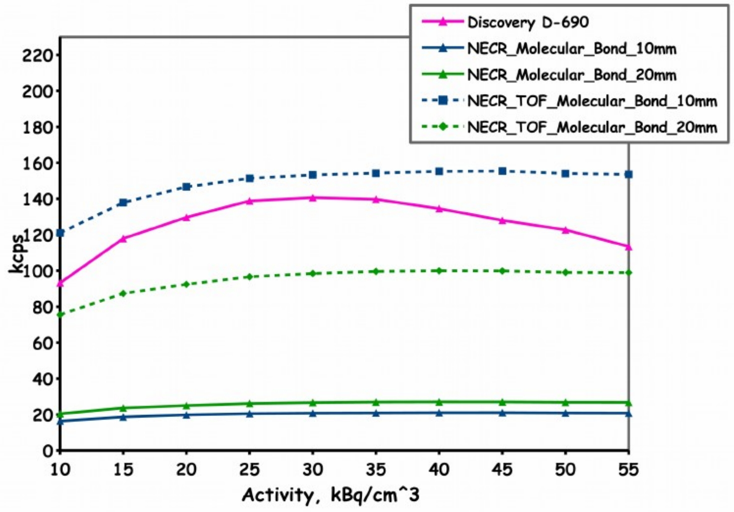
⇒ Need to apply a time calibration as a function of (x,y)

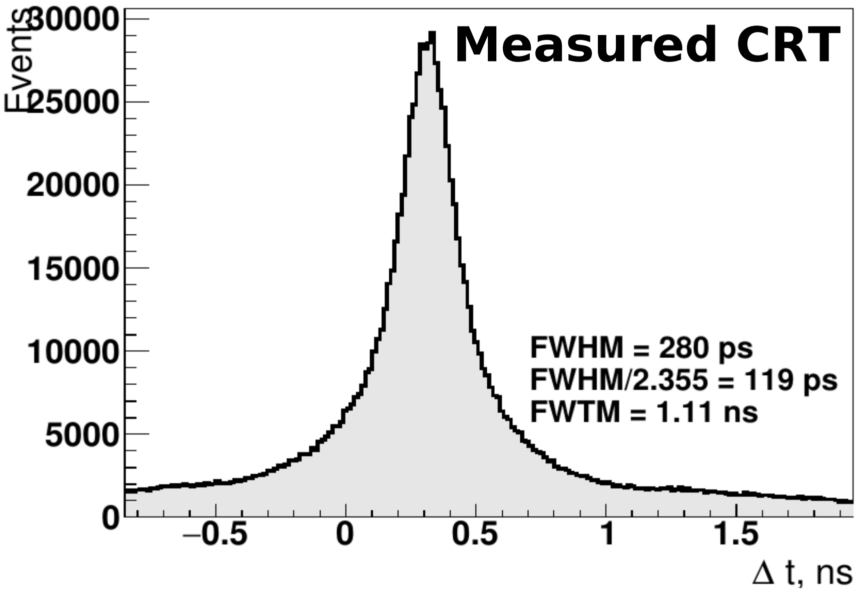
Distribution Width



Previous Studies: Results







$$\mathrm{NECR} = T^2/(T + S + 2R)$$

$$\mathrm{NECR}_{\mathrm{TOF}} = D/\Delta x * \mathrm{NECR}$$

T – rate of true coincidences
S – rate of scatter coincidences
R – rate of random coincidences

- Full chain of the high-efficient, large surface, Cherenkov based detection module : efficiency of ~**25%** and CRT of **280 ps** (PbF_2)
- In the optimal-case scenario the Cherenkov whole body PET could be comparable with commercial devices: not very encouraging.
- To optimized CRT: (1) Increased number of the detected optical photons; (2) Continuous read-out in order to use the full potential of the PMT

M. Alokhina,
"Design of the Cherenkov TOF whole-body PET ..."
PhD thesis, 2018

ClearMind Project

Efficient Cherenkov and Scintillation Detection With High Spatial Precision and high TOF for brain/whole body PET

ClearMind Collaboration :

- ***CEA Saclay - DRF/IRFU***, *D. Yvon, V. Sharyy, M. Follin, C-H. Sung, et al., (+ E. Delagne et al.), Patent accepted.*
- ***CNRS - IJC Labs - Orsay***, Service d'Electronique, D. Breton, J. Maalmi et al.
- ***CNRS - IN2P3/CPPM - Marseille***, C. Morel, M. Dupont, et al.
- ***CEA Saclay - DRF-ISVFJ/SHFJ*** – S. Jan, C. Comtat, et al.
- ***CEA Saclay - DES-ISAS/LGLS*** – J.M. Martinez

With :

Chemistry advices :

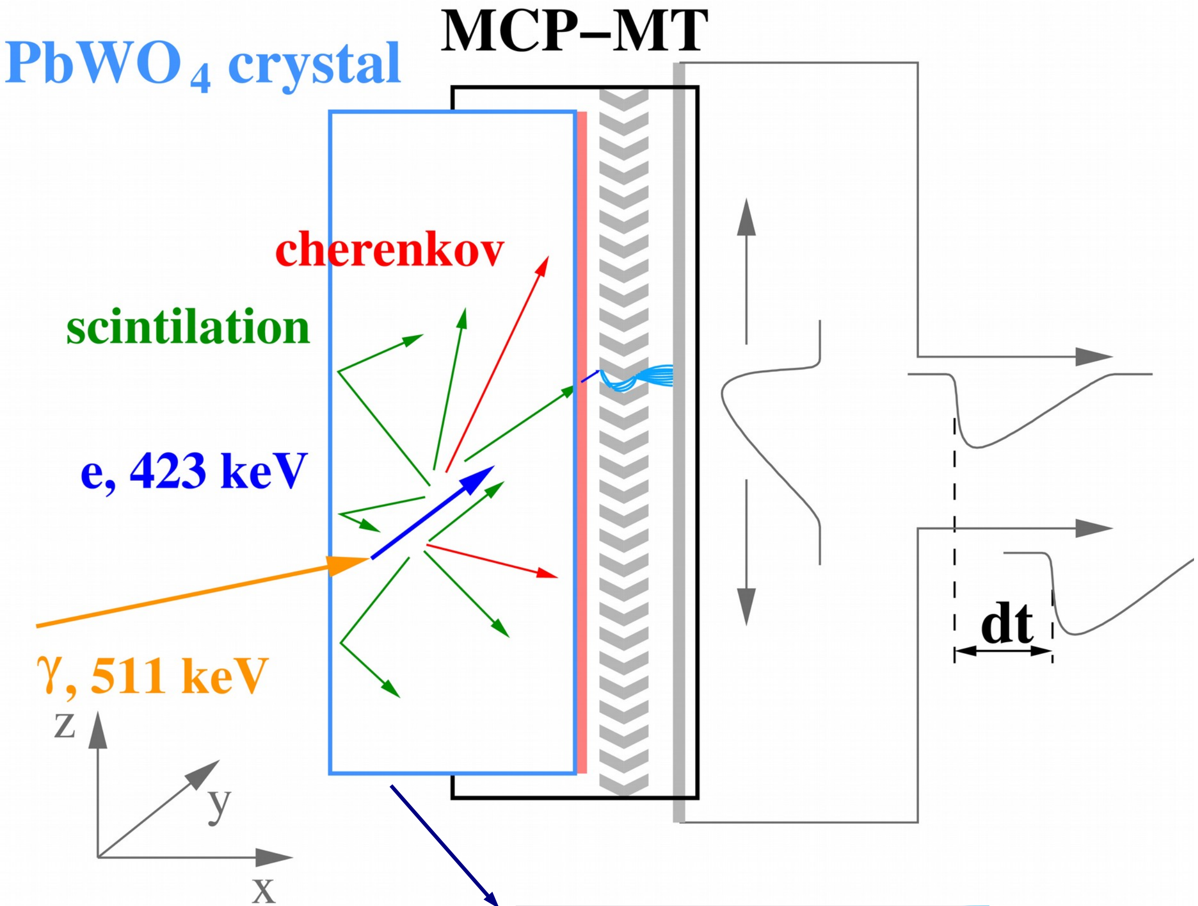
- ***CEA-DRF/IRAMIS*** – J-Ph. Renault, CEA-DEN/DPC/SCP – S. Chatain, CEA-DEN

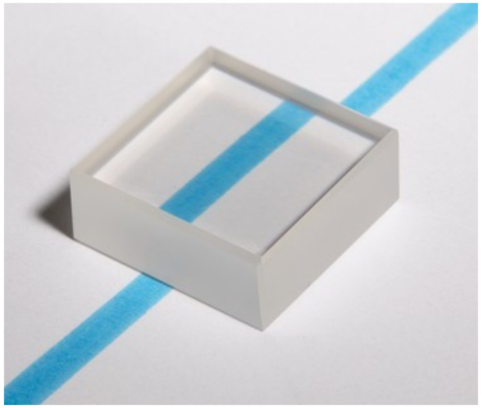
Scintillating Crystals :

- ***Belarusian State University***, *Research Inst. for Nuclear Problems*- M. Korjik.

Principles

- Direct deposition of the photocathode on the PbWO4 crystal: “***scintronic***” crystal
  - increase the number of detected Cherenkov photons
  - additional fast scintillation photons
- Use of monolithic crystal to reconstruct 3D interaction position and correct for DOI effect
- Use MCP for electron multiplication
- Use transmission line approach to reduce number of channels and improve PMT calibration

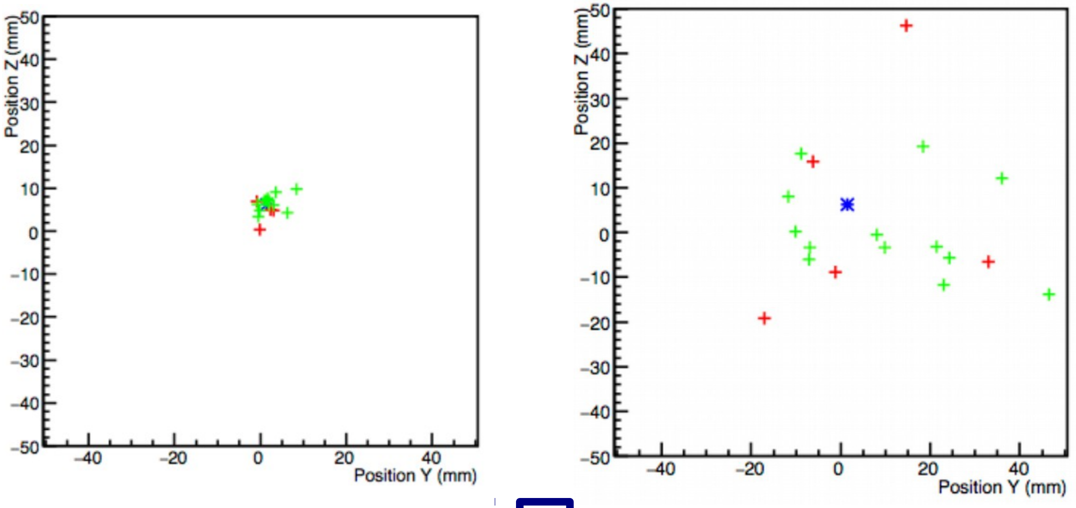




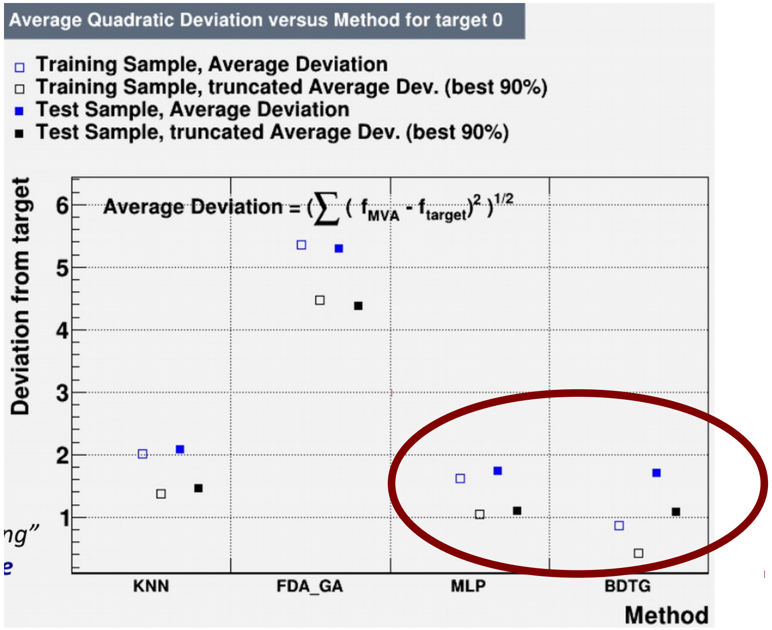
Patent CEA, FR1759065, 2017

ClearMind: expected performances

- Allow to increase by a factor of ~4, the number of generated photo-electrons
- Has a potential to reconstruct both all three coordinates inside the crystal with the precision of 1 – 2 mm.
  - The machine learning approach is needed to reach the optimal performance
- Time resolution: corrected for the DOI → expected CRT below 100~ps

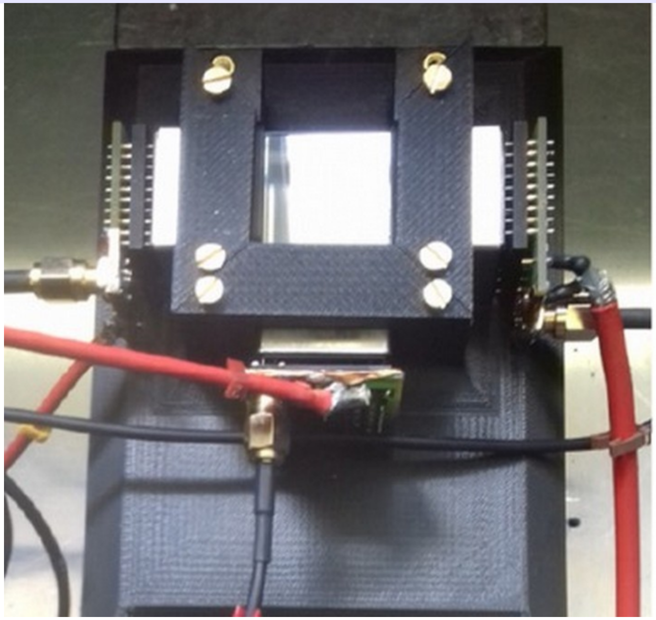


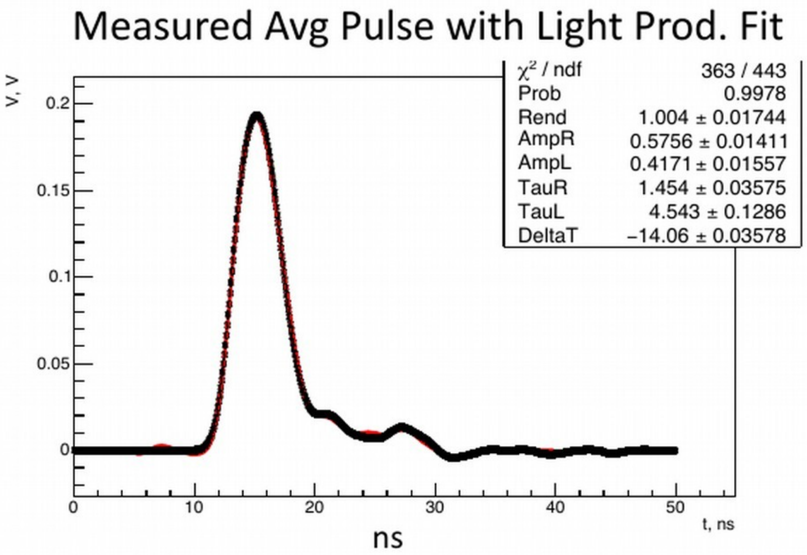
Machine Learning Approach



Crystal Performance

- Four PbWO4 technologies available:
  - CRYTUR: Panda II.
  - SICCAS : CMS
  - SICCAS: Yttrium-dopped
  - EPIC: Undoped PbWO 4
- Monté-Carlo simulation (GATE-GEANT4)
- Light-Yields Measurements: all doped crystals show similar light yields ~ 10% : 300 γ/MeV
- Scintillation time constant: short ~1.5 ns, slow ~ 5 ns @ 20°C
- Undoped crystal shows an additional very slow component.
- Large size Crystals are produced by Crytur

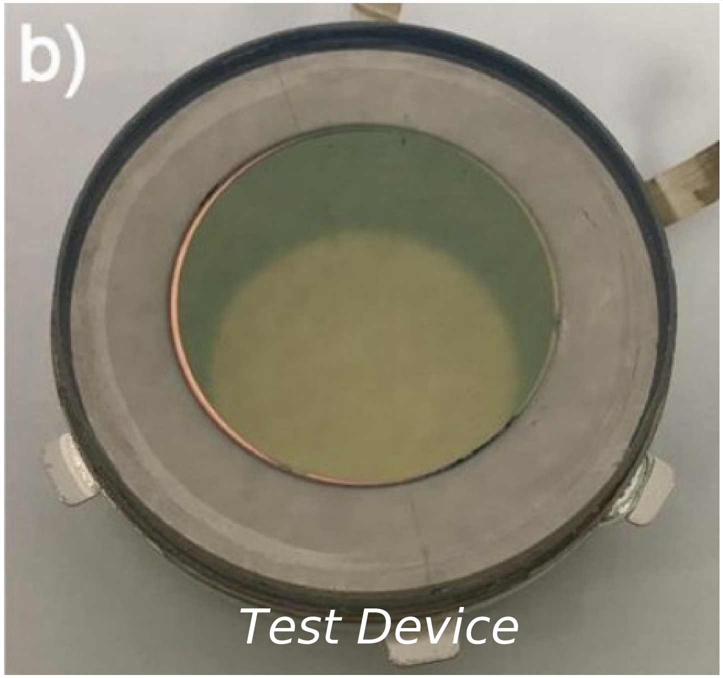




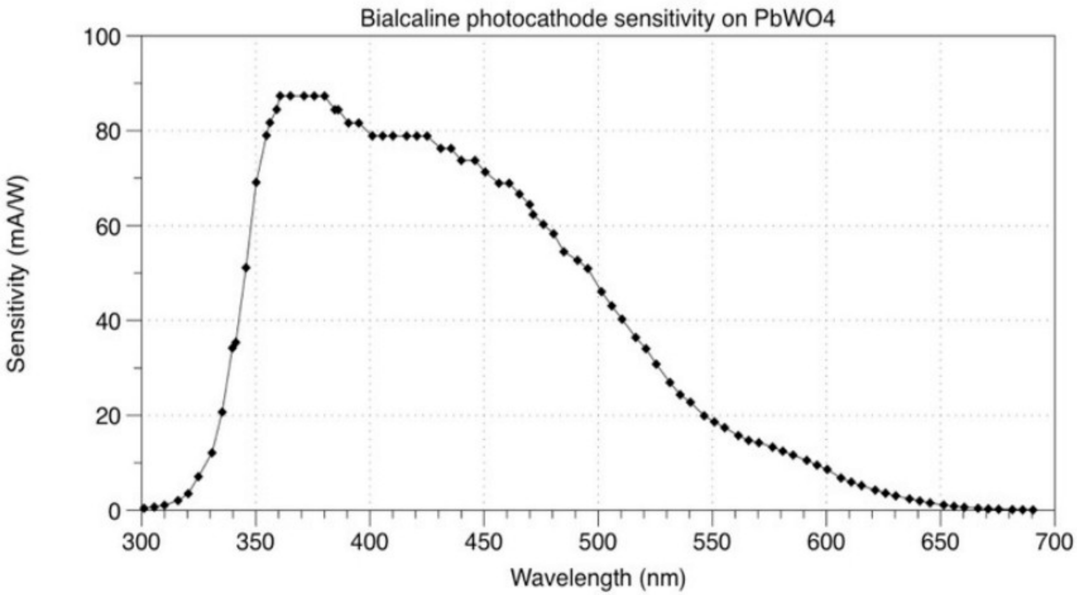
To be published soon: *M. Follin et al., JINST*

PhotoCathode Deposition Tests

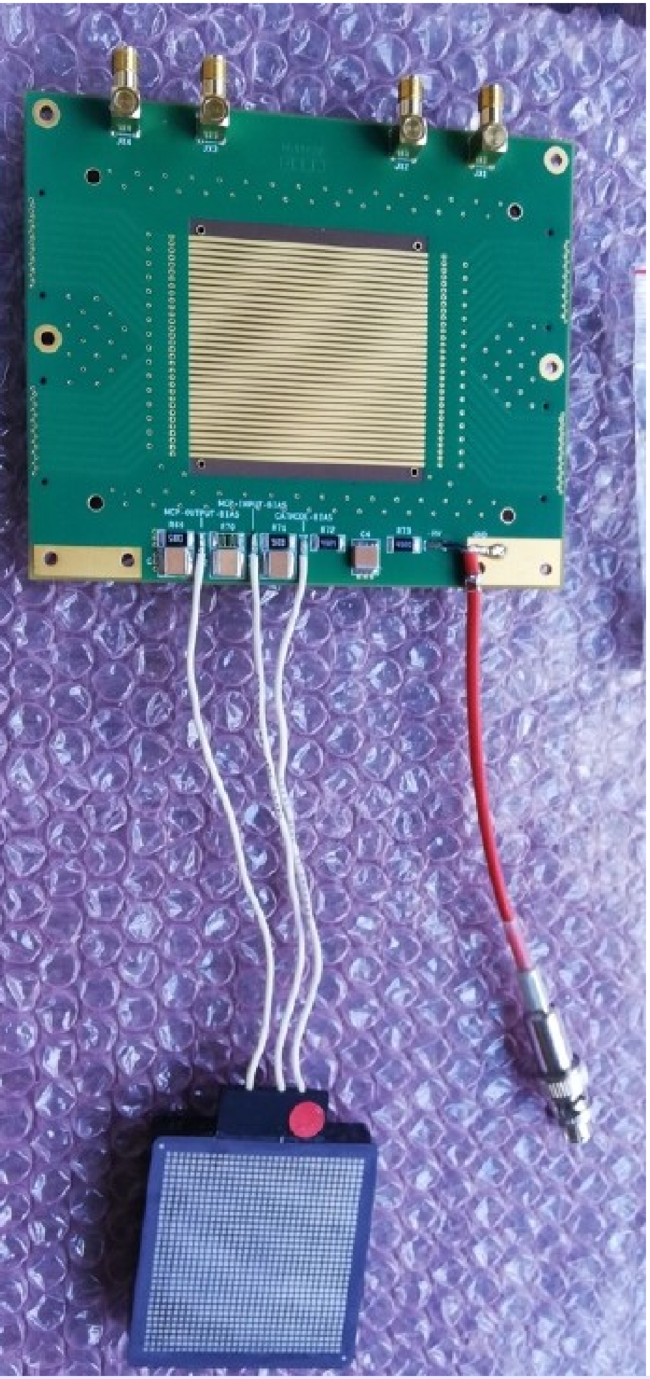
- R&D with Photek, UK
- Crystal produce by CRYTUR, Czech Republic
- Final test device:
  - 25% peak efficiency
  - Stable over 9 months
  - Still can be improved

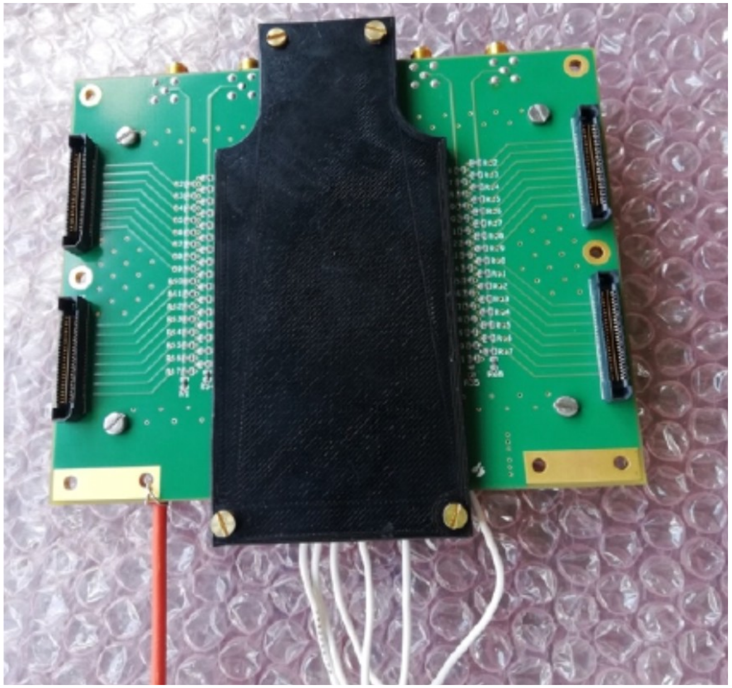


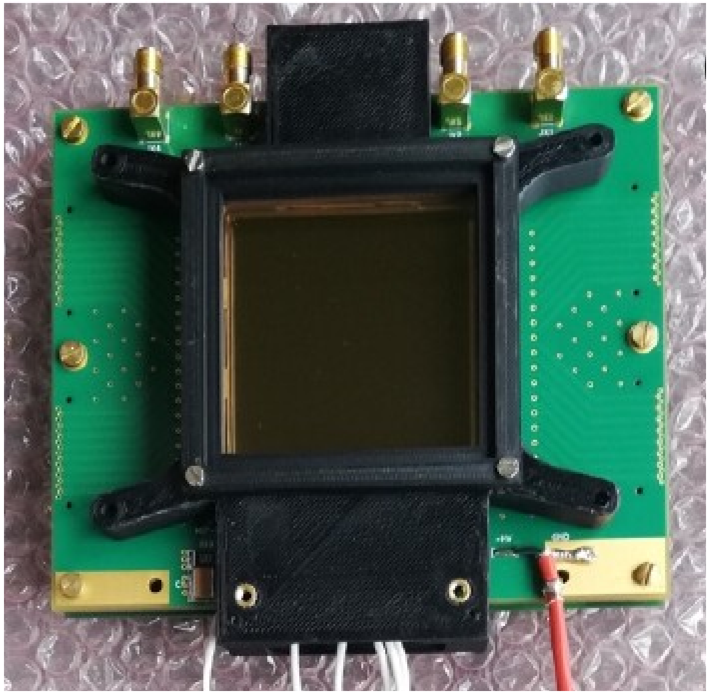
- **Major milestone achieved!**

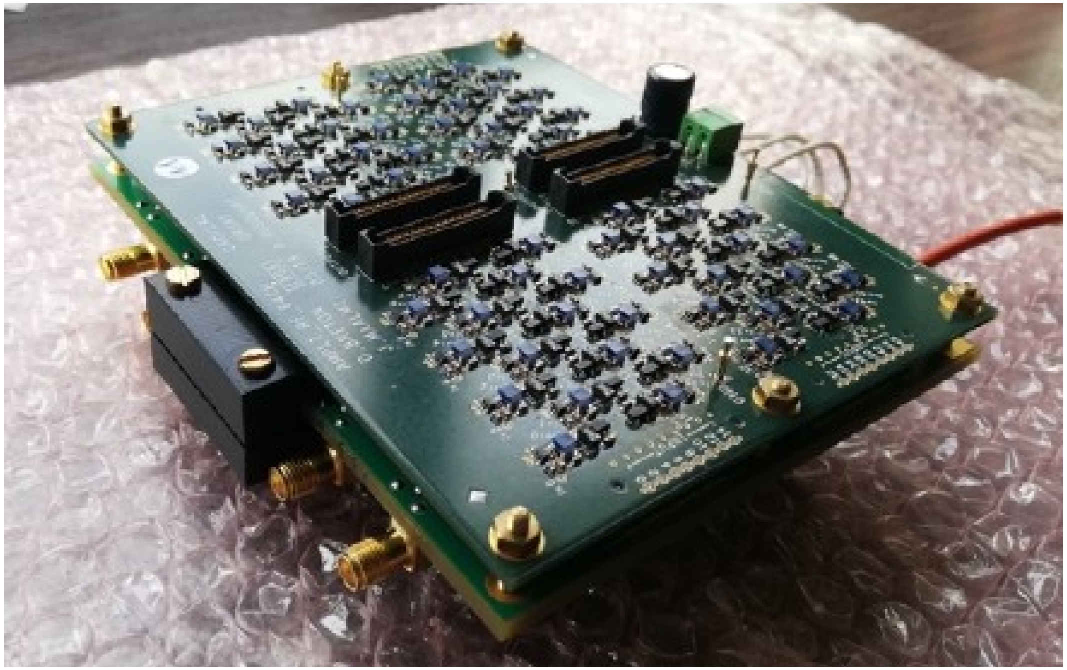


Transmission Line Readout



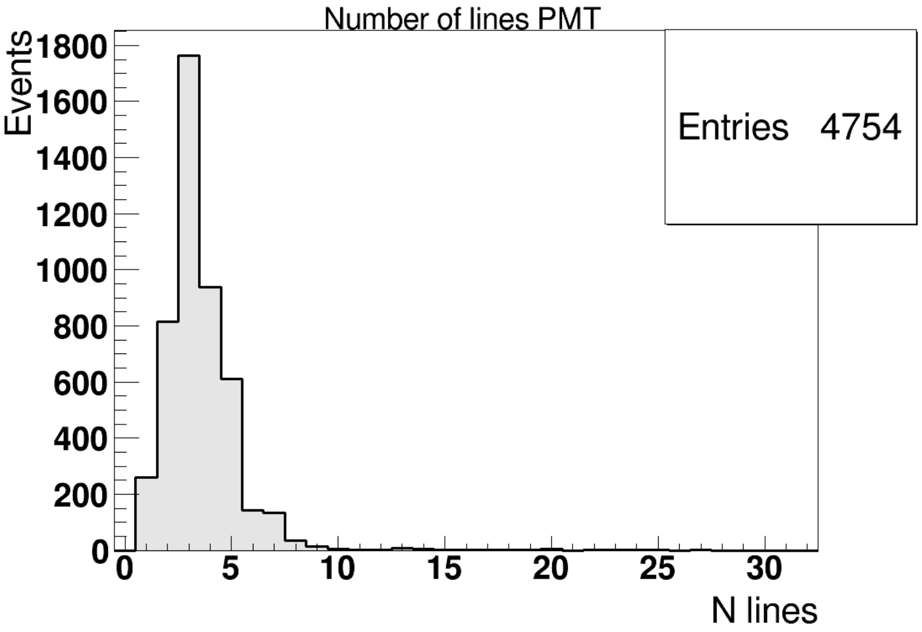




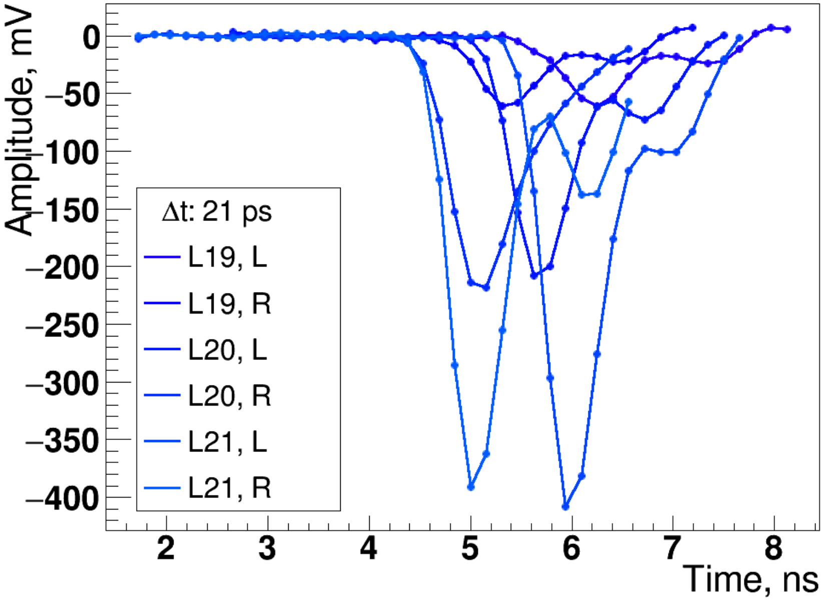


Read-out Through the Transmission Lines

- Use 10 µm Planacon MCP-PMT, 32x32 pads, 1.6 mm pitch
- Read-out with 32 transmission lines PCB.
- Both ends read-out through 40 db, 700 MHz LAL-made amplifiers and SAMPIC digitization module
- Using 20 ps pulsed laser to scan PMT

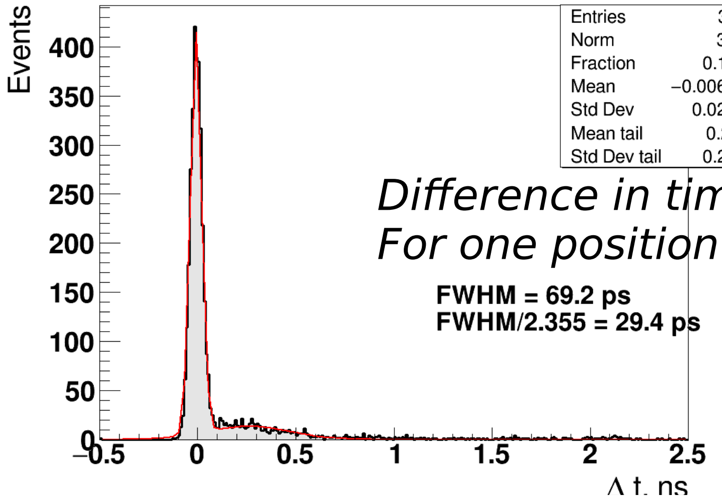


"Typical"signals in one event

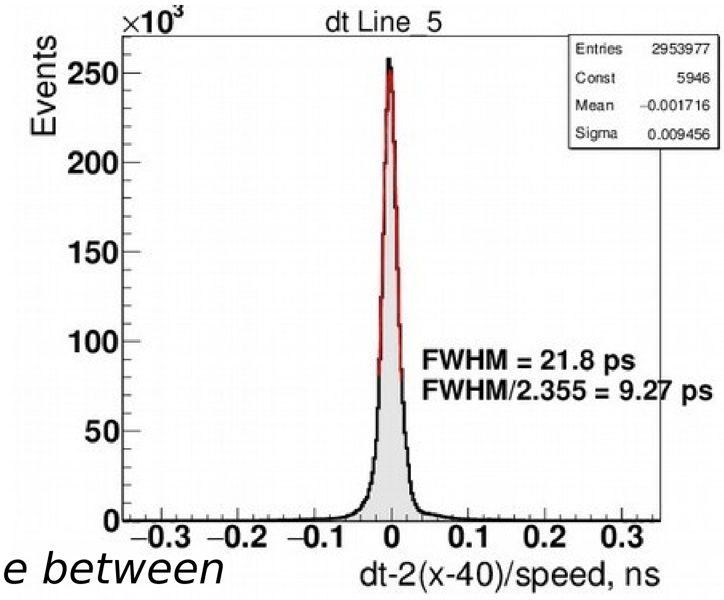


Read-out Through the Transmission Lines

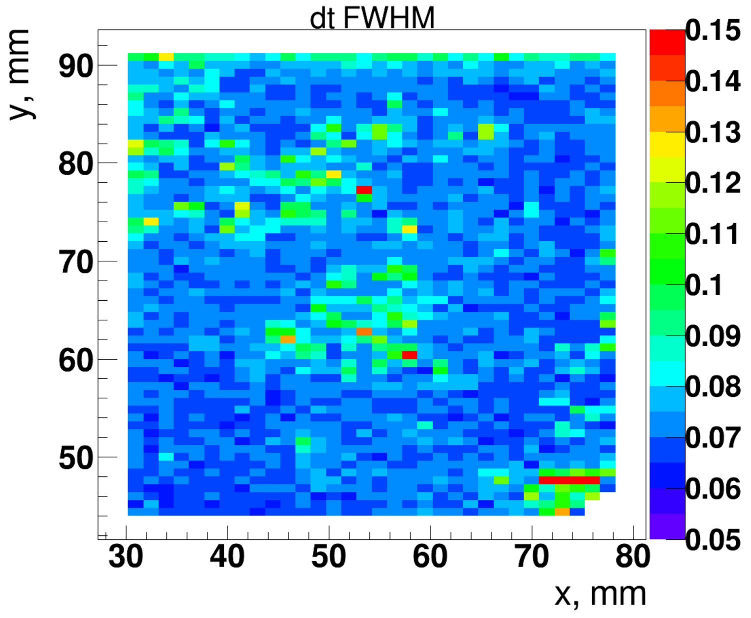
- Reach a ~ **20 ps** precision on time difference → spatial resolution ~ **1 mm (FWHM)**
- Measured PMT TTS down to **70 ps (FWHM)**

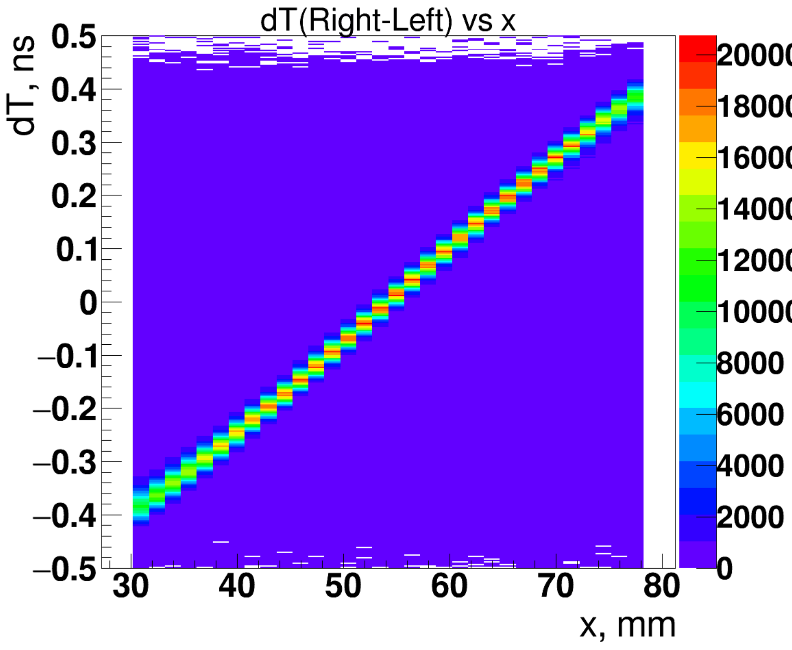


Difference in time: PMT-Laser
For one position



Difference in time between right and left ends for one position





Conclusion

- Development of the cutting-edge technology for use in PET, but not only.
- Main directions: high spatial precision and high TOF resolution
- Study a potential of the Cherenkov radiation for whole-body PET scanner by simulation and hardware test and identified main limitations for use of the Cherenkov technology

- The ongoing developments at IRFU have the ambition to overtake the identified limitations.
  - PET TOF high efficiency detection module with the 3D spatial resolution of **1–2 mm** and CRT < **100 ps**
- We are expecting to receive the 1st prototype before Christmas