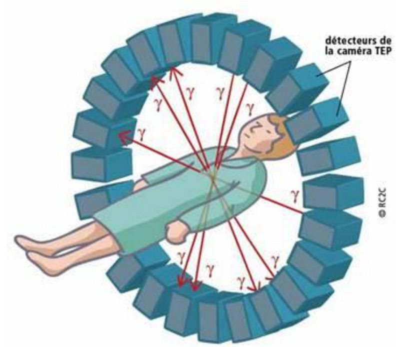
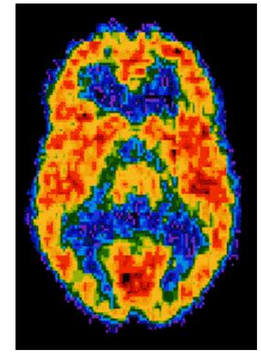
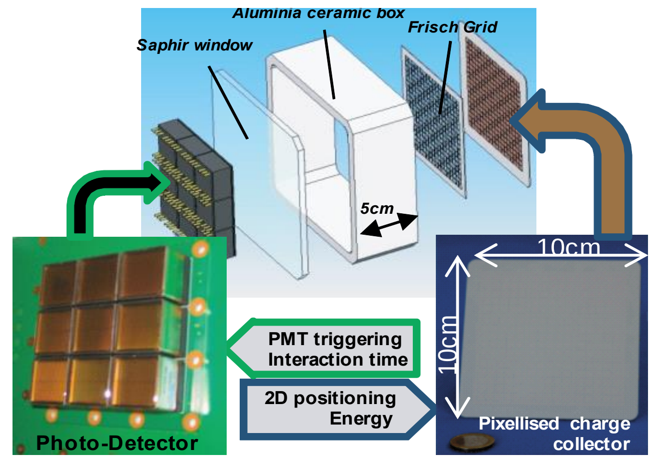
Status of the CaLIPSO High-Resolution PET Project

I. Achieving 1 mm^3 resolution for PET-scan
II. Physical principle
III. Optical detector
IV. Ionization detector
V. Full image simulation
VI. Conclusion







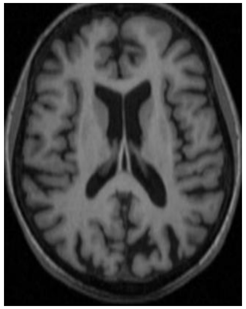
ICTR-PHE 2016

Xavier Mancardi

ACHIEVING 1 MM³ FOR BRAIN PET-SCAN

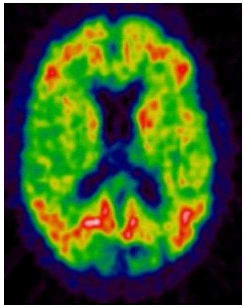
Magnetic Resonance Imaging (MRI)

- **Structure** visualization, 3D matter density
- **Excellent spatial resolution**: 1 mm^3 over the whole brain
- **Low sensitivity** to cells biochemical activity ~ 10^{-4} mol



Positron Emission Tomography (PET)

- Visualization and **quantification of biological activity**
- **Low spatial resolution,** $(2.2\ mm)^3$ at best over the whole brain
- **Excellent quantification** of the biochemical activity ~ 10^{-12} mol
- Irradiation of the patient and the **operator** ➔ Dose reduction



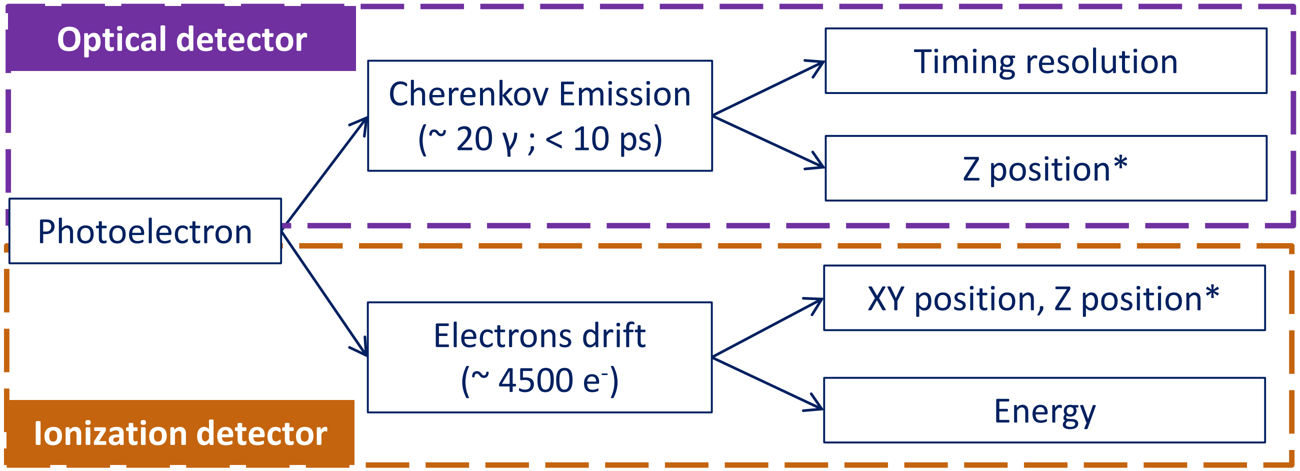
Issues

- **Localization** of γ interactions within the detector to **1 mm³**
- **Gain** in detection/imaging **efficiency** of a **factor 10**

➢ **Neuro-degenerative diseases research**

➢ **Positron annihilation spectrometry**

PHYSICAL PRINCIPLE



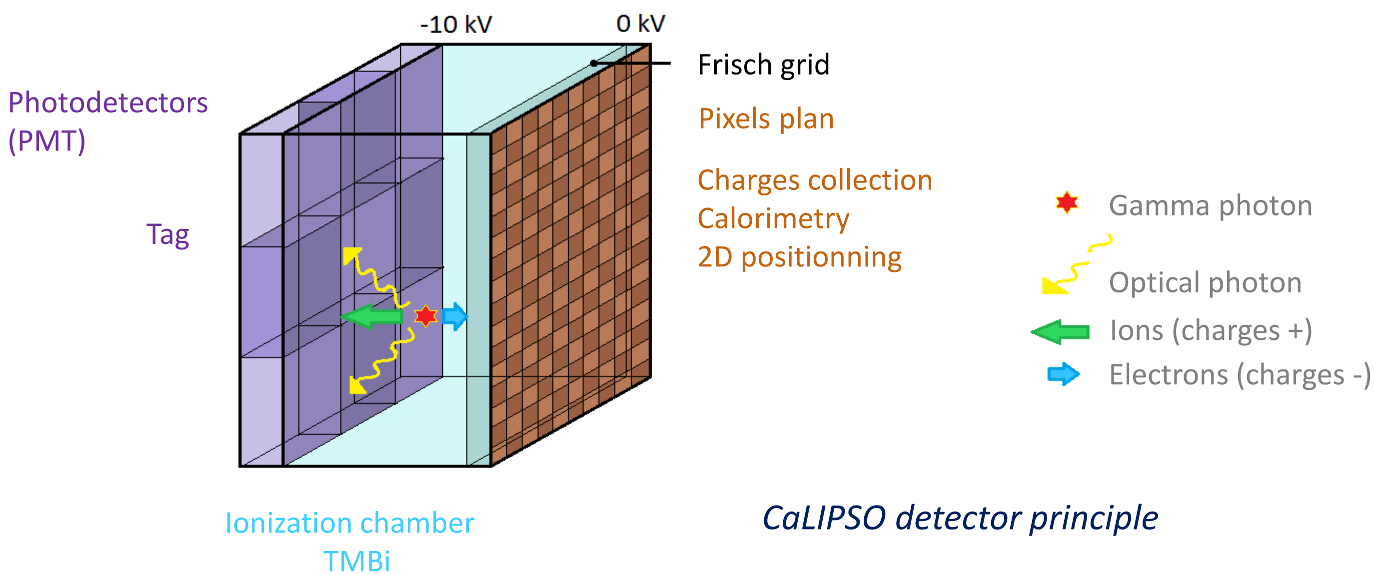
CaLIPSO

Expected performances:

→ 3D positioning: **1 mm³**

→ timing resolution ~ **100 ps**

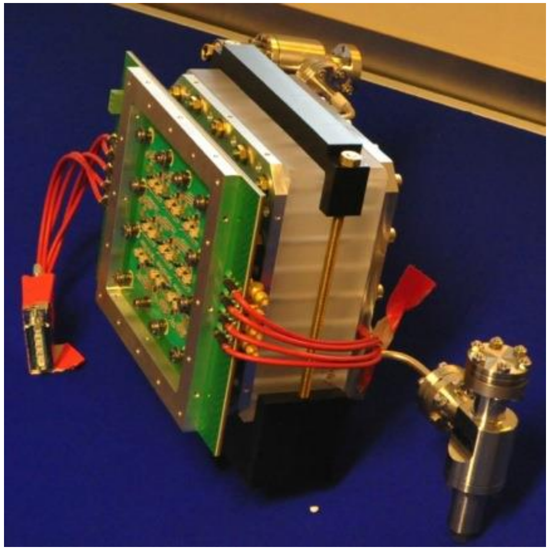
→ energy resolution ~ **10%**

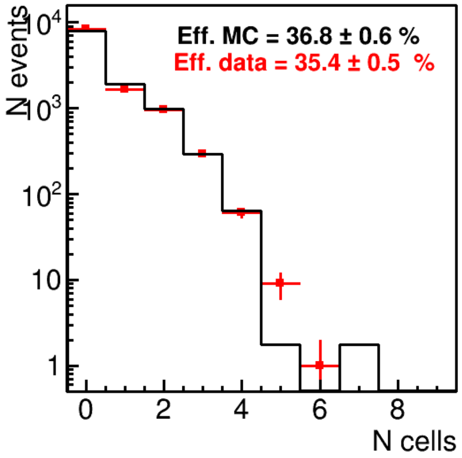


CaLIPSO detector principle

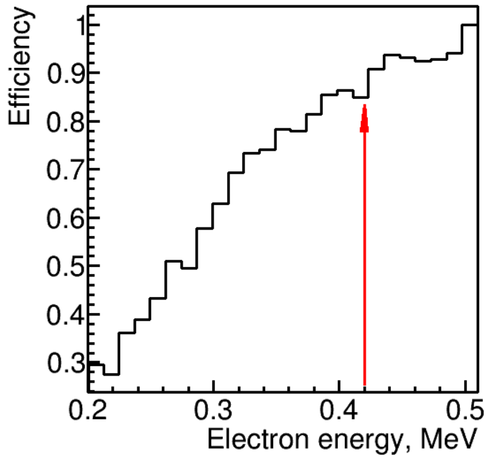
D. Yvon and al., CaLIPSO : A novel detector concept for PET imaging, IEEE Trans. Nucl. Sci., 61 :60–66, 2014.

CHERENKOV OPTICAL DETECTOR EFFICIENCY



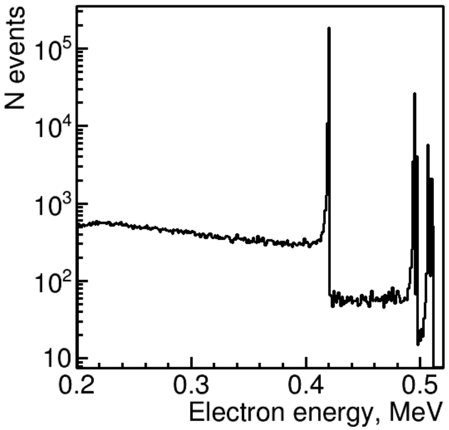


Cherenkov photons detected



Detection efficiency

- **Fully efficient** on 511 keV γ through PE conversion
  - **90%** detection efficiency at 420 keV
  - 27 % expected / 34,5 % experimental → few Compton interactions detected
- Monte Carlo matches data

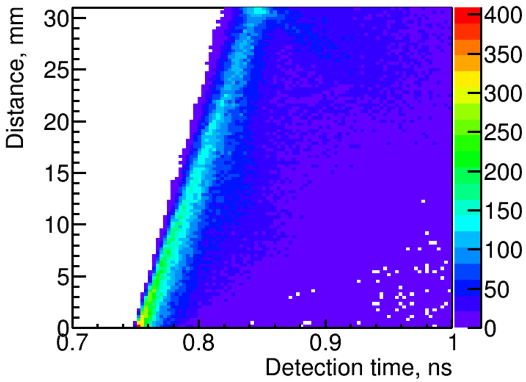


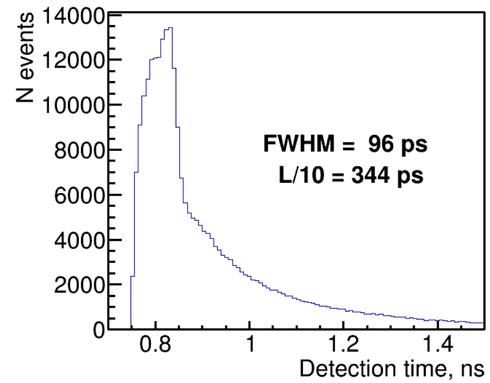
511 keV γ spectrum in TMBi

E. Ramos, et al., « Efficient, Fast 511-keV γ detection through Cherenkov radiation: the CaLIPSO optical detector », J. of Instr., in prep.

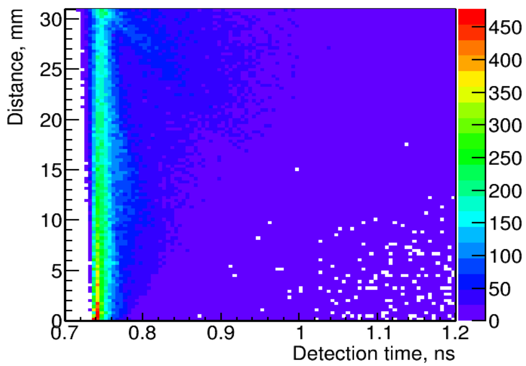
CHERENKOV OPTICAL DETECTOR TIMING RESOLUTION

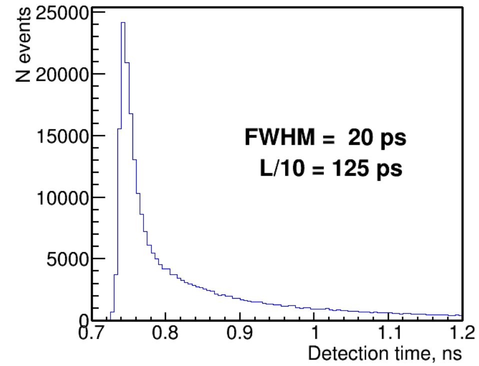
Detection time / position correlation





Detection time after decorrelation





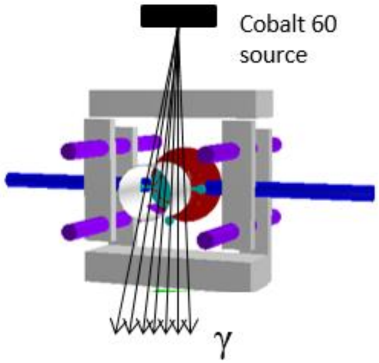
- 540 ps experimental due to R11265 PMTs
- Simulation shows correlation between detection time and interaction position
  - ➢ 96 ps correlated / **20 ps after decorrelation**
- Current fastest PMT → MCP-PMT with 70 ps FWHM resolution
  - ➢ Near future → **Coincident Resolution Time of 150 ps**

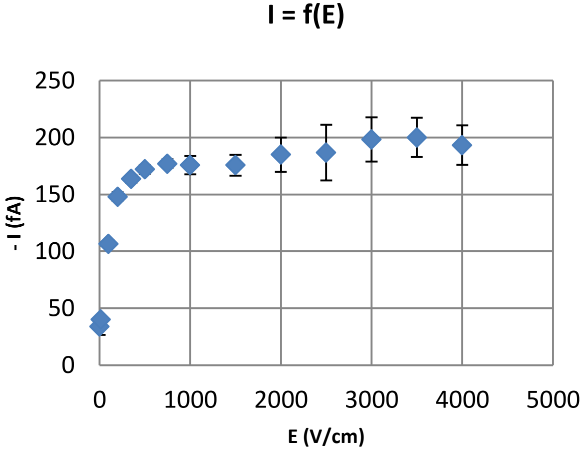
IONIZATION DETECTOR : SINGLE PIXEL DETECTOR

Single pixel detector

- **Ionization chamber**
- Our goals :
  - ➢ **10% energy resolution**
  - ➢ **200 ns timing resolution** on charge collection
- Ionization current → 3 main factors :
  - ➢ Charge production yield (number of free electrons / 100 eV)
  - ➢ Electron mobility → proved by ionization current / electric field dependency
  - ➢ Electron lifetime
- Charge measurements → closer to final detector
  - ➢ Electron mobility / lifetime values
- Very low signals (pA, fC) → eliminate noise sources

Ionization current measurements





P. Verrecchia, et al., « CaLIPSO: TMBi properties for particles detection », IEEE TNS-MIC conf. record, Anaheim, Nov. 2012

IONIZATION DETECTOR : ULTRAPURIFICATION ISSUE

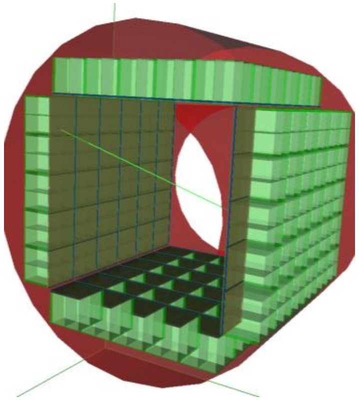
- Energy information lost by electronegative impurities capturing secondary electrons
- Electrons lifetime > 20 µs needed
  - Electrons scavengers < 0,1 ppm oxygen equivalent
  - Molecular sieves, getter materials, silica gel, activated alumina…
  - **Large effort**
- Ultra-high vacuum cleaning procedure

Ultrapurification stations

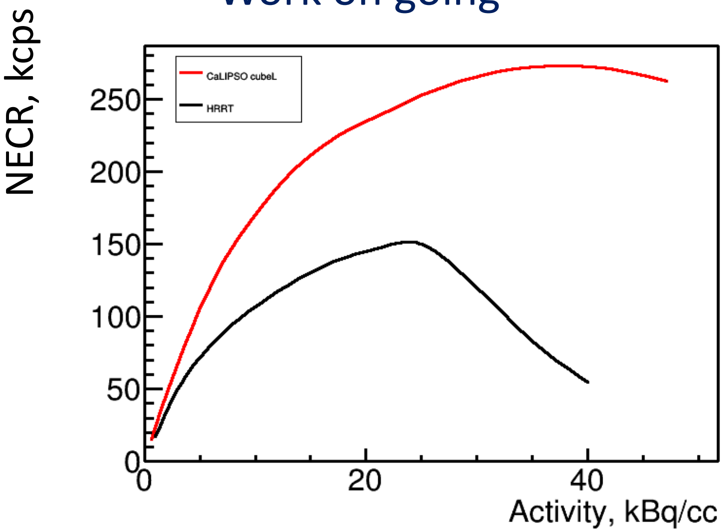
FULL PET-SCAN SIMULATION

Olga Kochebina

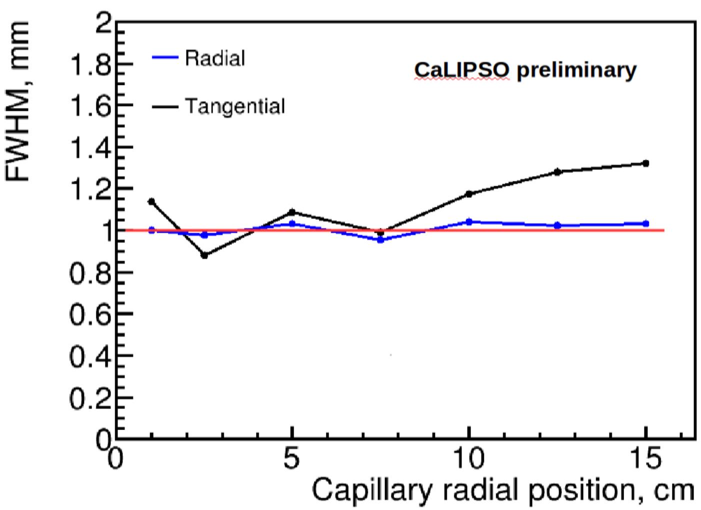
- GATE software (led by CEA/SHFJ)
- Improve NECR → improve efficiency
  - ➢ Better than Siemens HRRT (before TOF information)
- Improve resolution
  - ➢ ~ 1 mm at FOV center (2,3 mm for HRRT)
  - ➢ No significant Depth Of Interaction effect (2,3 - 3,2 mm for HRRT)
- Work on going



PET CaLIPSO geometry



NECR comparison HRRT / CaLIPSO



Spatial resolution regarding radial position

O. Kochebina, IEEE NSS/MIC, conf. record, San Diego, Nov 2015, in Press.

CONCLUSION

- CaLIPSO Project : Ambitious technology for High-resolution PET-scan
  - Excellent efficiency (photofraction, solid angle, TOF) → reduced dose
  - Foreseen spatial resolution : 1 mm^3
  - Coincident Resolution Time < 150 ps → TOF information
- Now Operational
  - Optical detector fully efficient for photoelectron detection
  - Single pixel detector (ionization)
  - Efficient purification achieved on reference liquid tetramethylsilane
- On going
  - TMBi ultrapurification
  - Optical detector upgrade with MCP-PMT
  - Full PET-scan simulation with GATE → foreseen performance

CALIPSO TEAM

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Responsable scientifique

G. Tauzin

Chef de projet

P. Verrecchia

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S. Sharyy

Physique du détecteur

X. Mancardi

Thèse Démons. ionisation

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J.P. Mols

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Mécanique et Ultra-Vide

J.P. Bard

Électronique et labo

Ph. Abbon

Elec. Analog. Rapide

M. Kebbiri

Techno. Détec. Avancées

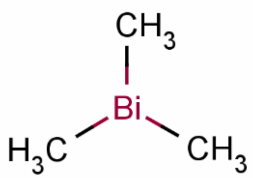
C. Canot

Thèse Détec. Opt. rapide.

THANK YOU FOR YOUR ATTENTION

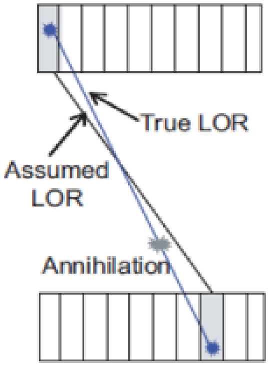
- D. Yvon, J-Ph Renault, « Détecteur de photons à haute énergie » (High energy photon detector), Patent, Ref: FR 1 052 047, 22 March 2010, and WO2011/117158 A1.
- D. Yvon al., "The CaLIPSO detector project for enhanced PET imaging", IEEE TNS-MIC conf. record. Anaheim, Nov. 2012, 10.1109/NSSMIC.2012.6551441
- P. Verrecchia, et al., « CaLIPSO: TMBi properties for particles detection », IEEE TNS-MIC conf. record, Anaheim, Nov. 2012, 10.1109/NSSMIC.2012.6551104
- D. Yvon, « Détecteur de photons à haute énergie », Patent, 12 novembre 2013 Reference: 13 61037 au nom du CEA.
- D. Yvon, J-Ph. Renault, G. Tauzin, et al., "CaLIPSO: An novel detector concept for positron annihilation detection", ANNIMA conf. record June 2013, 10.1109/ANIMMA.2013.6728041
- D. Yvon, J-Ph. Renault, G. Tauzin et al., "CaLIPSO: An novel detector concept for PET imaging", IEEE TNS, vol. 61 (2014) 60.
- E. Ramos, D. Yvon, P. Verrecchia, G. Tauzin et al., « Trimethyl Bismuth Optical Properties for Particle Detection and the CaLIPSO Detector », IEEE Trans. on Nuclear Science, Vol. 62 (2015) p. 1326 - 1335
- O. Kochebina, IEEE NSS/MIC, conf. record, San Diego, Nov 2015, in Press.
- E. Ramos, et al., « Efficient, Fast 511-keV γ detection through Cherenkov radiation: the CaLIPSO optical detector », J. of Instr., in prep.

TMBi has the best coincident photoelectric conversion yield (47%)



- **A factor 2 gain** compared to the reference detector (LSO crystal)

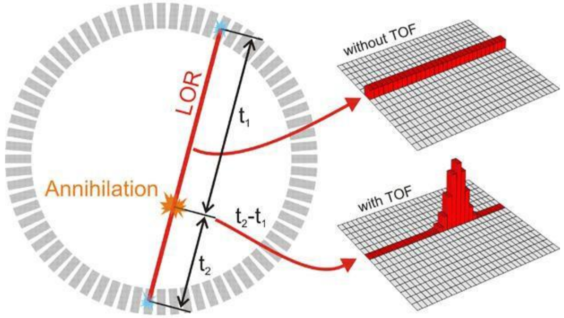
1mm^3 3D interaction positioning in detector



- Insensitive to the Depth Of Interaction effect
- Can be placed closer to the body
- Large gain in solid angle: **efficiency x ~ 4**

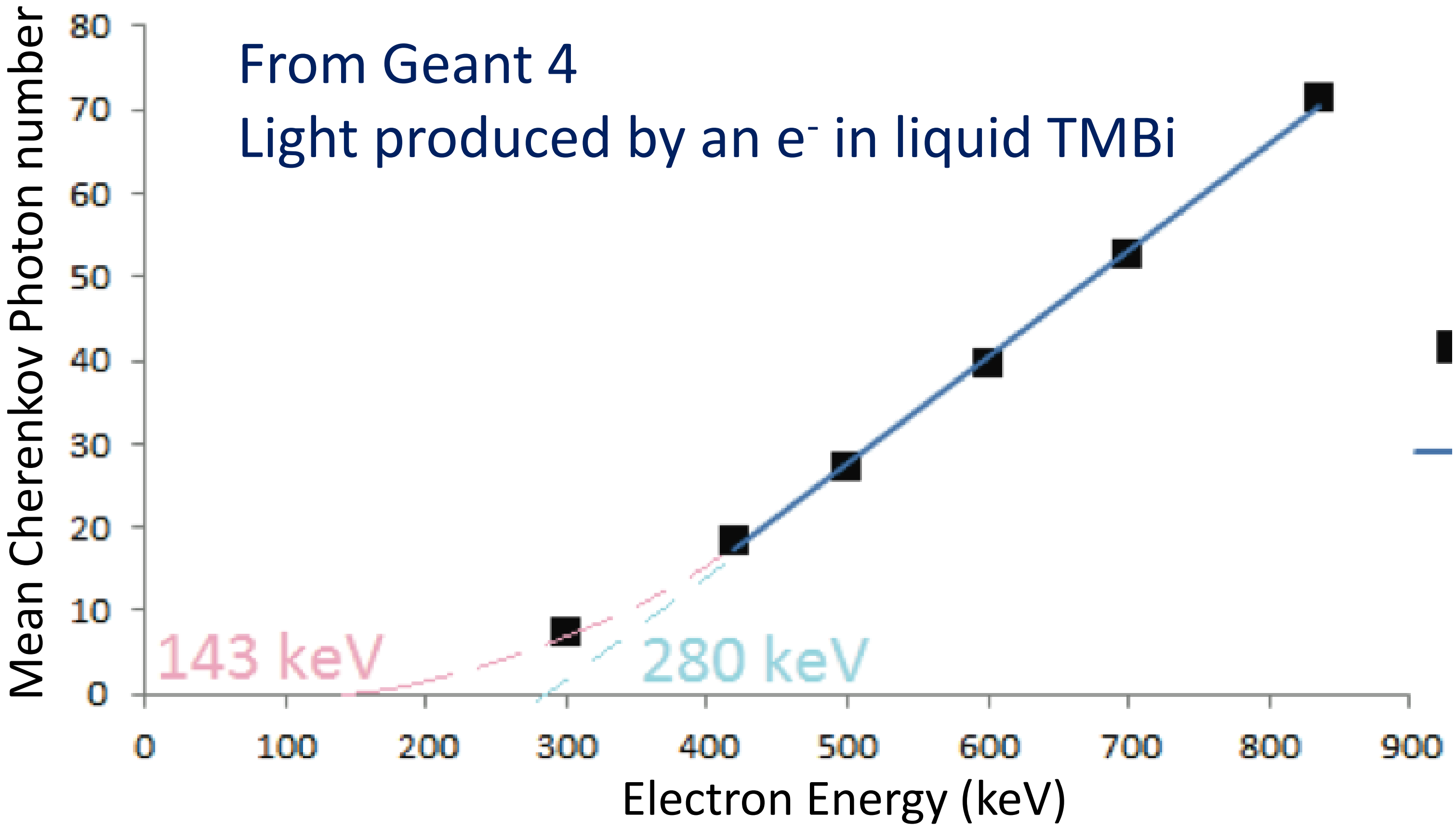
Time of Flight information enhances image contrast

- $G = (S/N_{TOF})/(S/N_{noTOF}) = \alpha\,(2D/(c\,\delta t))^{1/2}$
- Δt Coincident Resolution Time, D typical organ size, $\alpha \sim 0.8$
- Brain ~ 20 cm, CRT of 150 ps (FWHM)
- *G ~ 2.4*, => Equivalent efficiency **gain of *a factor of 5.7***

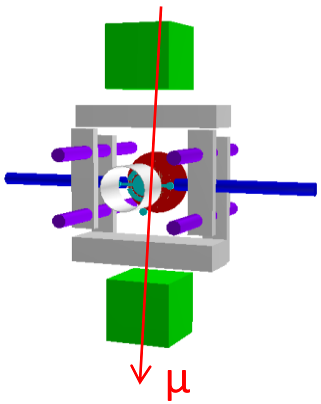


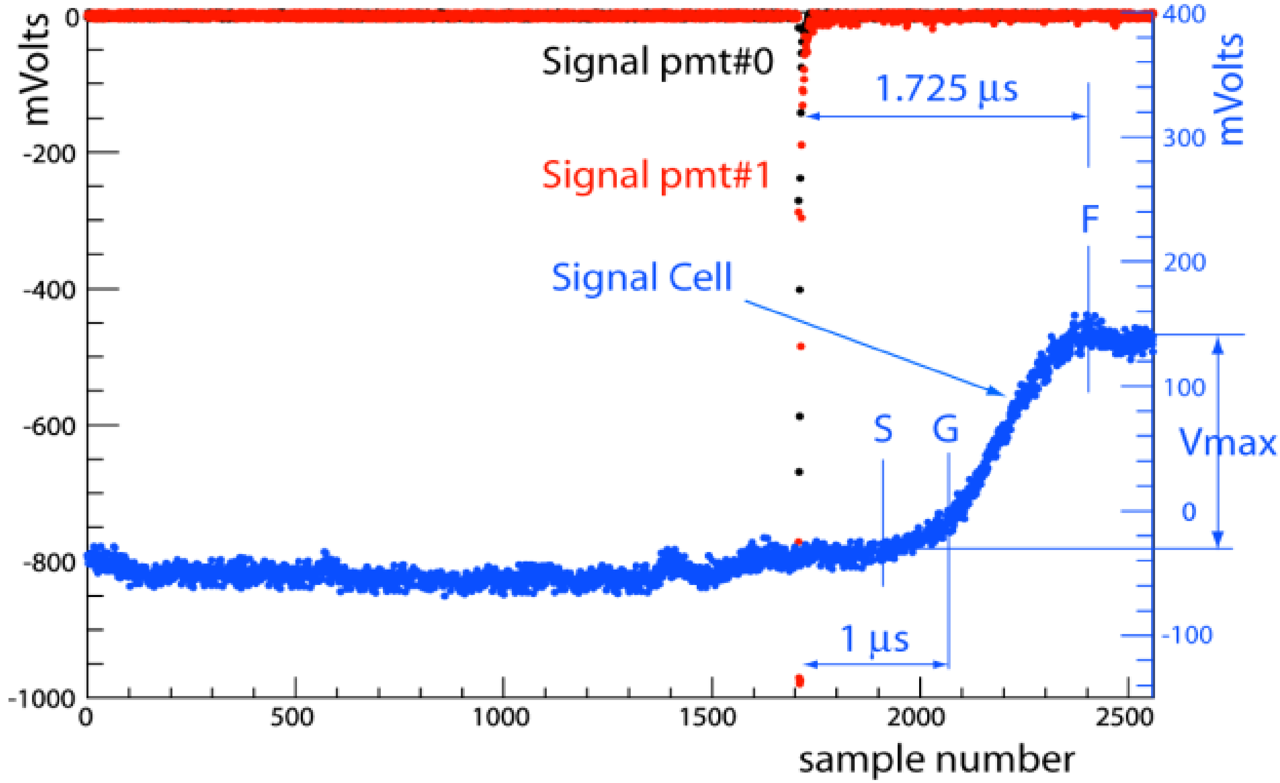
T.F. Budinger. Time-of-Flight Positron Emission Tomography : Status Relative to Conventional PET. Journ. of Nucl. Med., 24 :73–78, 1983.

CHERENKOV LIGHT PRODUCTION



CHARGE MEASUREMENTS

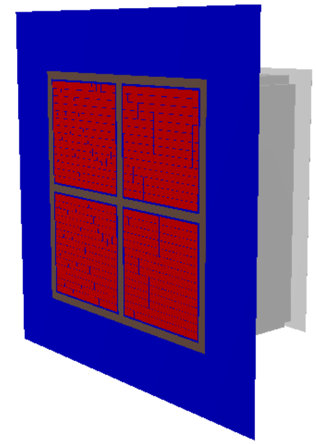




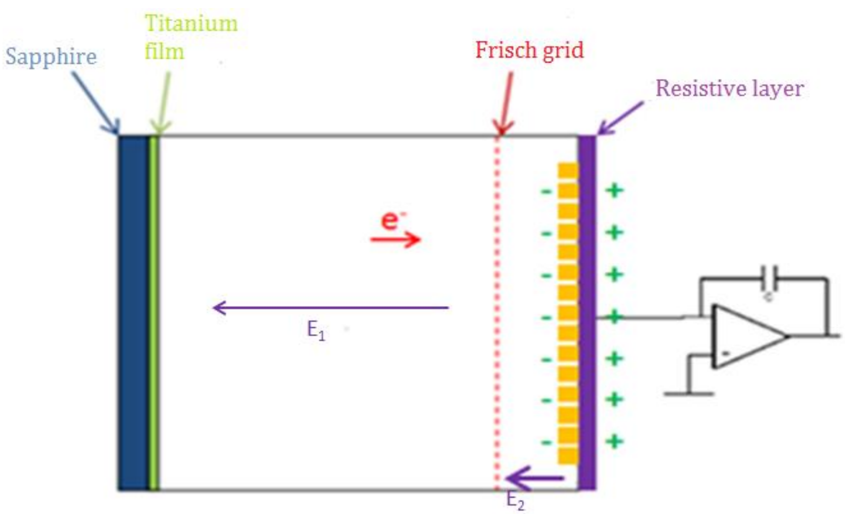
- Drift time = 725 ns $= \frac{distance\_anode}{drift\ speed} = \frac{d}{\mu E}$

IONIZATION DETECTOR : FUTURE

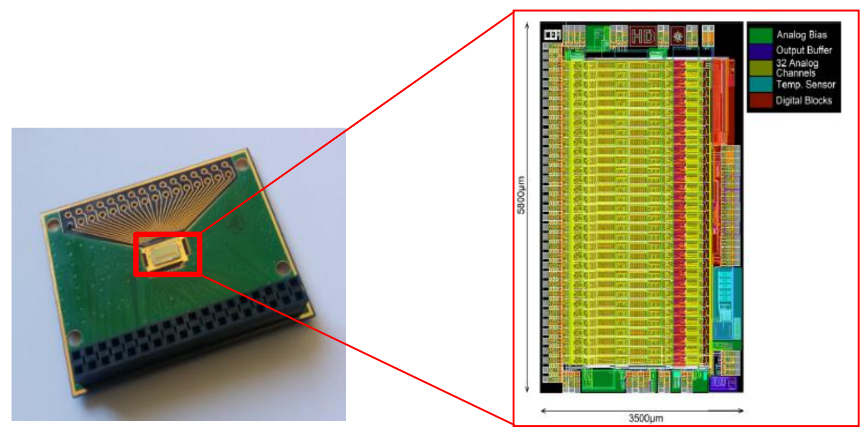
- No feedthrough
  - readout by capacitive coupling
  - Thin film deposits on alumine (IN2P3/CSNSM)
- Pixellized detector (1 mm²)
  - Low noise iDeF-X multichannel ASIC electronics (CEA/IRFU)



Pixelated detector



Capacitive readout principle



IDef-X chip

D. Attié and al.. Piggyback resistive Micromegas. . JINST., 8 C11007, 2013.
O. Gevin and al.. IDeF-X V1.0 : Performances of a New CMOS Multi Channel Analogue Readout ASIC for Cd(Zn)Te Detectors. Proc. IEEE NSS-MIC conf. rec, 2005.

MAIN DETECTORS IN PET

Properties / Detector	Atten Length (cm)	Coinc . PhotElecE Eff.(%)	Timing Resolution (ps, FWHM)	Energy Resolution (% FWHM)	G Interac. Postion. (mm)	End user friendly
LSO/LYSO	1.23	12	300 - 500	10	2 to 10	YES
$LaBr_3$	2.3	1.9	100 - 300	3	4 to 10	YES
CdTe/CZT	2.0	2.2	slow	1- 3	0.1	YES
CaLIPSO	2.9	22	?150? - 380	10	0.15	Will be !

LSO/LYSO : The reference detector.

LaBr3 : Excellent timing, poor PE Efficiency, fair positioning.

Only relevant for full body, Time of Flight PET config.

CdTe/CZT : Excellent position reconstruction, poor PE Efficiency.

Only relevant for single mouse PET imaging

CaLIPSO : Best PE efficiency, Excellent positioning, very good timing.

Take the best of all technologies – *Needed* for high-res efficient Brain PET