Quantification of CaLIPSO PET scanner potential for personalized medicine in oncology and neurology

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Outline

- Simulation of CaLIPSO PET scanner with GATE
- Quantification results
  - Noise Equivalent Count Rate
  - Image resolution
- Image reconstruction
- Perspectives and conclusions

CaLIPSO PET scanner

Calorimètre **L**iquide **I**onisation **P**osition **S**cintillation **O**rganométallique

Efficient PET scanner designed for **brain studies,** neurodegenerative diseases, neuro-oncology

→ diagnosis

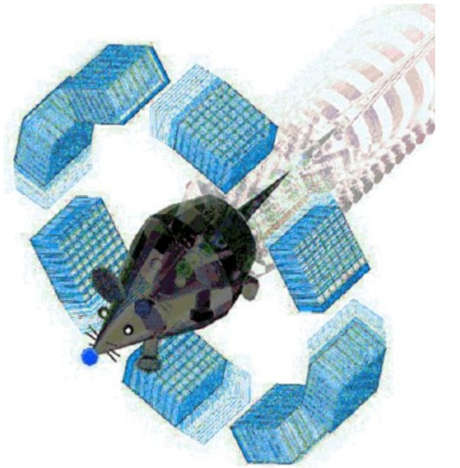
→ monitoring of the functional changes over the treatment

- Innovative liquid as detection medium **TMBi:** TriMethyl Bismuth $Bi(CH_3)_3$
  - → Dielectric, stable, limpid
  - → Highest (bismuth) photoelectric conversion efficiency ~ 47 %
  - → Density = 2.3 g/cm^3
- Motivation: **high image resolution** and **detection efficiency**

CaLIPSO	**PET HRRT by Siemens**
Photoelectron conversion eff. ~ 47%	Photoelectron conversion eff. ~ 30%
Energy resolution < 10 % (FWHM)	Energy resolution ~ 20-30 %
Spatial resolution **1 mm^3**	Spatial resolution 2.3-3.2 mm^3
TOF	No TOF
Time res. CRT ~ 150 ps (FWHM)	State of the art: Time res. CRT ~ 350 ps

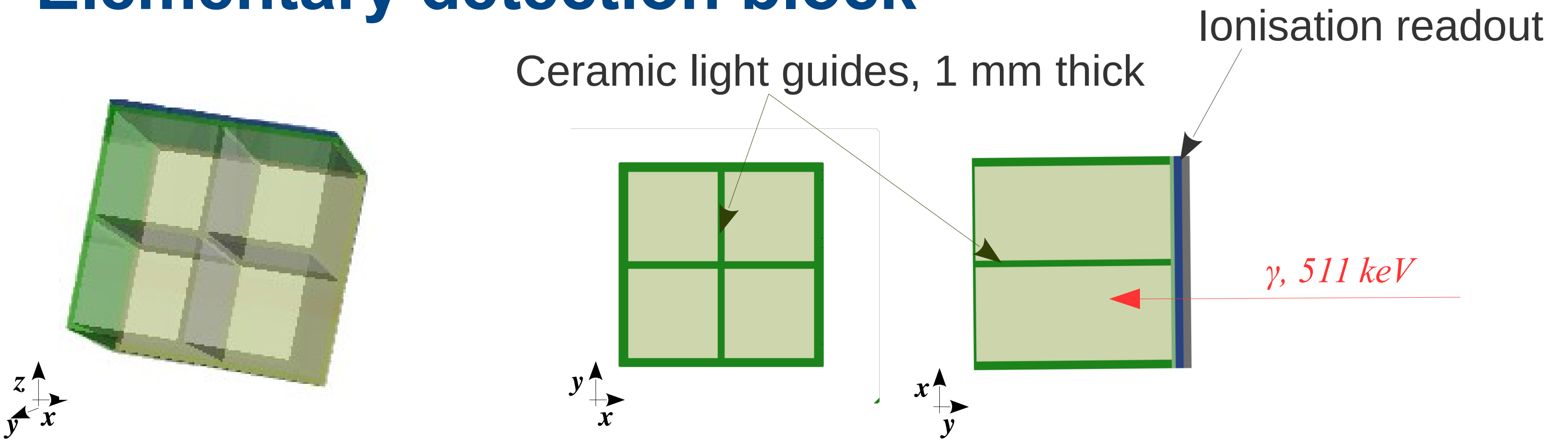
Bataille et al. IEEE-NSS 4 (2004) 2570-2574

Simulations with GATE platform



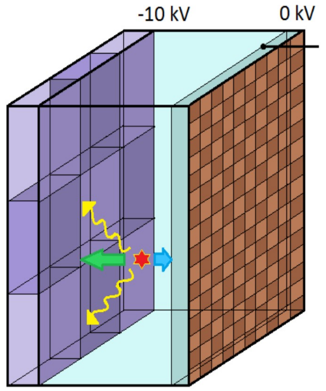
- Simulations of Preclinical and Clinical Scans in Emission Tomography, Transmission Tomography and Radiation Therapy
- Based on Geant4 (C++)
- Open source
- Easy to learn and use
- Possible to configurate simple or highly sophisticated experimental settings

Elementary detection block



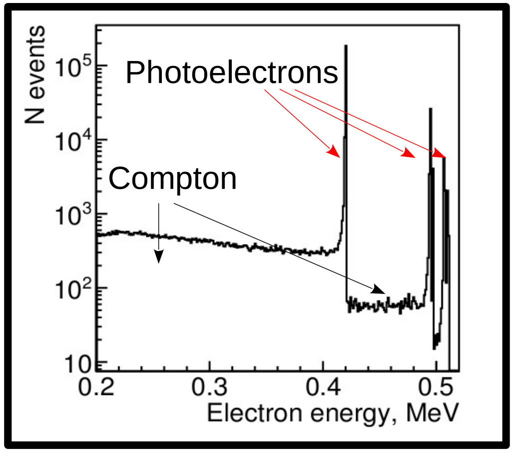
- Block 5.3 × 5.3 × 5.0 cm^3 filled with TMBi
- Size defined by MCP-PMT size, PLANACON™, Photonis
- Ceramic light guides divide volume in 4 cells
- **Optical properties based on prototype measurements**
  Charge detection properties based on the simplest model

Semianalytic models

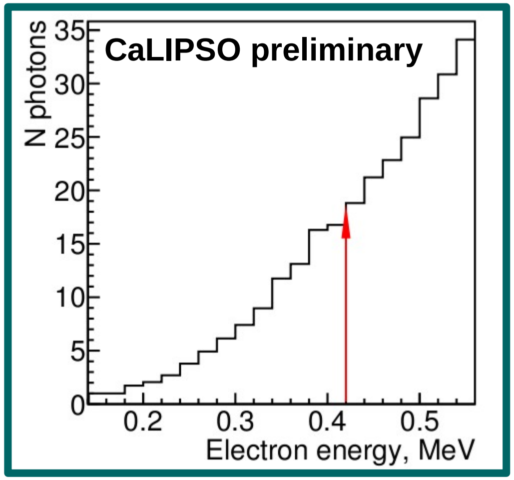


- Take too long to perform detailed simulations in GATE
- Parametric approach for optical and ionization detection
- Use simplified models from detailed MC simulations: apply detector response functions
  → for the efficiency and resolution in time of the optical signal
  → for the energy and spatial resolution of the ionization

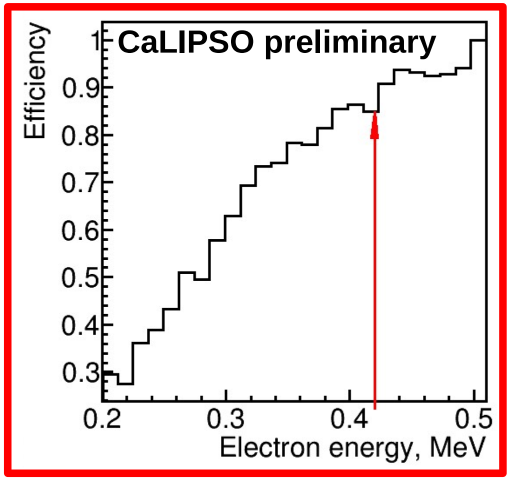
511 keV photon conversion in TMBi:
→ Photoelectric (47%)
→ Compton



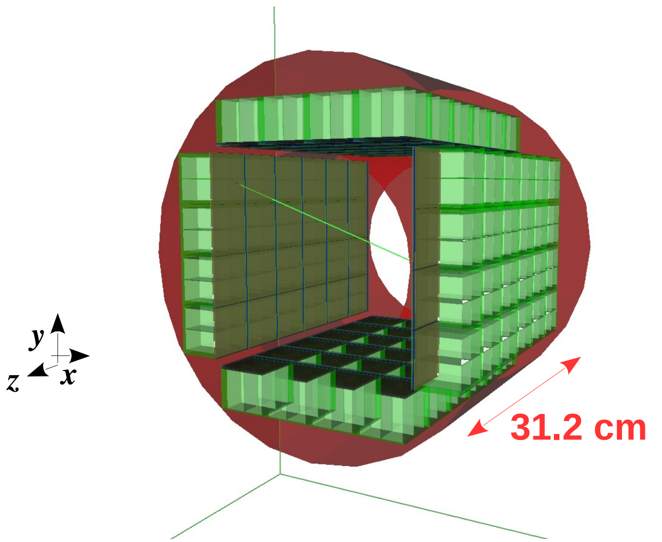
Number of Cherenkov photons

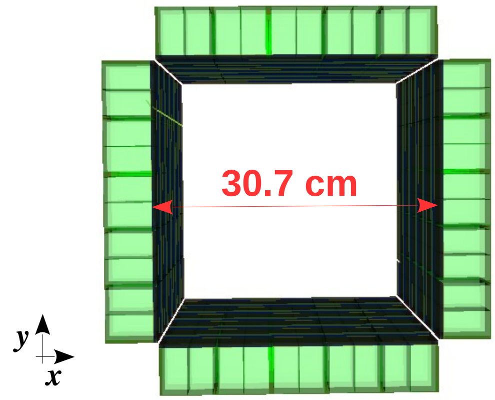


Detection efficiency



Geometry definition of head-size CaLIPSO scanner





FOV
→ **Diameter: 30.7 cm**
→ **Axial : 31.2 cm**

→ 4 sectors: 5×6 blocks

- Cube geometry
  - → possible thanks to accurate 3D positioning of photons interactions
  - → simplify the manufacturing

- Coincidence window = 3 ns

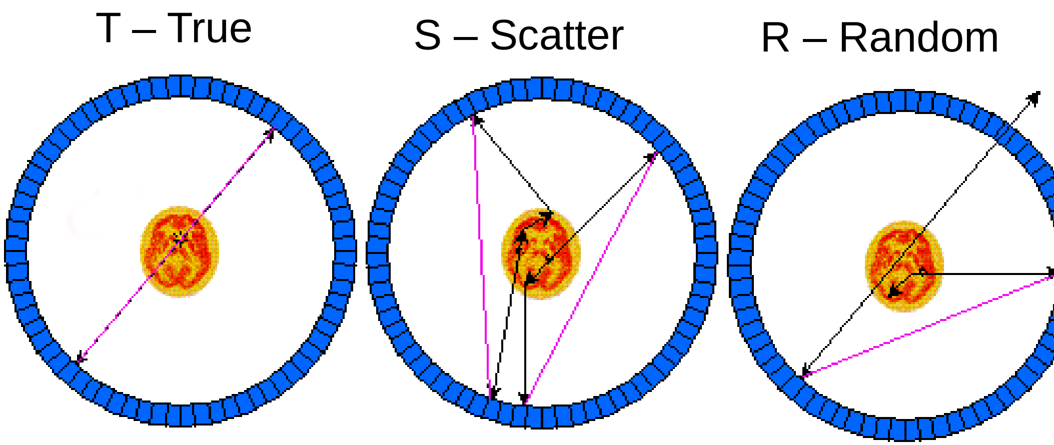
- no dead-time yet (expected ~5 μs, max. occupancy ~ 20kHz/cell)
- TOF information not yet used for reconstruction (CRT~150 ps → 3 cm)

Noise Equivalent Count Rate (NECR)

- Estimation of an image contrast

- Ratio between true, scatter and random coincidences

Coincidences:

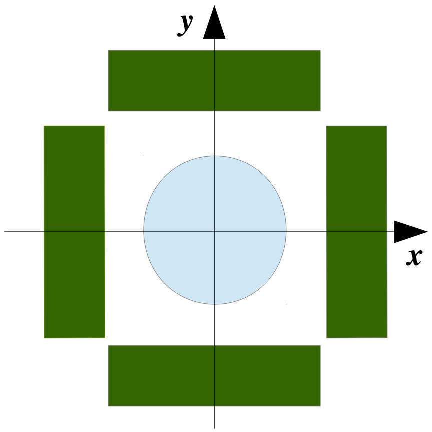


$$NECR = \frac{T^2}{T + S + 2R}$$

T = True
S = Scatter
R = Random

- Higher NECR → better image contrast

Results: Noise Equivalent Count Rate

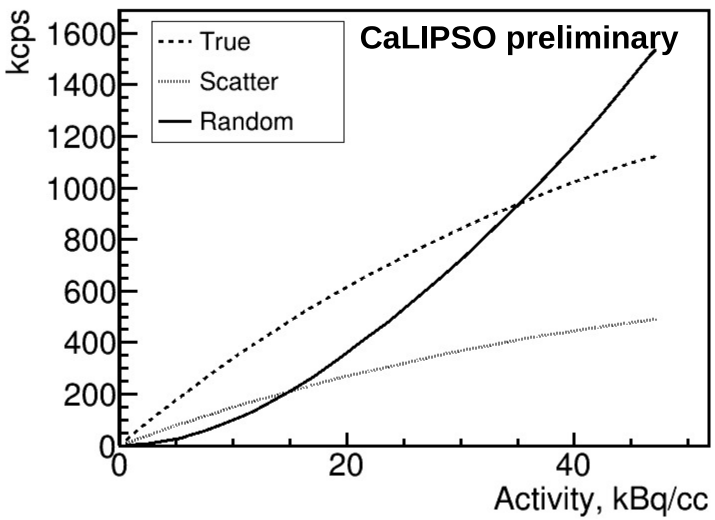


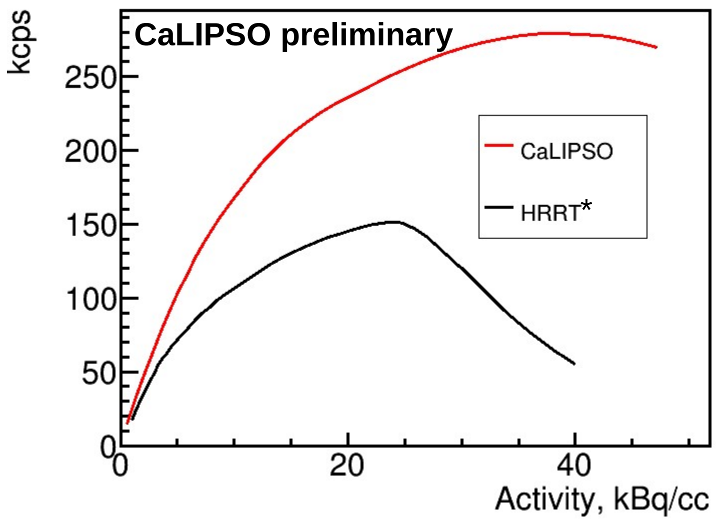
Simulation with:

- Cylindrical phantom NEMA-1994, Ø = 20 cm, L = 20 cm
- Filled with water, uniformly distributed activity

$$NECR = \frac{T^2}{T + S + 2R}$$

T = True
S = Scatter
R = Random





- CaLIPSO NECR is larger than for HRRT scanner
  → better image contrast

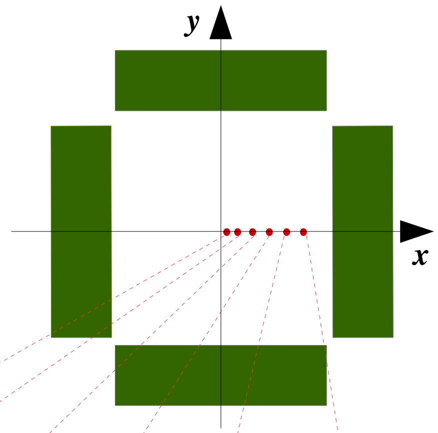
* de Jong et al, Phys. Med. Biol. 52 (2007) 1505

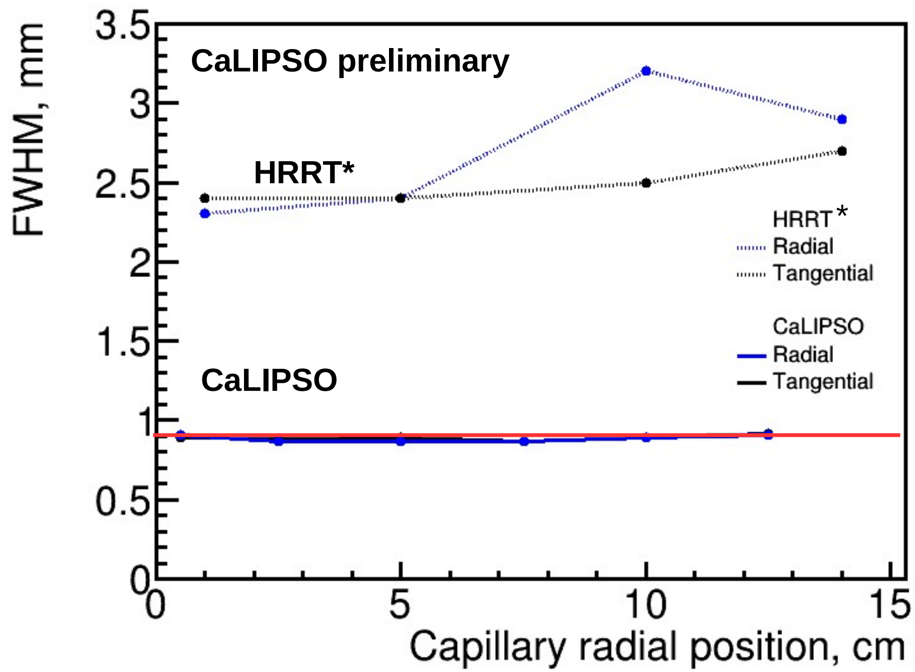
Results: image resolution

Simulation with :

- Point sources in different positions of Field of View

Capillary Ø = 0.2 mm, L = 0.2 mm

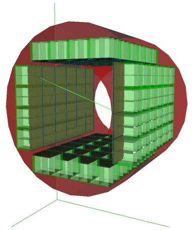




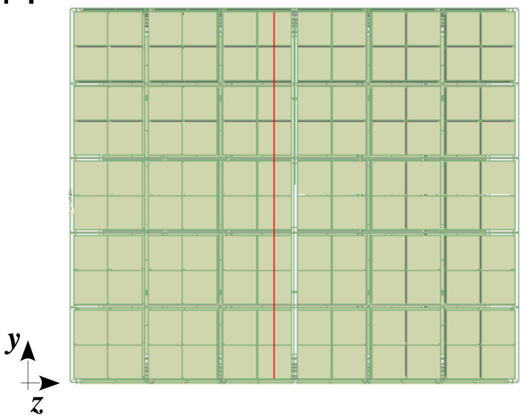
- Image resolution is less than 1 mm (FWHM)

* de Jong et al, Phys. Med. Biol. 52 (2007) 1505

Image reconstruction



- Issues
  - Foressen CaLIPSO will have a high spatial resolution of 1 mm^3:
    "detection elements": $1.6\cdot10^7$, LORs: $1.3\cdot\mathbf{10^{14}}$
  - HRRT:
    "detection elements": $1.2\cdot10^5$, LORs: $7.2\cdot10^9$



- Problems for such amount of data
  - Impossible to use sinograms
    (one plane with TOF → 302 Gb)
  - Calculation of sensitivity and normalization maps require $1.3\cdot\mathbf{10^{14}}$ LORs

- Preliminary results to prove the concept
  → 2D simulations of one plane of the scanner:
  "detection elements": $5.2\cdot10^4$, LORs: $1.4\cdot\mathbf{10^9}$
  → without attenuation medium

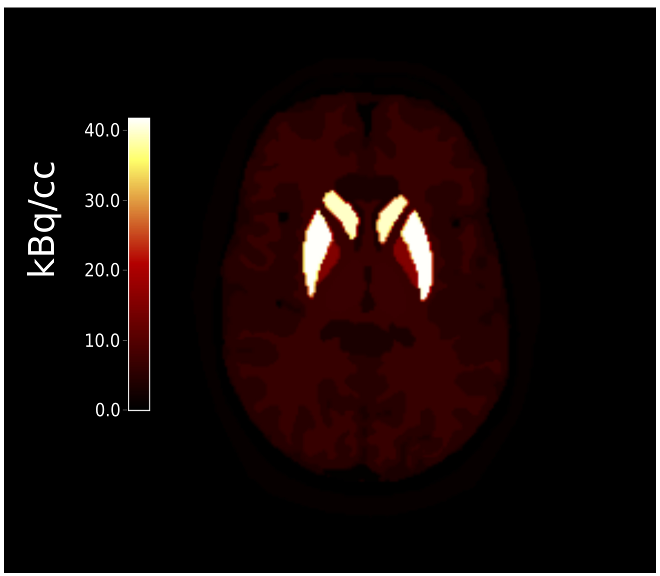
- Use platform CASToR (Customizable and Advanced Software for Tomographic Reconstruction)
  → Open source
  → Under development
  → http://www.castor-project.org/

Image reconstruction: ^{11}C-PE2I

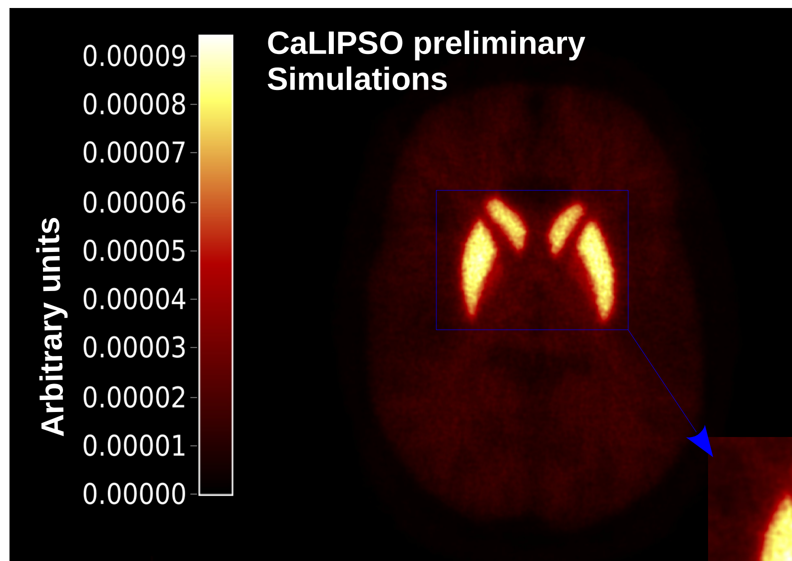
- CASToR platform for reconstruction
- Iterative algorithm, OSEM: 10 iterations, 16 subsets

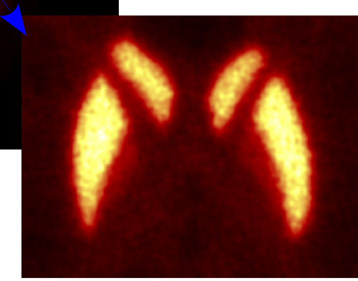
- Positron range for ^{11}C is ~ 1 mm (FWHM), i.e. slightly larger than expected machine resolution

Generated



Reconstructed





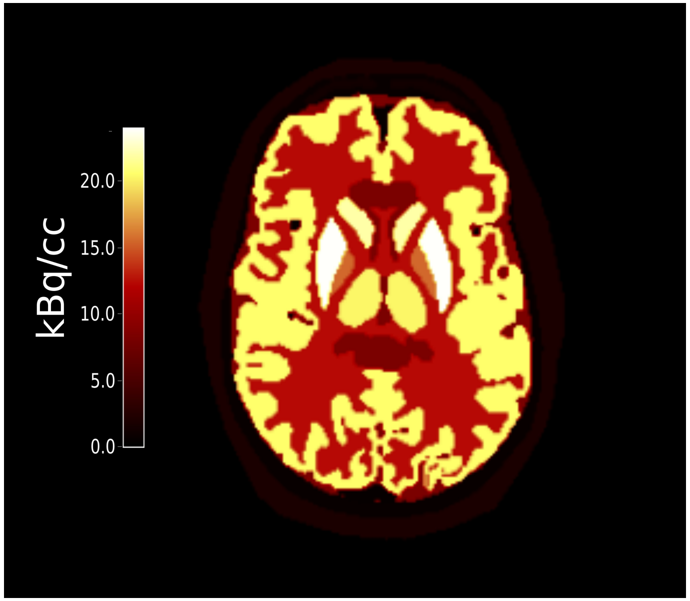
Pixel size : 0.25 mm
Gaussian smoothing, σ: 0.5 mm

Image reconstruction: ^{18}F-FDG

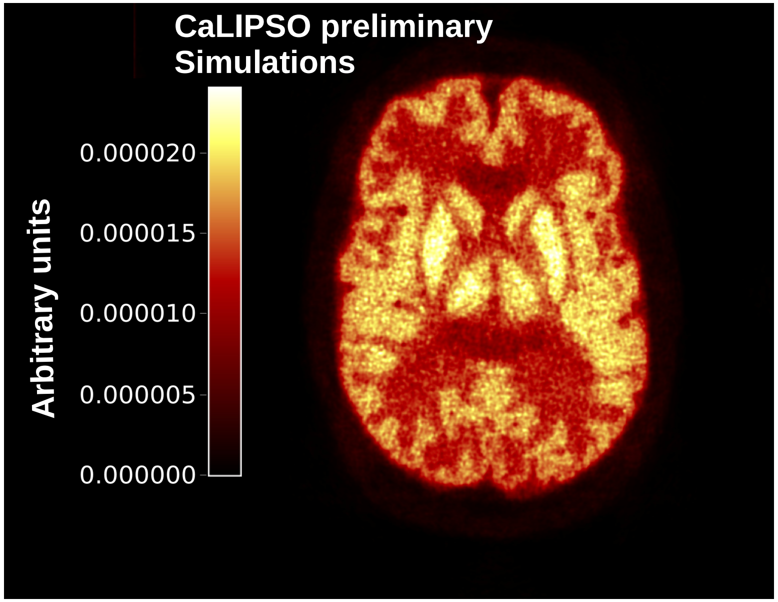
HRRT
Real data

- CASToR platform for reconstruction
- Iterative algorithm, OSEM: 10 iterations, 16 subsets
- Positron range for ^{18}F is ~ 0.6 mm (FWHM)

Generated



Reconstructed



- The high potential of CaLIPSO PET scanner

Pixel size : 0.25 mm
Gaussian smoothing, σ: 0.5 mm

Conclusions and perspectives

- The work on CaLIPSO simulations for full scale scanner is advanced

- CaLIPSO detector performances are very promising
  - Image resolution less than ~ 1 mm (FWHM)
  - Enhanced NECR compared to reference high resolution brain scanner

- Confirmation of the potential of CaLIPSO project for high resolution brain PET-scan

- **High resolution = sensitivity problem !**
  - Small size of voxels → possible lack of statistics in each voxel
  - High sensitivity is needed

Time Of Flight potential

- Improving spatial resolution to 1mm³ means lower statistics in each voxel
  → Need to improve signal to background ratio

- Use Time Of Flight (TOF) to enhance image contrast
  CaLIPSO: time resolution **δt = 70-150* ps**

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

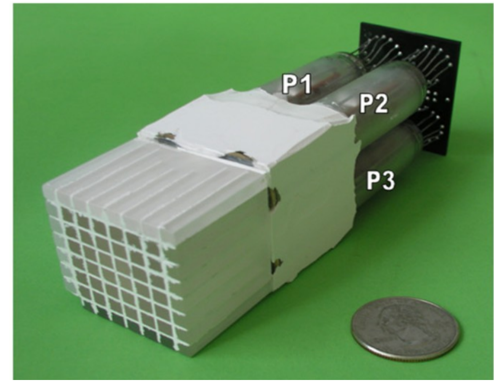
** see presentation of D. Yvon*

with δt = 150 ps → G ~ 2.4 for image contrast
with δt = 70 ps → G ~ 3.5 for image contrast

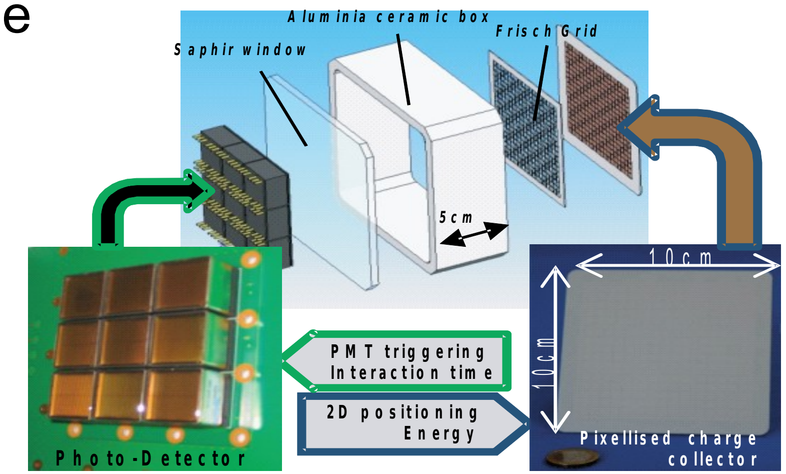
Thank you for your attention

Gamma detection

- Industrially produced scanners: scintillator crystals
  - PE conversion efficiency ~ 10-20%
  - Spatial resolution 2.5 mm³
  - Time resolution, σ ~ 350 ps



- CaLIPSO: new detection principle, double detection of light and ionization signals
  - PE efficiency ~ 50%
  - Spatial resolution 1 mm³
  - Time resolution , σ ~ 150 ps



Gamma detection

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 positionning.

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

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