Early Career Researcher in Medical Applications @ CERN

Short Talks - 14th September 2022, CERN Council Chamber

Introduction to PET and TOF-PET

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1.
Positron Emission Tomography

A general description

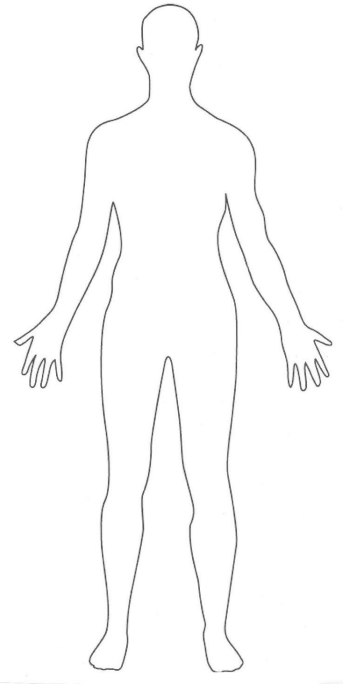
In vivo imaging technique to quantitatively measure

the 3D distribution of radiolabeled biomolecules

”

Principle

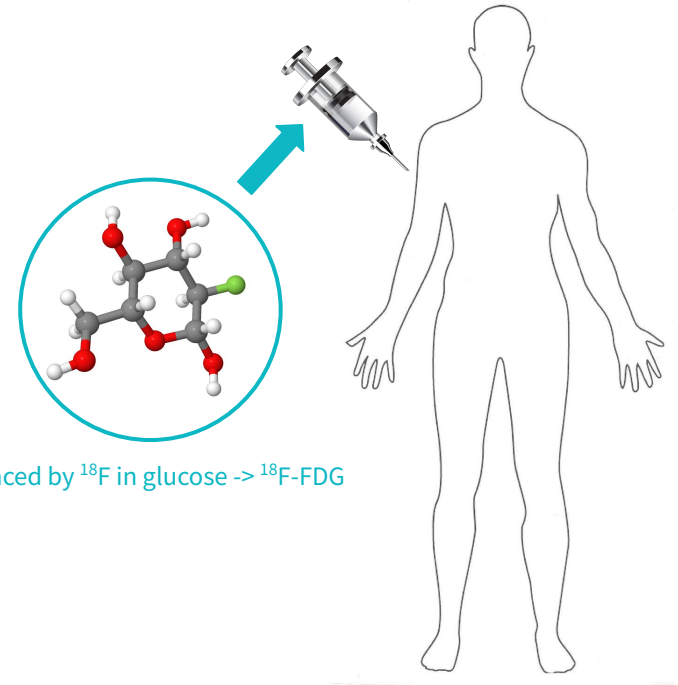
“Get an image of life, not of shapes”



Principle

"Get an image of life, not of shapes"

- Choose a biomolecule
- Mark it with a β^+ emitter
- Inject in the patient
- Let it spread
- Collect the signal
- Build an image



Example: OH^- replaced by ^{18}F in glucose -> ^{18}F-FDG

What kind of signal do we expect?

Signal

Beta$^+$ decay

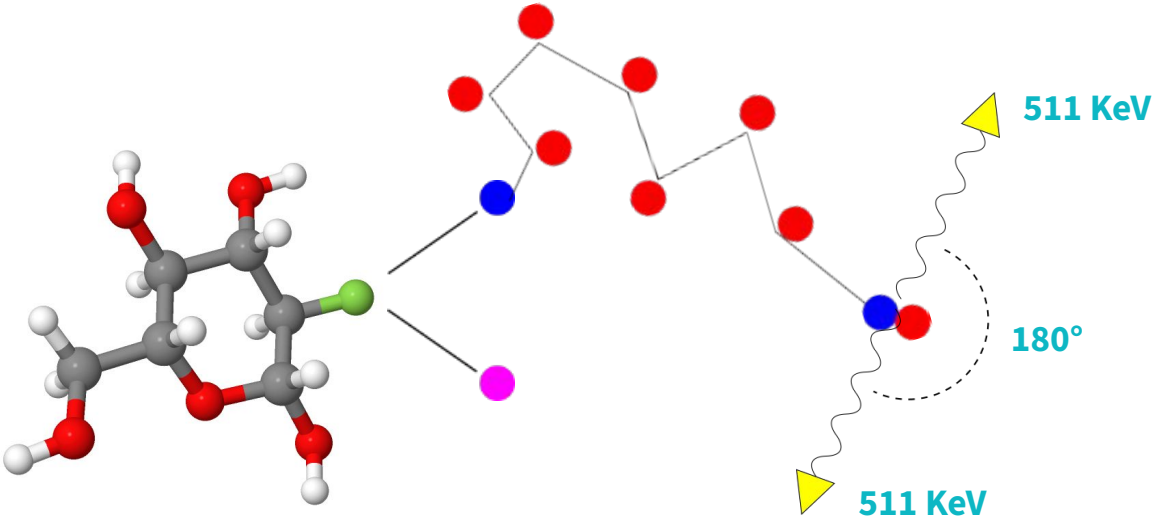
0-3 MeV, 1-120 min

Random walk

0.5-3 mm range

Annihilation

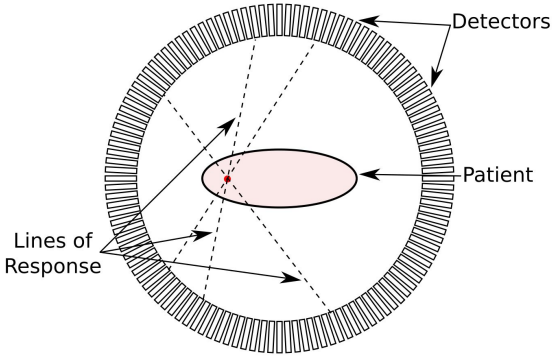
2 collinear 511 KeV gammas



Detection and images

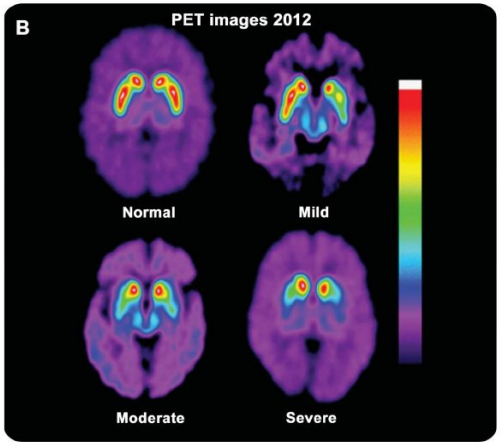
Detection of coincidences

Lines of response



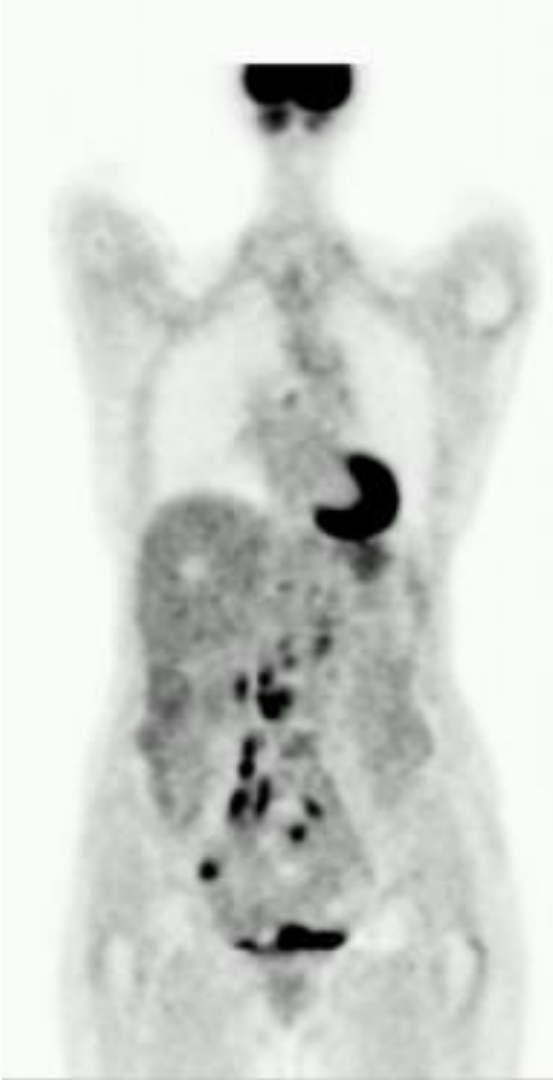
Tomographic reconstruction

Biomolecule distribution



Applications

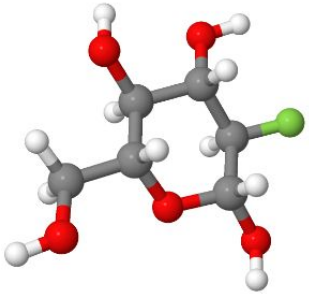
- Main tracer ^{18}F-FDG (> 90% @2013)
- Main application: oncology
  - Measurement of glucose metabolism
- Other applications:
  - Brain studies
  - Cardiac studies
  - …



The PET system

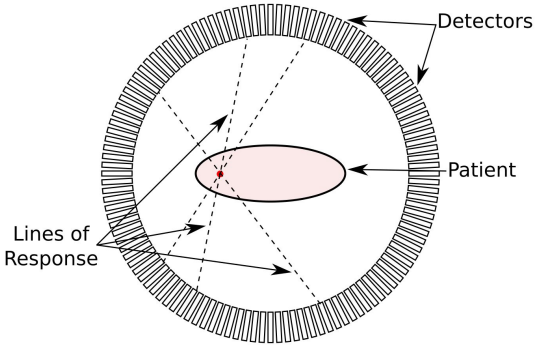
Biology

Radiotracers



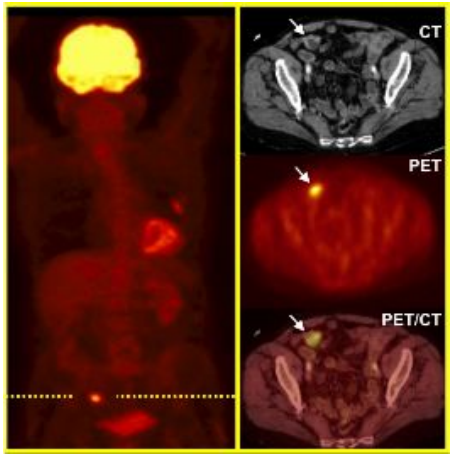
Physics

Detectors

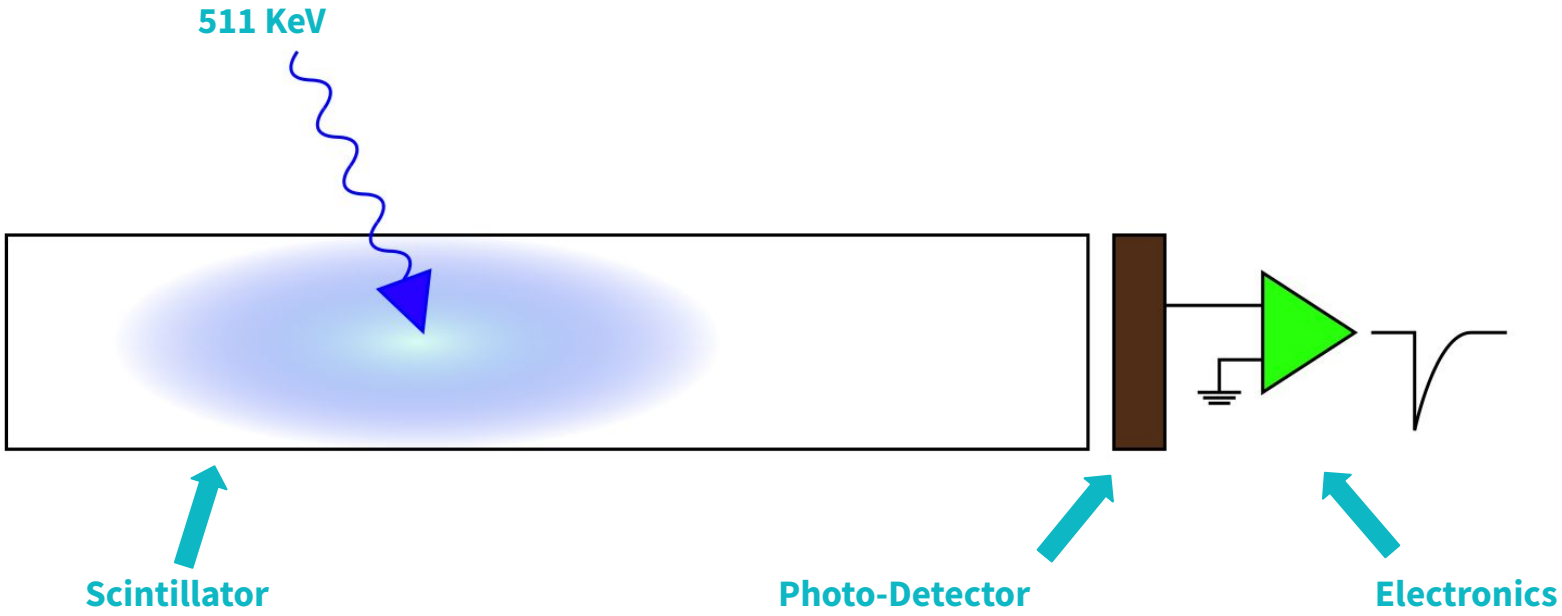


Software

Reconstruction

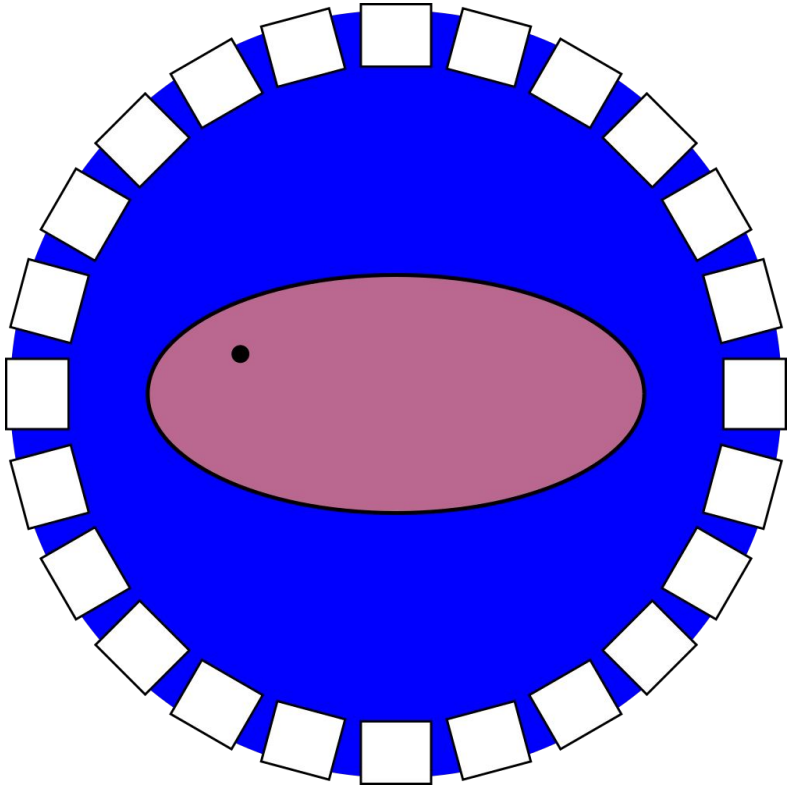


Detecting gammas



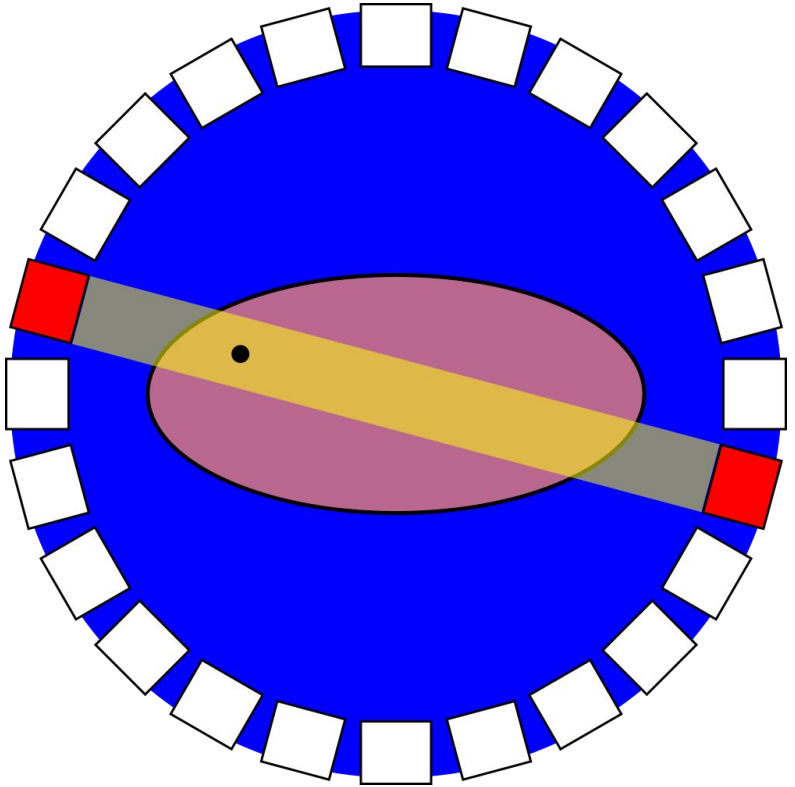
Sensitivity and spatial resolution

- Cylindrical coverage



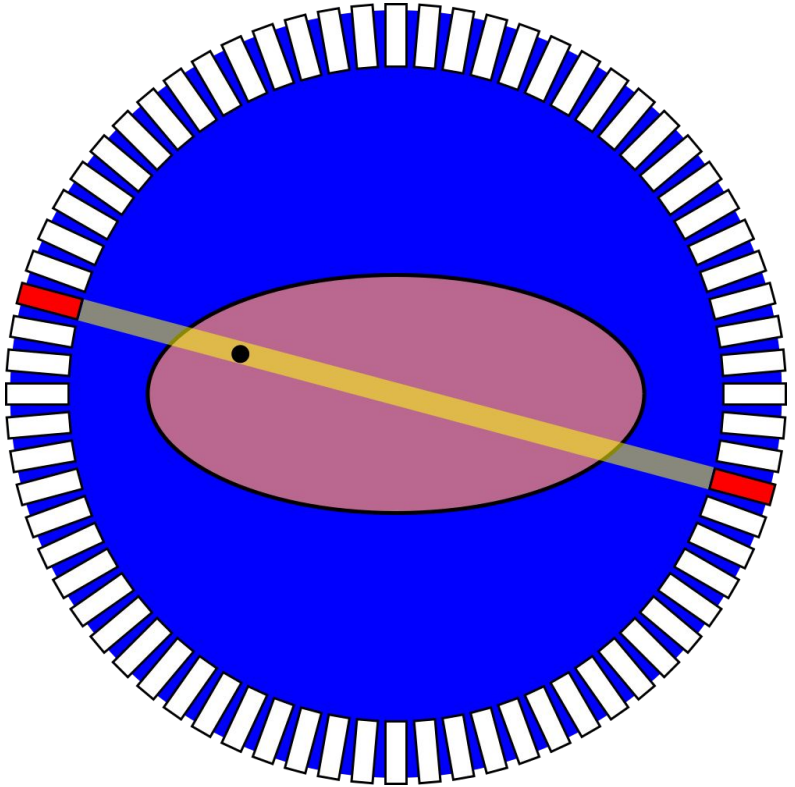
Sensitivity and spatial resolution

- Cylindrical coverage
- Spatial resolution
  - Crystal section



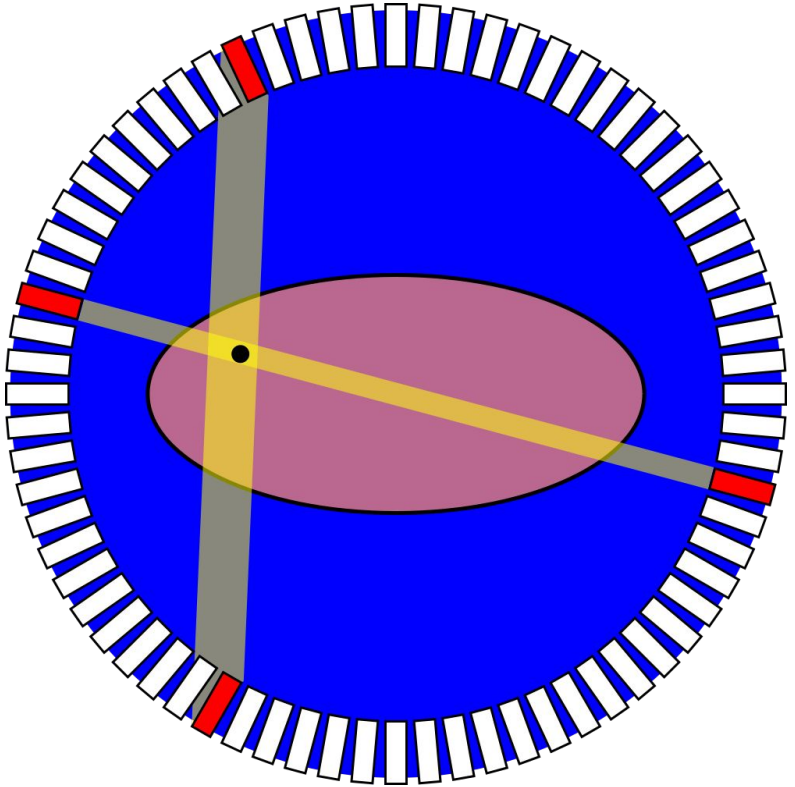
Sensitivity and spatial resolution

- Cylindrical coverage
- Spatial resolution
  - Crystal section
  - Segmentation



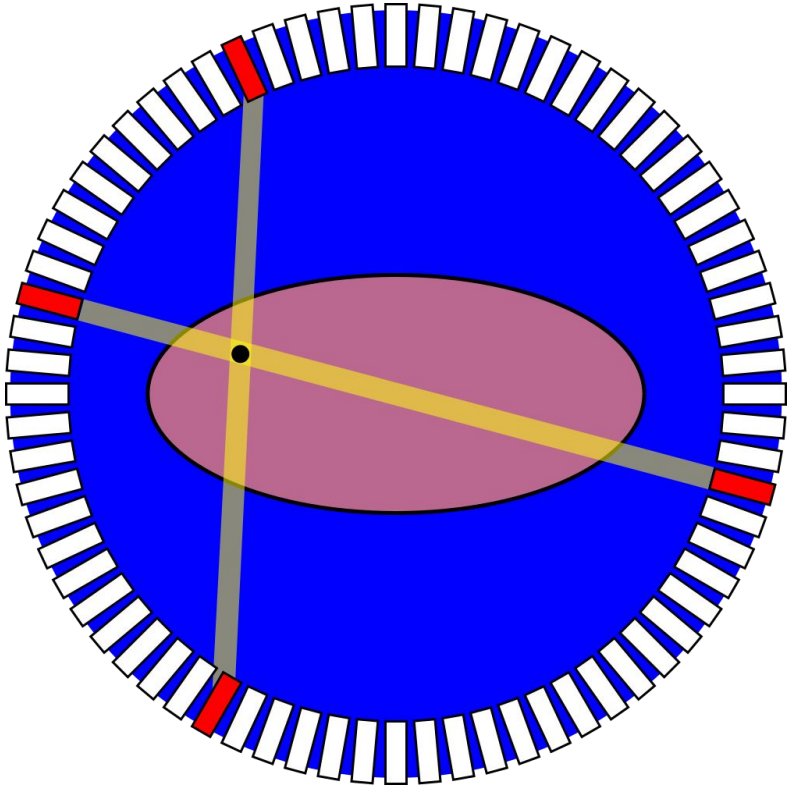
Sensitivity and spatial resolution

- Cylindrical coverage
- Spatial resolution
  - Crystal section
  - Segmentation
- Parallax effect
  - Degrades resolution



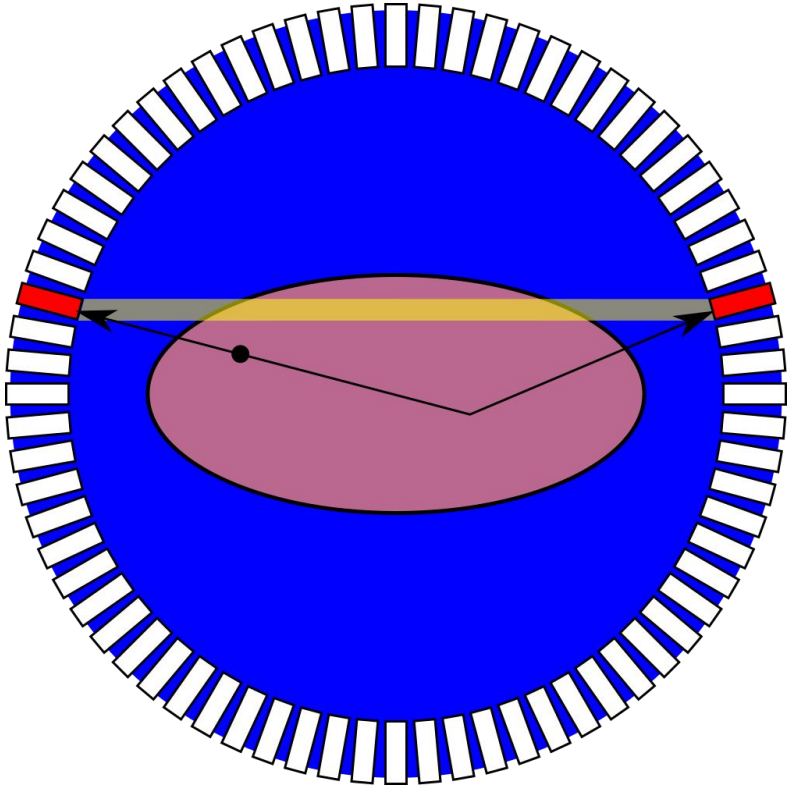
Sensitivity and spatial resolution

- Cylindrical coverage
- Spatial resolution
  - Crystal section
  - Segmentation
- Parallax effect
  - Degrades resolution
  - Can be recovered by measuring Depth of Interaction (DOI)



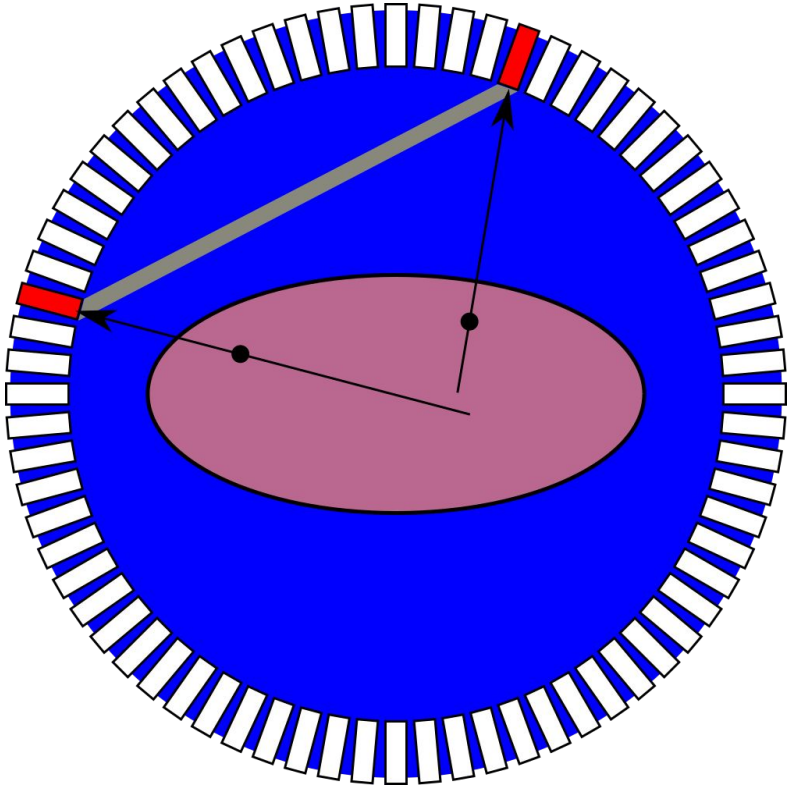
Identify good events

- Measure energy (~10% FWHM)
  - Select 511 KeV
  - Reject scattered photons



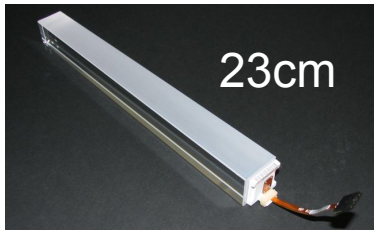
Identify good events

- Measure energy (~10% FWHM)
  - Select 511 KeV
  - Reject scattered photons
- Measure time (~ns)
  - Reject random coinc.
- Apply corrections
  - Normalization
  - Attenuation
  - …

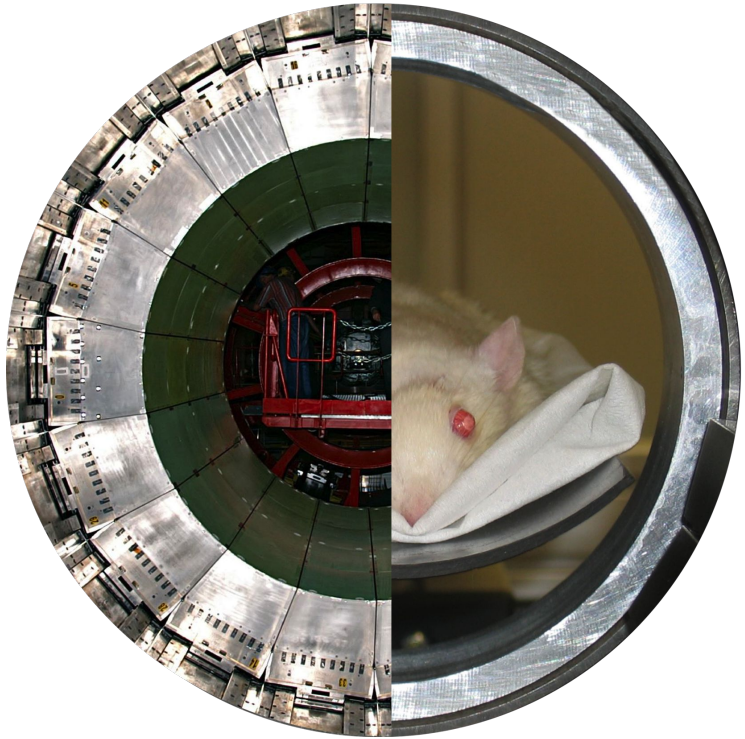


Ok, but why PET research at CERN?

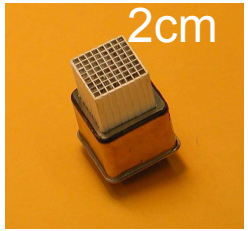
CMS ECAL



~10^{12} eV



PET



~10^{6} eV

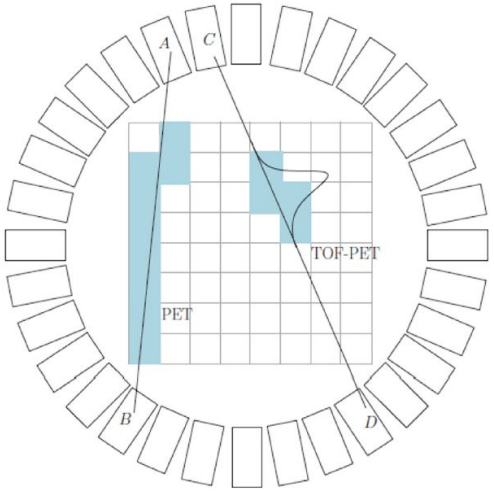
Similar technologies, very different dimensions and energy scale!

2.
Time of Flight PET

Why does it matter, and where is it going

Time of flight (TOF)

Compute the difference in time of arrival of the two gammas



Time resolution (ns)	Δx (cm)	TOF NEC gain	TOF SNR gain
0.1	1.5	26.7	5.2
0.3	4.5	8.9	3.0
0.6	9.0	4.4	2.1
1.2	18.0	2.2	1.5
2.7	40.0	1.0	1.0

Improve event localization

$$\Delta x = c\frac{\Delta t}{2}$$

Improve Signal-to-Noise ratio

$$SNR_{TOF} \sim \sqrt{\frac{D}{\Delta x}} \cdot SNR_{CONV}$$

Where D is the effective object diameter

Benefits of TOF

- Improved lesion detectability

M. Conti - Eur J Nucl Med Mol Imaging (2011) 38: 1147

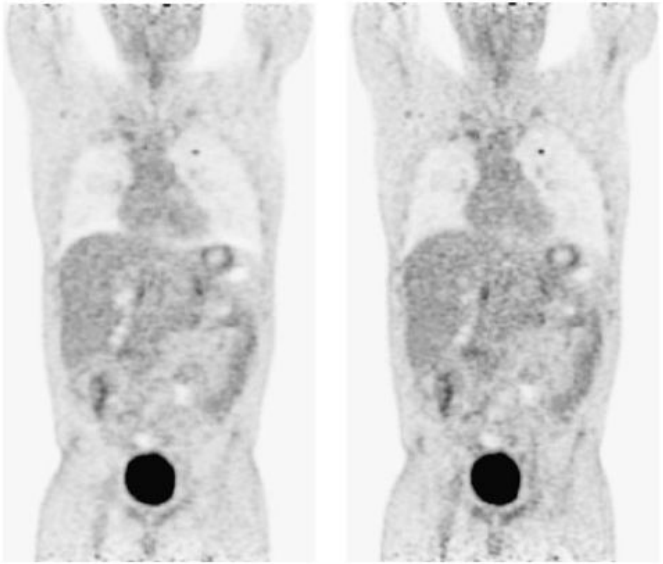


Fig. 1 Coronal images reconstructed from a non-TOF scan (*left*) and a TOF scan (*right*) in a patient with lung cancer. The acquisition time was 3 min per bed position for both images. At the same number of counts, the image quality is better with the TOF reconstruction

Benefits of TOF

- Improved lesion detectability
- Reduced scan time

M. Conti - Eur J Nucl Med Mol Imaging (2011) 38: 1147

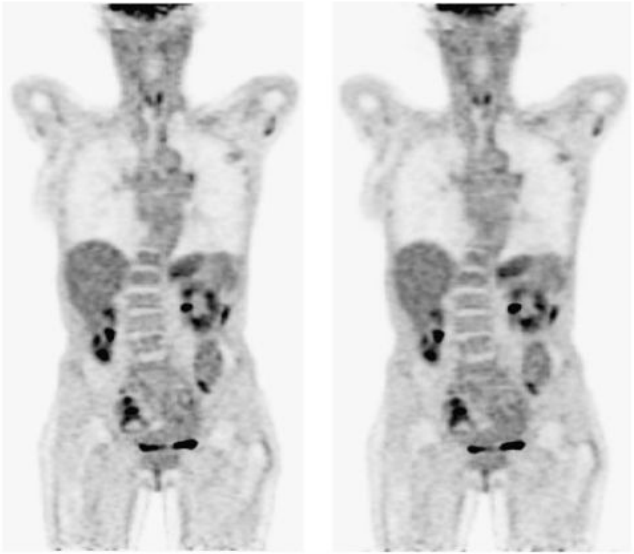


Fig. 2 Coronal images reconstructed from a non-TOF scan (*left*) and a TOF scan (*right*). The acquisition time was 2 min per bed position for the non-TOF scan and 1 min per bed position for the TOF scan. The quality of the non-TOF image and that of the TOF image with half of the counts are similar

Benefits of TOF

- Improved lesion detectability
- Reduced scan time
- Faster reconstruction convergence

S. Surti, J.S. Karp - Physica Medica 32 (2016) 12–22

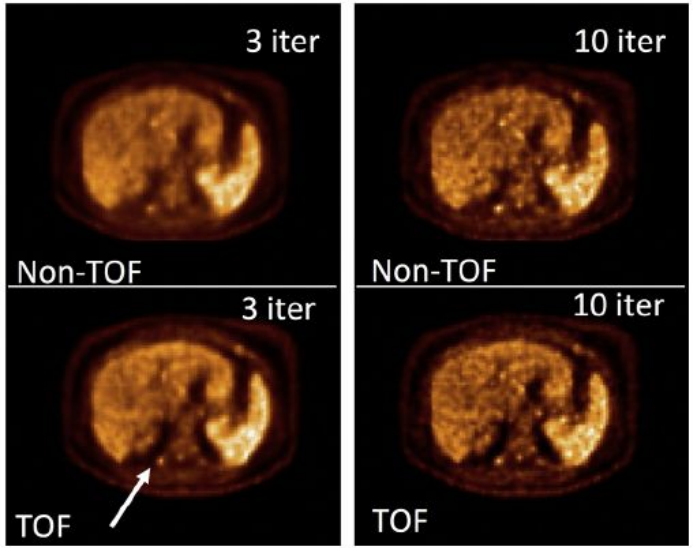
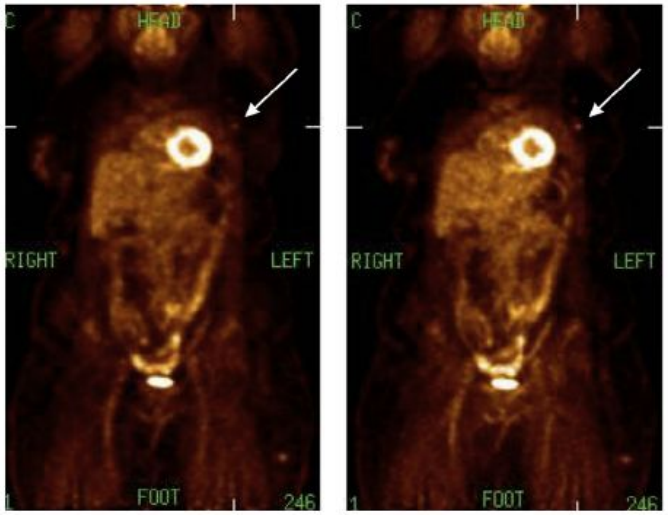


Figure 2. Reconstructed transverse slices of a clinical ^{18}F-FDG study. As indicated, images are shown for Non-TOF and TOF reconstruction and for iterations 3 and 10 of the reconstruction algorithm. The arrow indicates the lesion for which an accurate SUV is measured after 3 iterations of the TOF reconstruction algorithm.

Benefits of TOF

S. Surti, J.S. Karp - Physica Medica 32 (2016) 12–22

- Improved lesion detectability
- Reduced scan time
- Faster reconstruction convergence
- Improved image quality in large patients



Benefits of TOF

- Improved lesion detectability
- Reduced scan time
- Faster reconstruction convergence
- Improved image quality in large patients
- Better image reconstruction for incomplete acquisitions

S. Surti, J.S. Karp - Physica Medica 32 (2016) 12–22

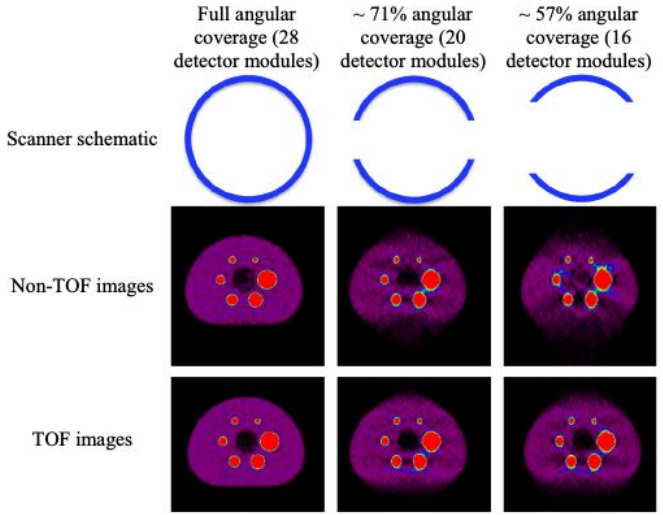


Figure 4. Reconstructed images from a NEMA image quality phantom using full or partial angular data acquired on a clinical TOF PET/CT. The six hot spheres in a ring have diameters of 37, 28, 22, 17, 13, and 10 mm and have an activity uptake of 9.7:1 with respect to background. The central cold region is a lung insert.

Best TOF-PET on the market: Siemens Biograph Vision

J. S. Reddin et al. doi: 10.1109/NSSMIC.2018.8824710

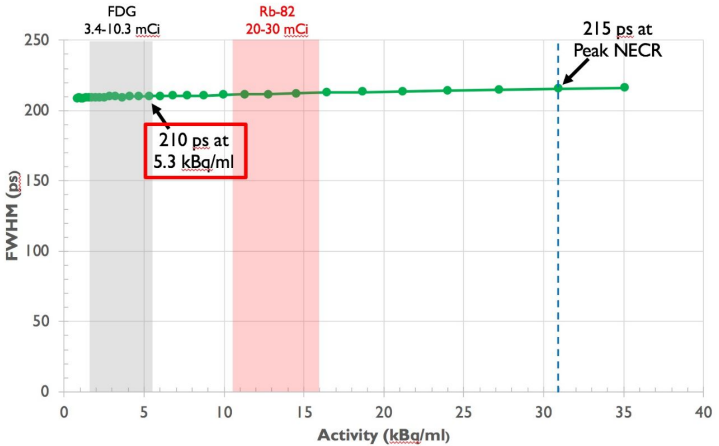


Fig. 7. The NEMA NU 2-2018 time of flight resolution is 215 ps at peak NECR and 210 ps at 5.3 kBq/ml.

Demonstrated 210 ps FWHM resolution over the entire scanner

TOF: why more?

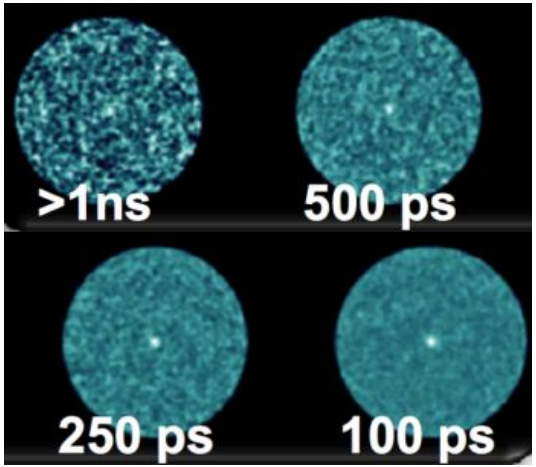
200ps

Better SNR

Picture from FP7 European EndoTOFPET project

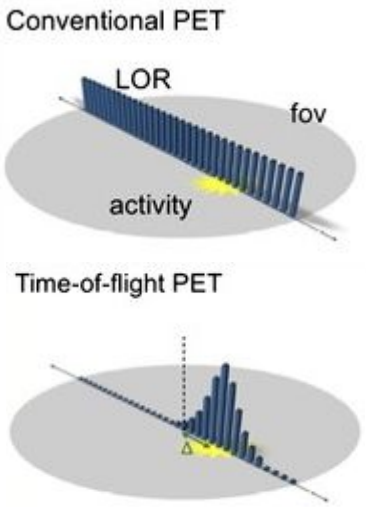
100ps

Even better SNR

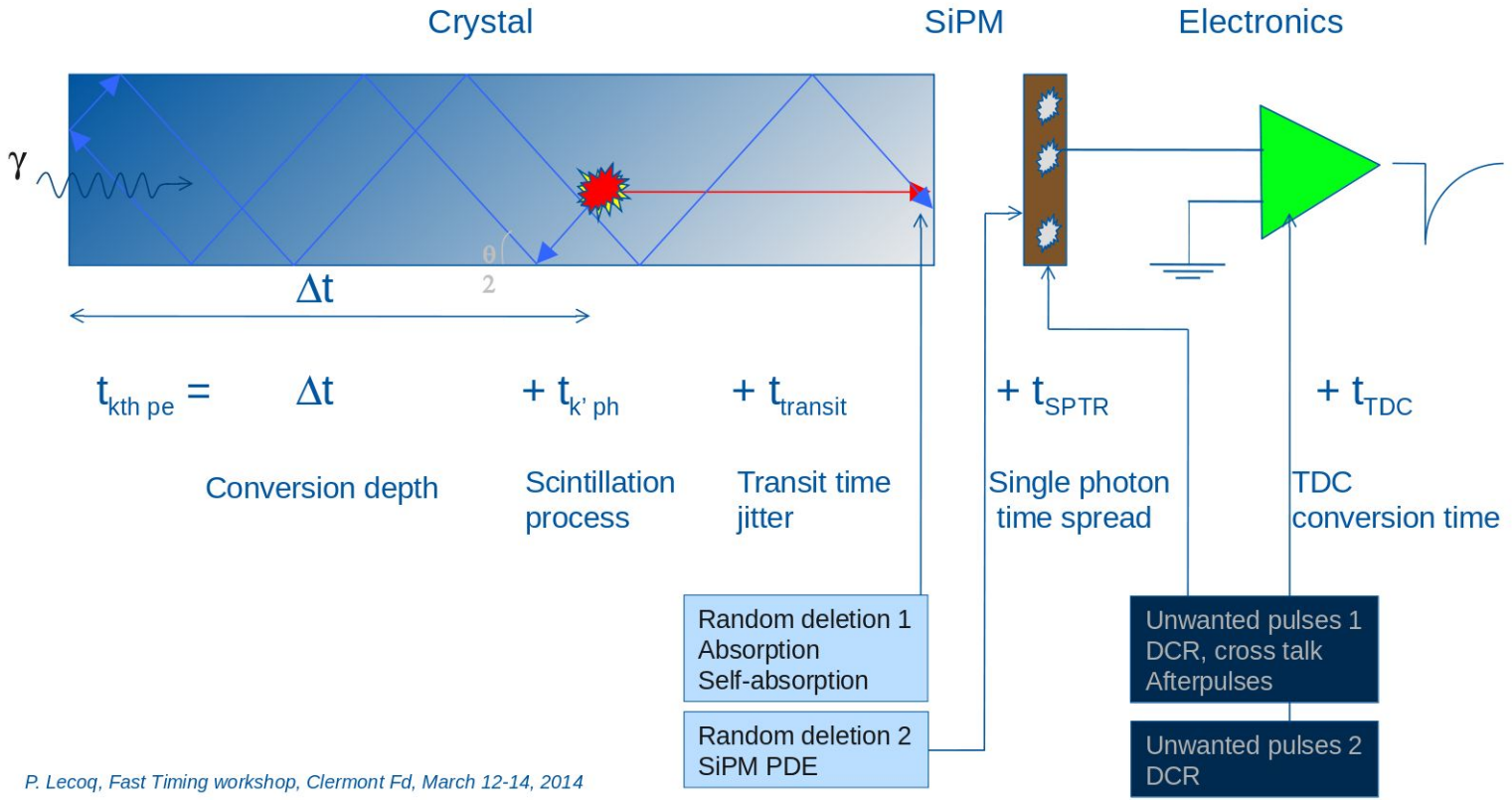


10ps

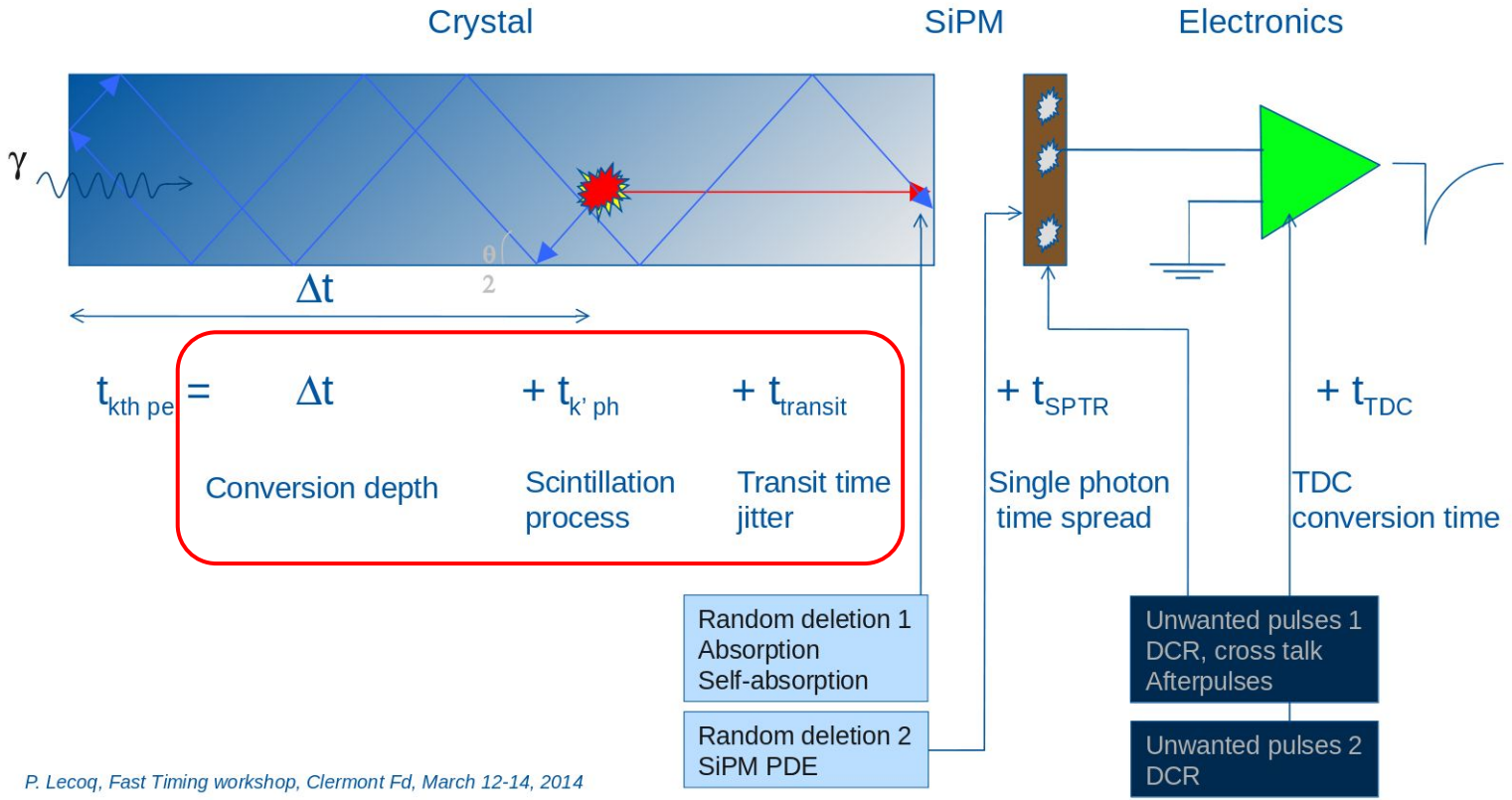
No reconstruction (almost…)



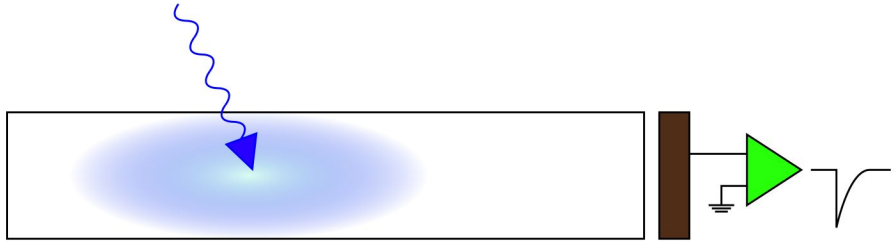
Optimizing the detection chain



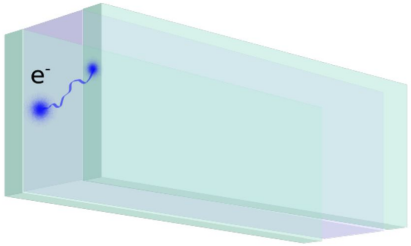
Optimizing the detection chain



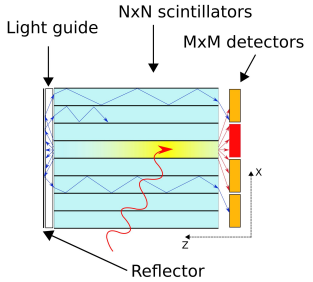
Our approach



Faster light production



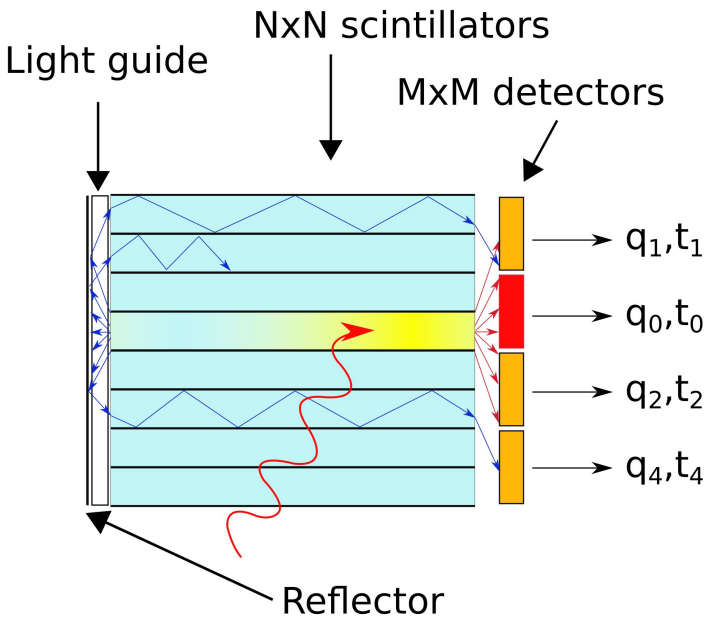
Measurement of DOI



A work supported by several CERN KT/MA projects!

A new method for Depth of Interaction

CERN KT Fund "Development of a new ClearPEM module"



$$Q = \sum_i q_i$$

→ Energy

$$w = \frac{q_0}{\sum_i q_i}$$

→ DOI

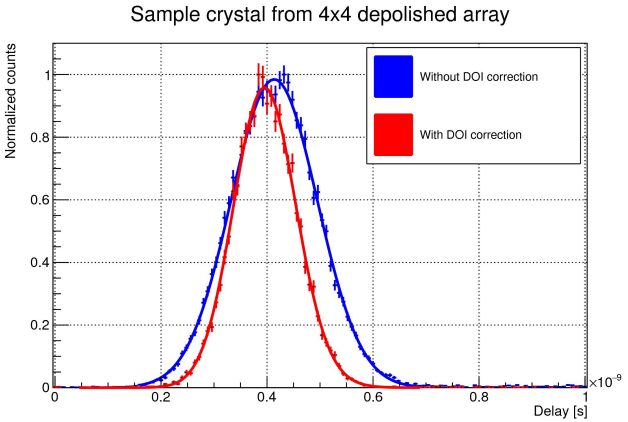
$$\hat{t_0} = \frac{\sum_i a_i (t_i - \Delta_i(w))}{\sum_i a_i}$$

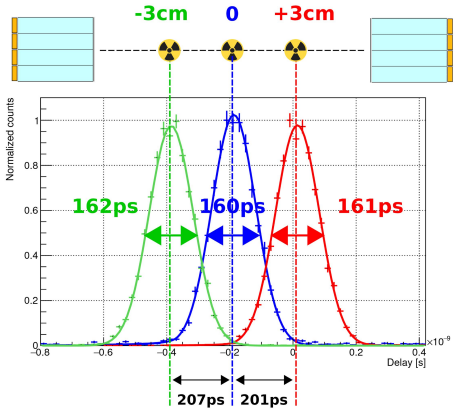
→ Timing

M. Pizzichemi et al. 2019 Phys. Med. Biol. 64 155008

A new method for Depth of Interaction

CERN KT Fund "Development of a new PET module"





LYSO array type	Crystals dim. [mm^3]	En. Res. FWHM @ 511 keV [%]	DOI Res. FWHM [mm]	CTR FWHM [ps]
4x4	3.1 x 3.1 x 15	9.5 ± 0.2	3.0 ± 0.2	**159 ± 2**
8x8	1.5 x 1.5 x 15	9.9 ± 0.2	3.0 ± 0.2	**157 ± 2**

M. Pizzichemi et al. 2019 Phys. Med. Biol. 64 155008

Thank you for your attention!

And now to Fiammetta, for the cutting edge stuff…

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