MCMA2017

ADVANCES IN FLUKA PET TOOLS

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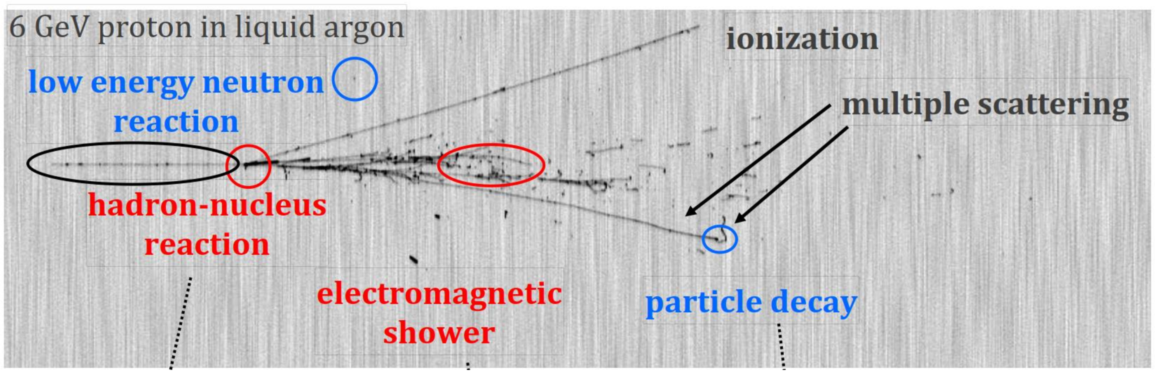
Naples, 18/10/2017

Rationale: Why FLUKA for PET



Physics Models

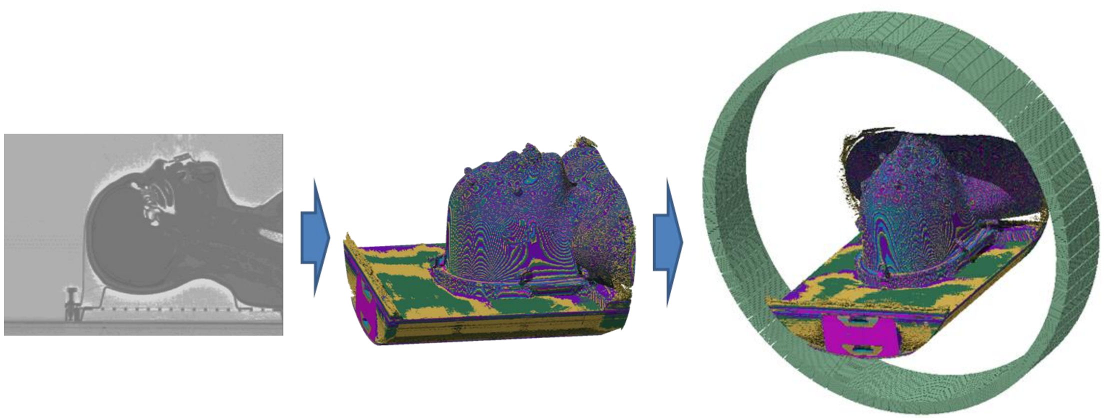
- All Hadrons , Leptons
- On-line evolution of induced radioactivity and dose
- Benchmarked in the MA energy range (in addition to HEP)

See talk G.Battistoni Id. 54

FLAIR Complete IDE* for all FLUKA simulation phases

(input, geometry editor, debugging, post-processing output visualization)

**Integrated Development Environment*



Voxel geometries

natively integrated with FLUKA tools for QA MC-TPS

DICOM information from clinical CT to FLUKA Voxel geometry

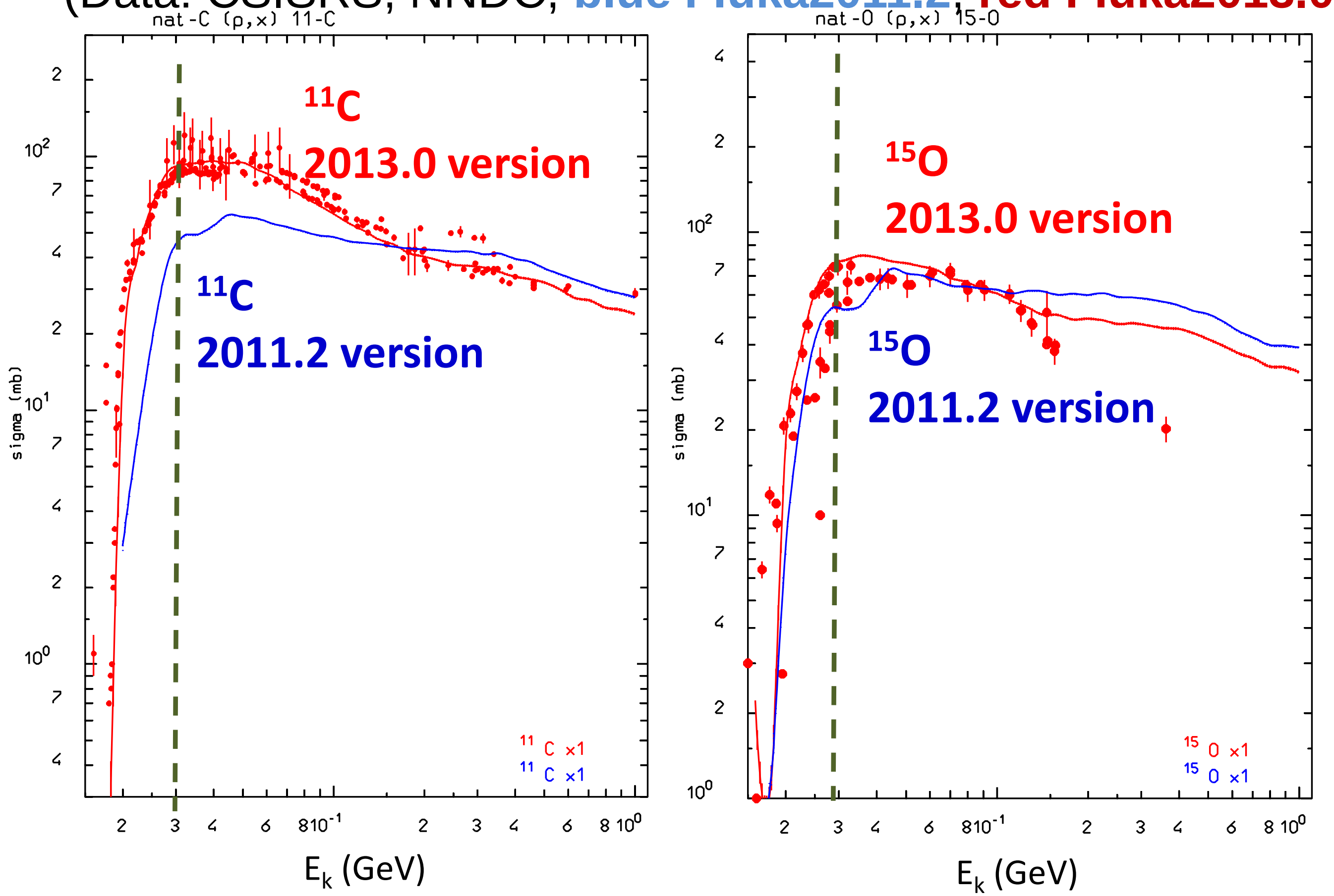
Rationale: Why FLUKA for PET

FLUKA code development for (p,d), (n,d) reactions

Excitation functions **$^{12}C(p,x)^{11}C$ and $^{16}O(p,x)^{15}O$, relevant for PET :**

Now deuteron formation at low energies is treated directly and no longer through coalescence

(Data: CSISRS, NNDC, **blue Fluka2011.2**, **red Fluka2013.0**)

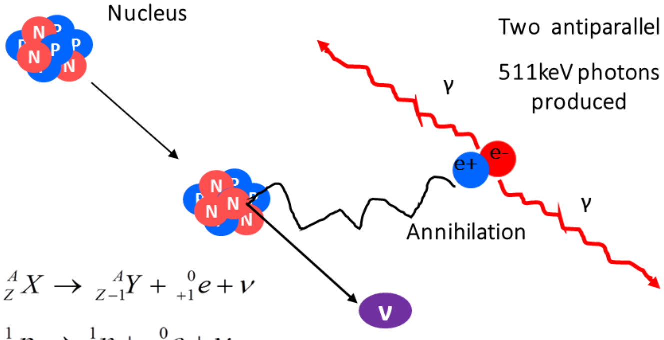


Rationale: Why FLUKA for PET

Most recent FLUKA code developments

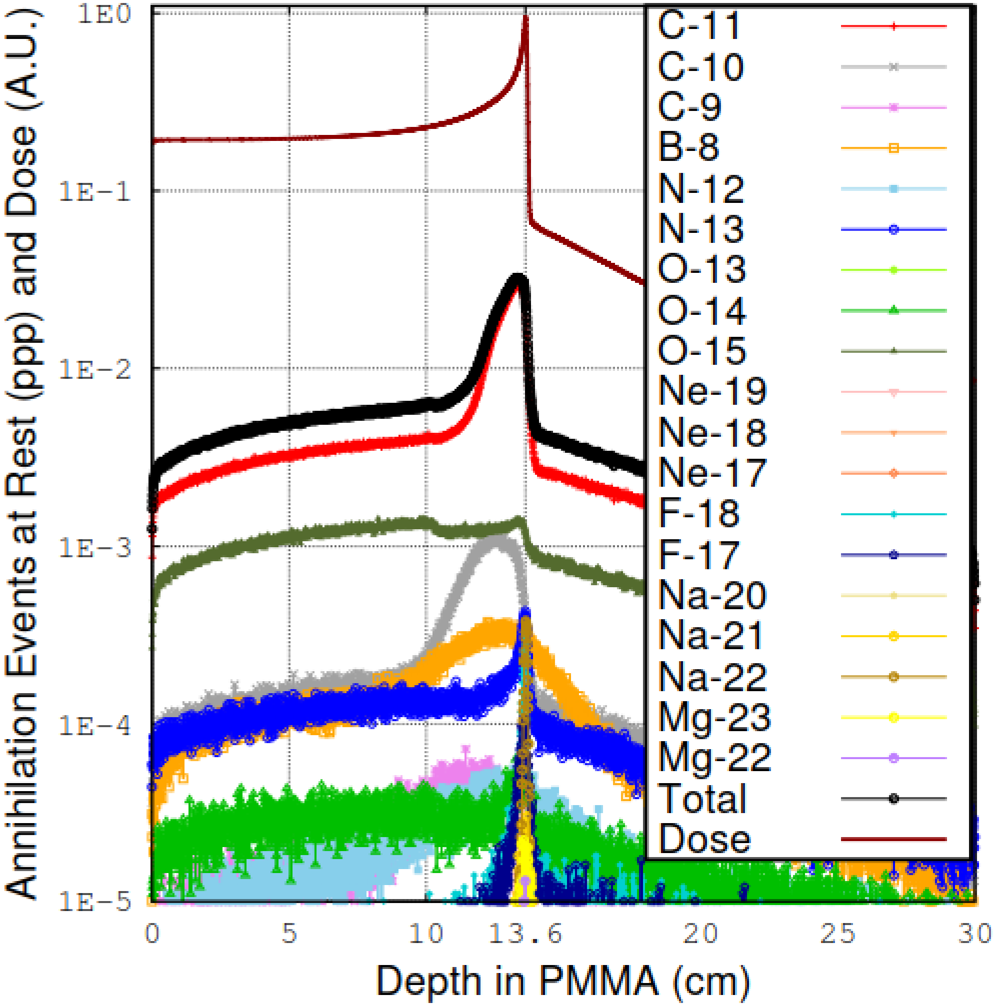
- Scoring annihilation at rest and activity binning

- New flag for keeping track for (parent) Isotope:



$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + \nu$$

$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu$$



NSS-MIC 2017,Atlanta

Rationale: Why FLUKA for PET

Most recent FLUKA application for in-beam PET

Protons in PMMA

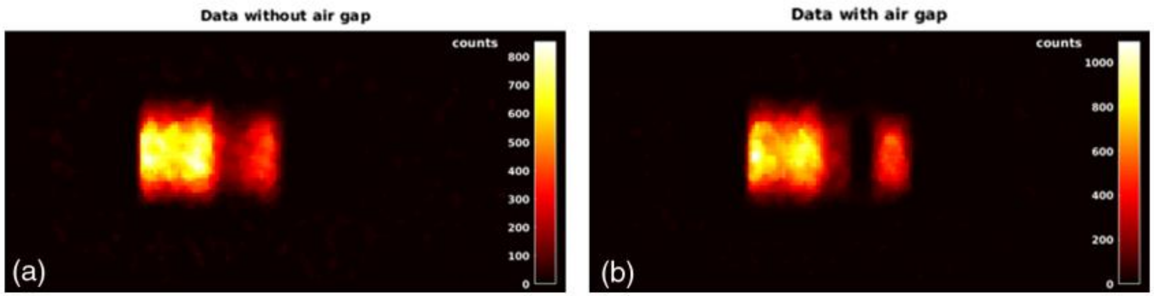
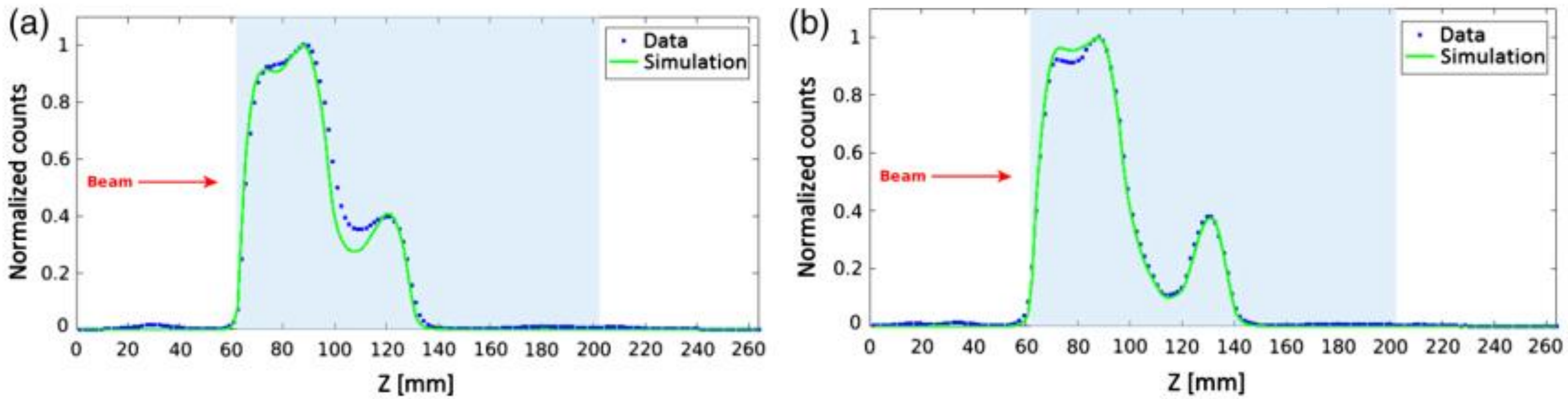


Fig. 8 (a) Image (central slice) of the phantom A obtained for an acquisition time of 519 s. (b) Image (central slice) of the phantom B obtained for an acquisition time of 485 s. In both acquisitions, only inter-spill and after-treatment data are considered.

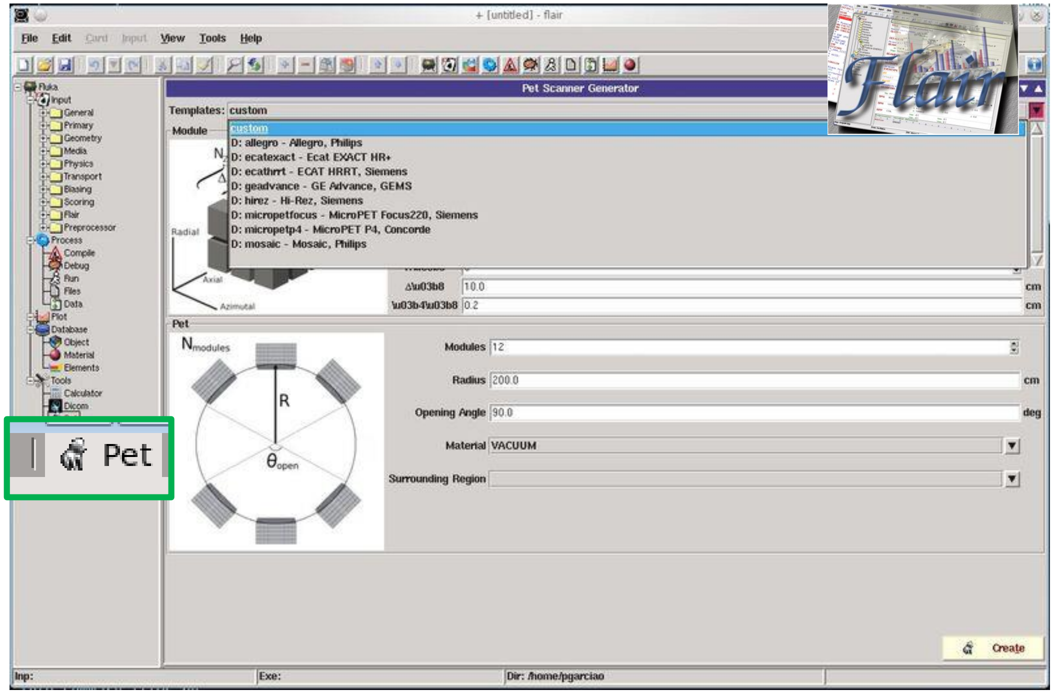


M.G. Bisogni “INSIDE in-beam positron emission tomography system for particle
range monitoring in hadrontherapy,” J. Med. Imag. 4(1), 011005 (2017), doi: 10.1117/1.JMI.4.1.011005.

Results on patient presented by E.Fiorina Id. 143

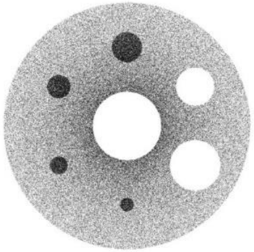
FLUKA PET tools : the Origins..

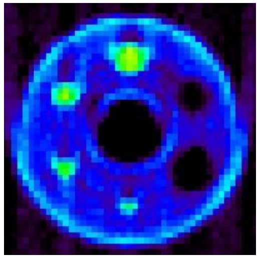
- Integrated in FLAIR
- Developed in 2013
- Tested for conventional PET
- Generic Radioactive sources
- Example for small PET scanner
- Fixed position of the PET scanner
- Only one image reconstruction algorithm (FBP)

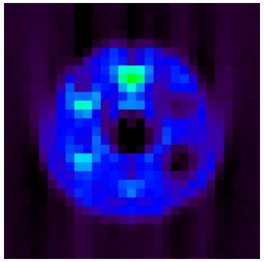


Useful for:

- Inferring the dose map from the β+ emitter distribution
- Test new PET design/options



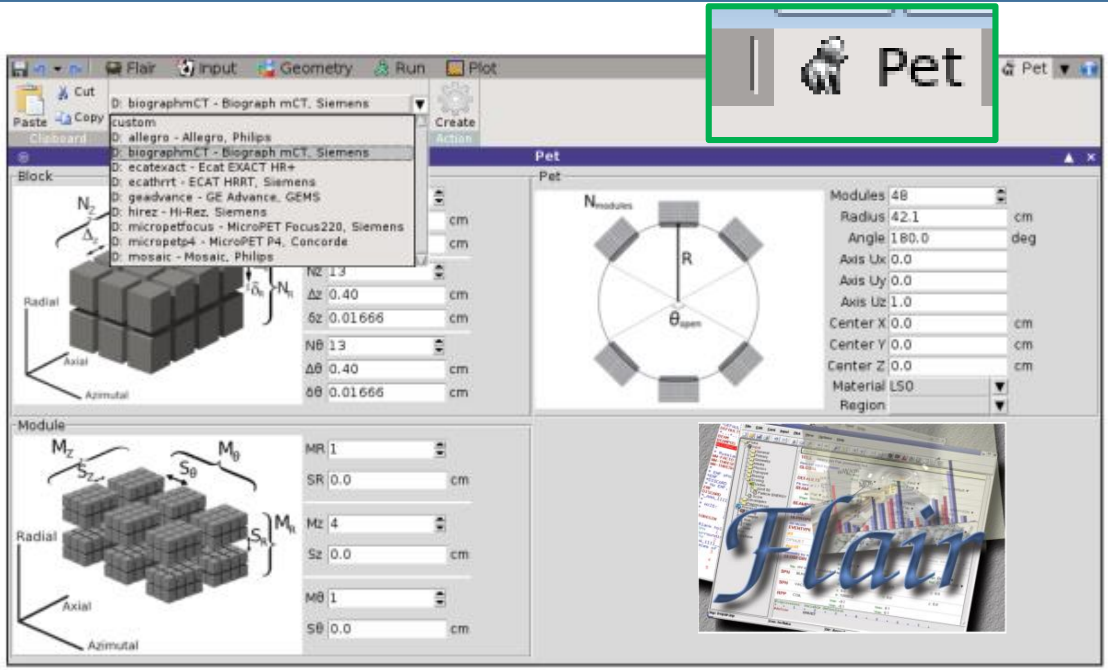


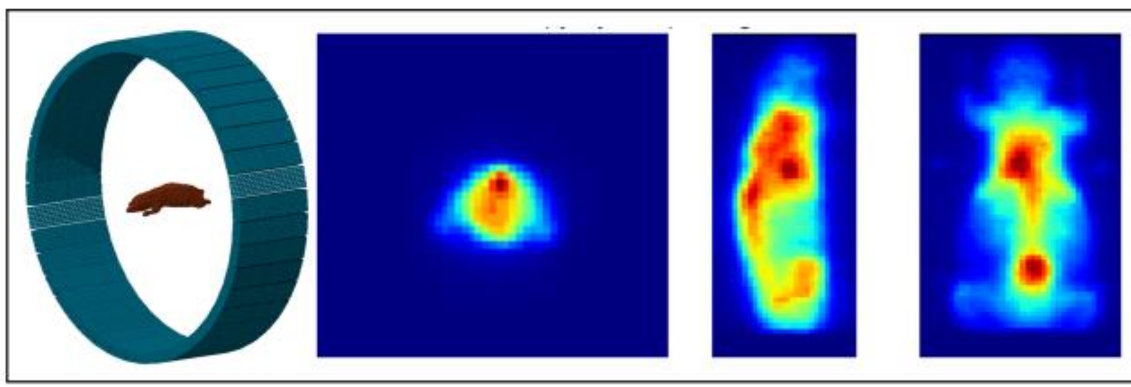


P. G. Ortega ANIMMA2013

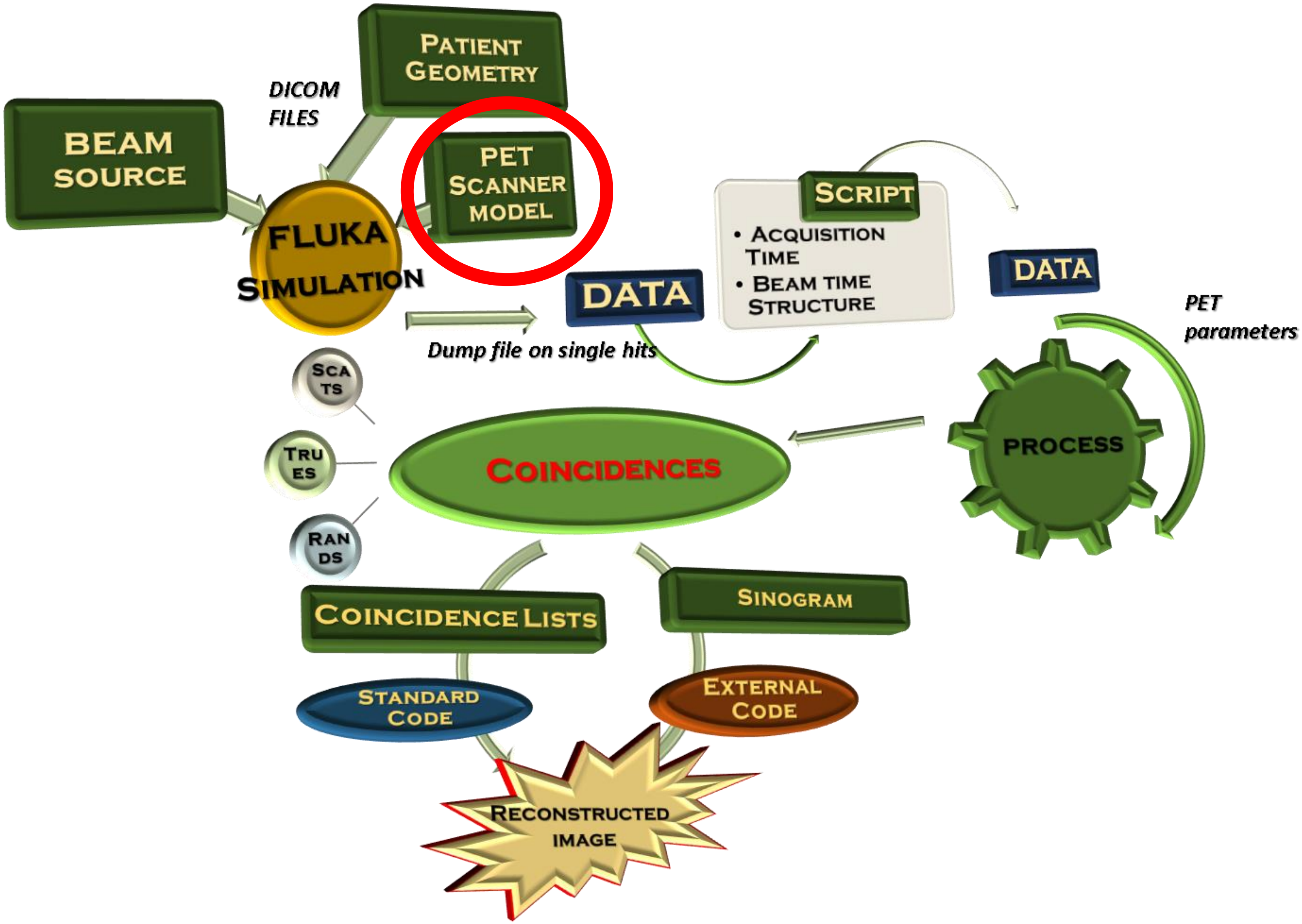
FLUKA PET tools: today

- Rototranslations
- Integration of post processing and scoring routines in Fluka
- New PET scanners and validation with NEMA source
- In-beam PET , beam time structure and acquisition time
- Studies with RIB (Radioactive Ion Beams)
- MLEM code





WORKFLOW



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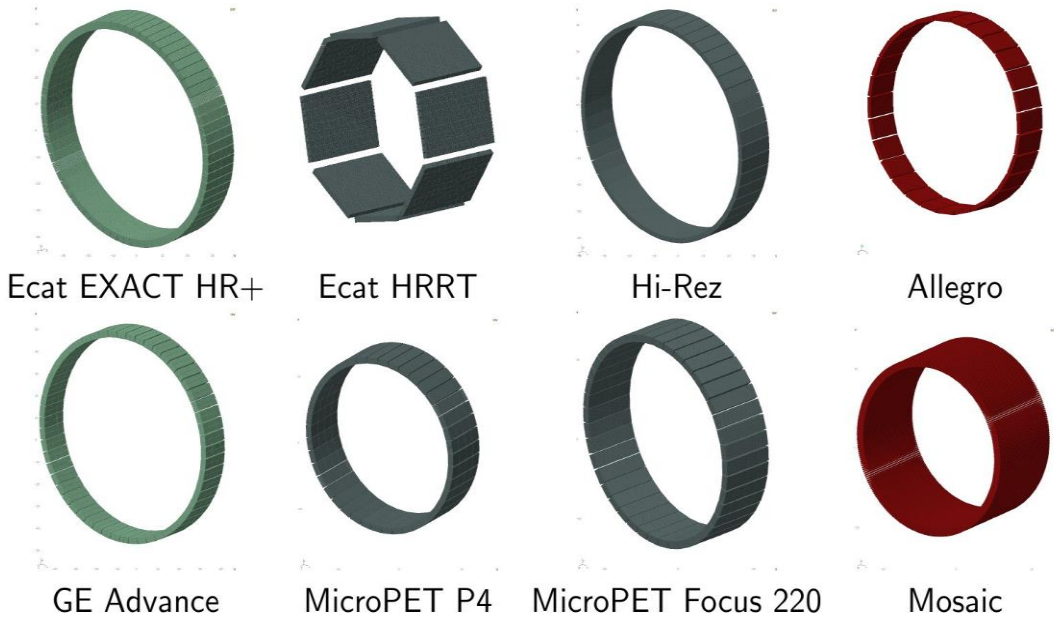
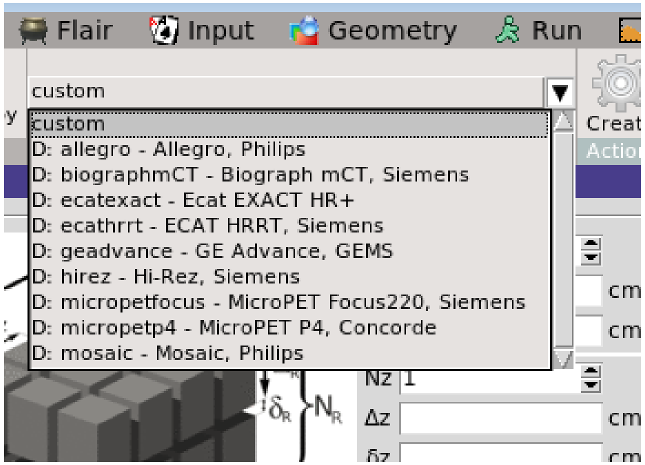
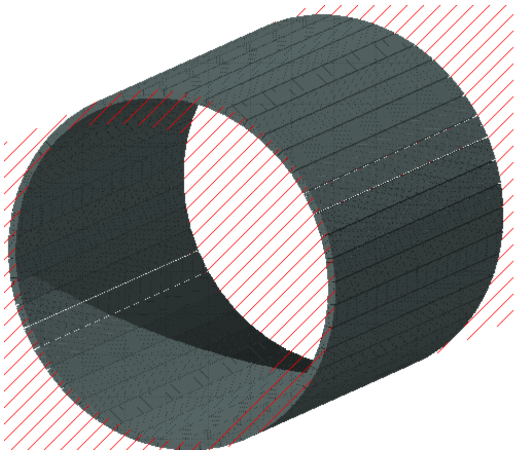
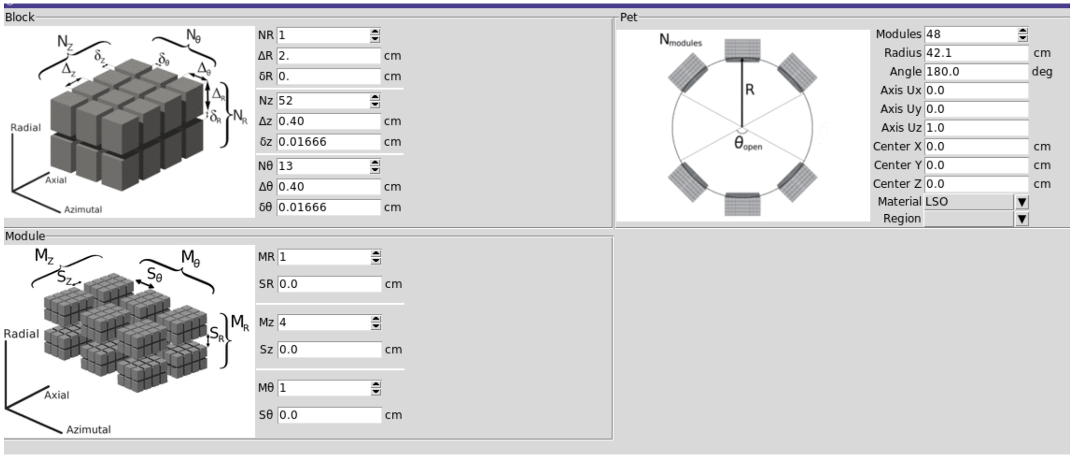
External Code
Reconstructed image





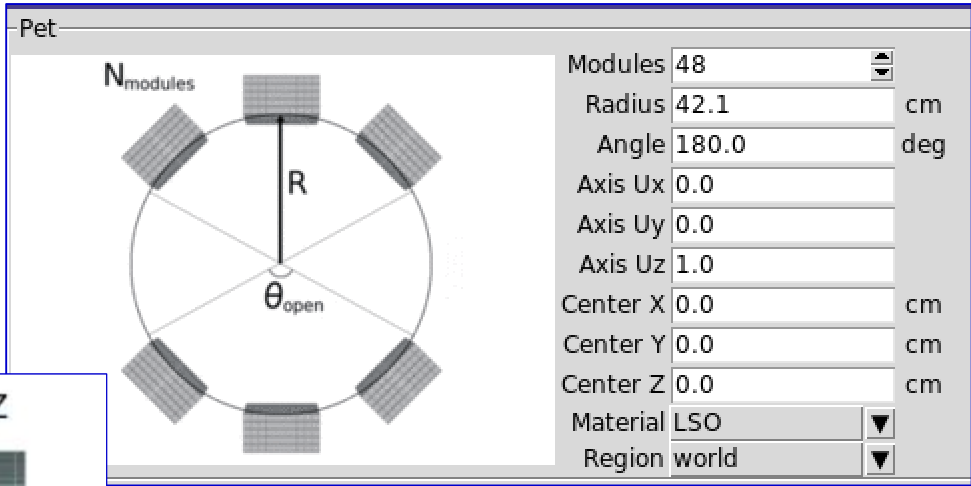
BIOGRAPH , Siemens

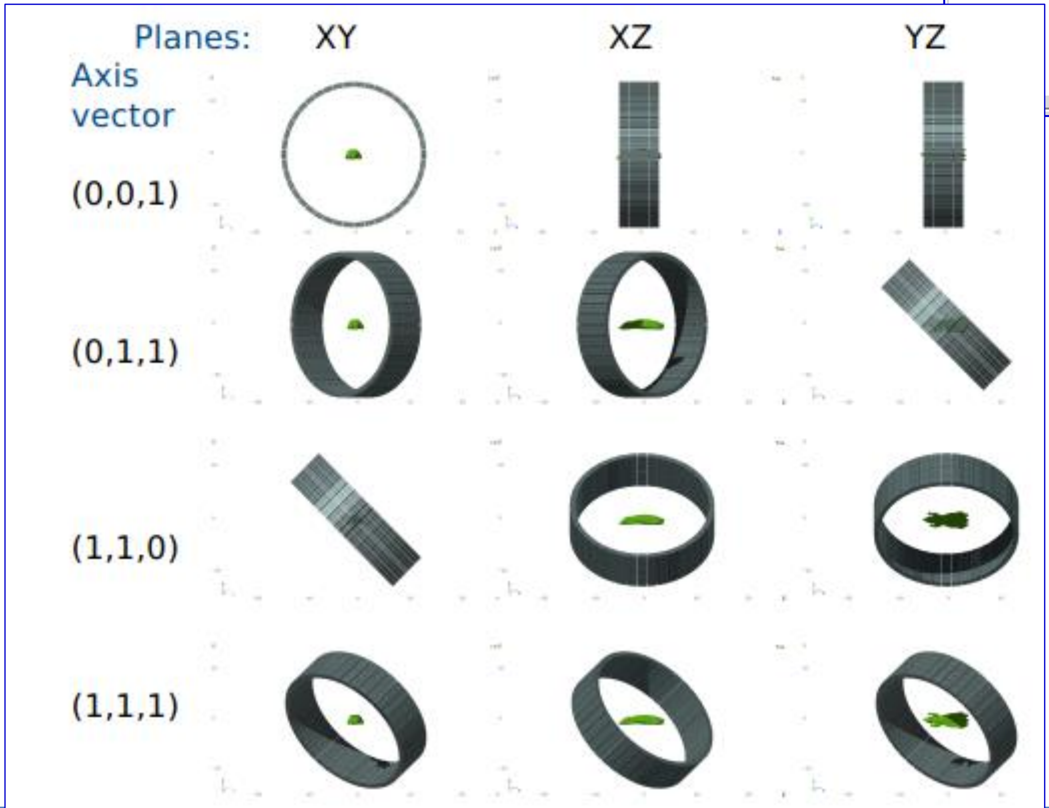




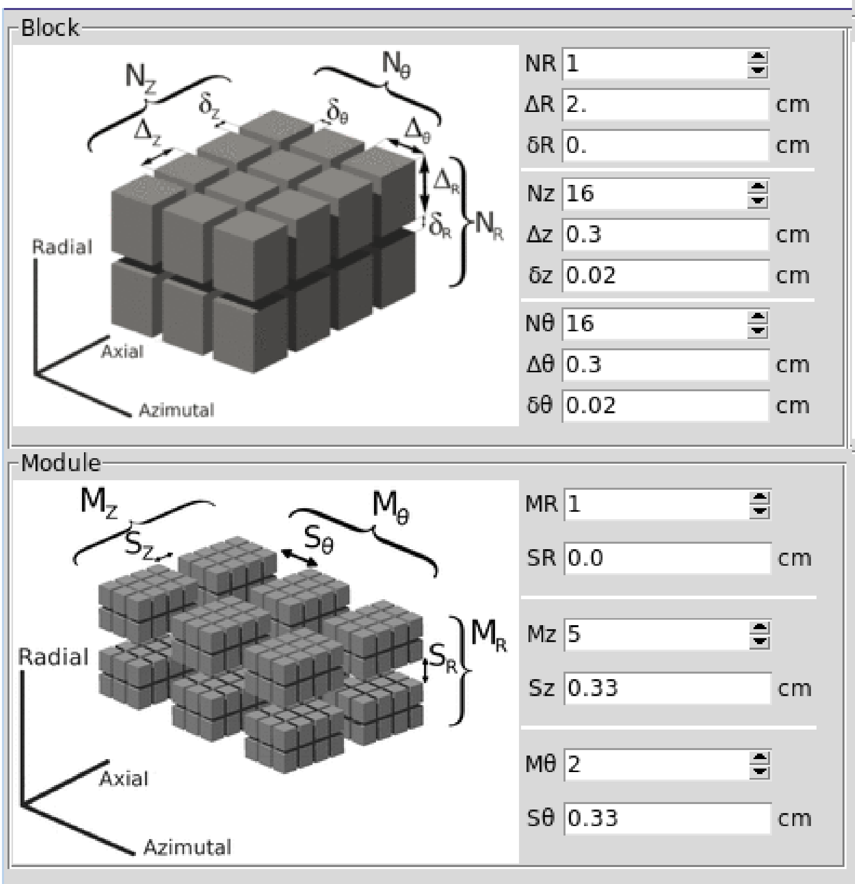
Rototranslations

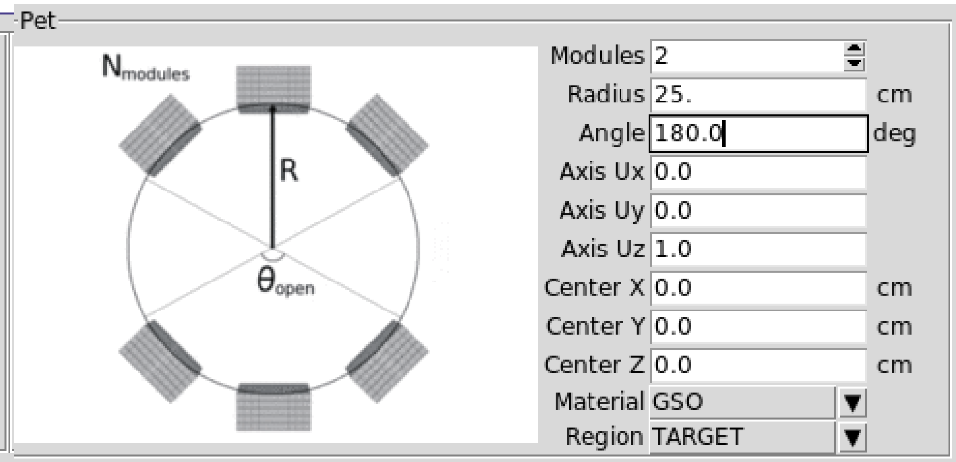
Possibility to roto-translate the scanner by defining a translation vector for the center and a rotation vector for the axis

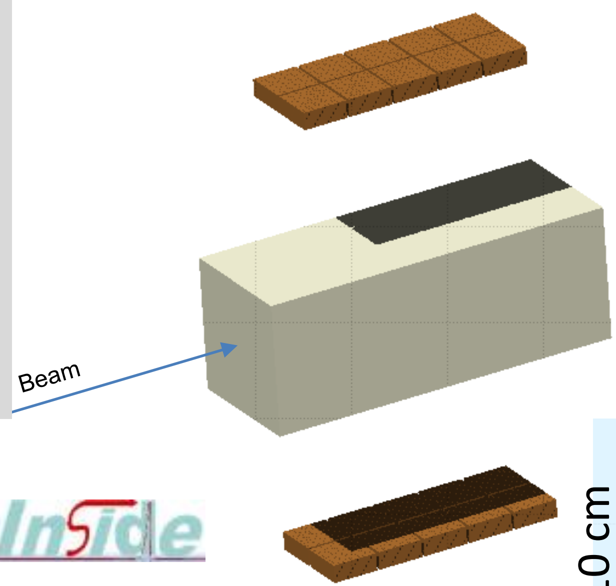


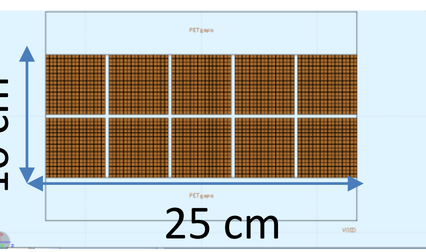


Geometry for New Detectors



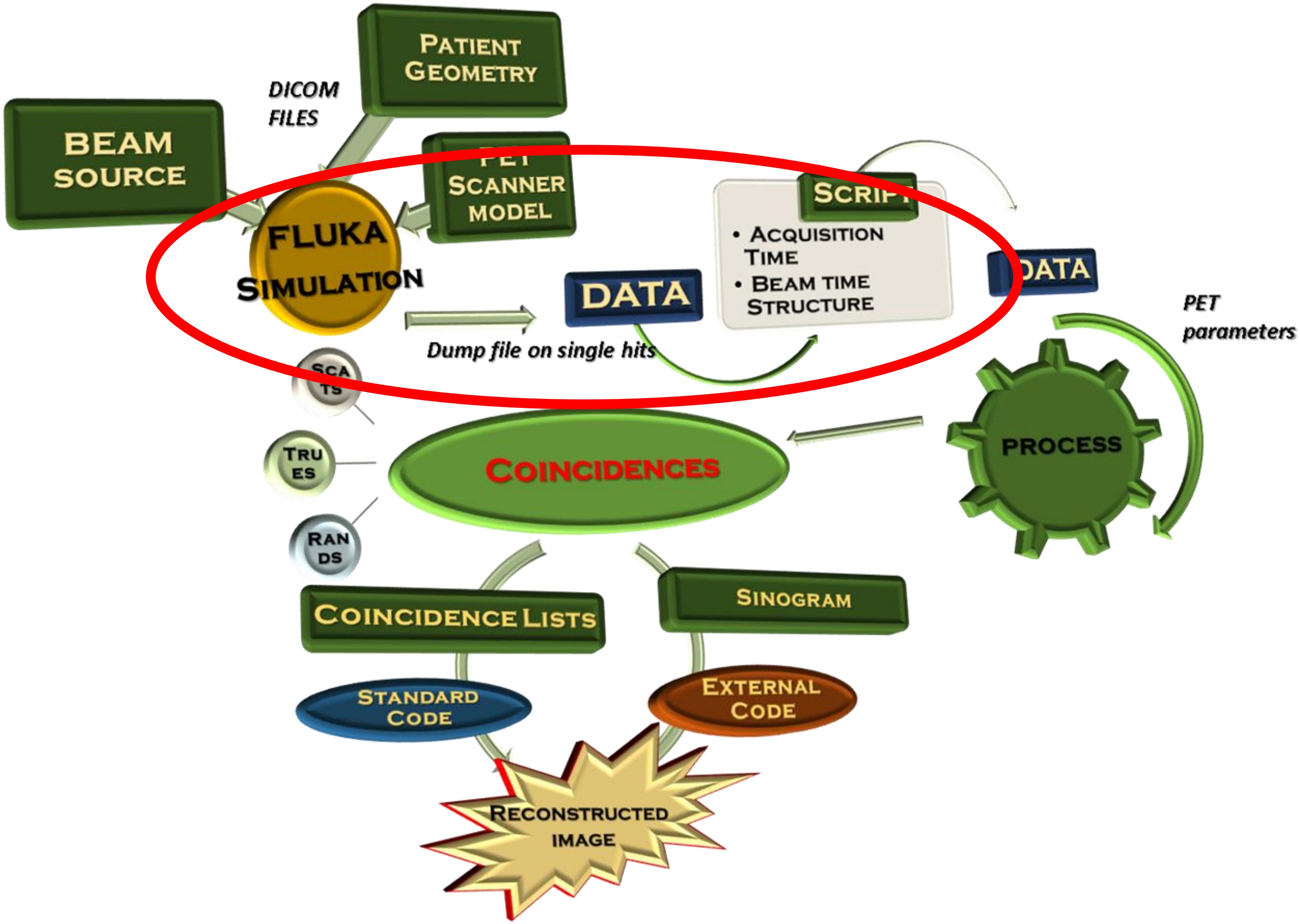






Results on patient presented by E.Fiorina Id. 143

WORKFLOW



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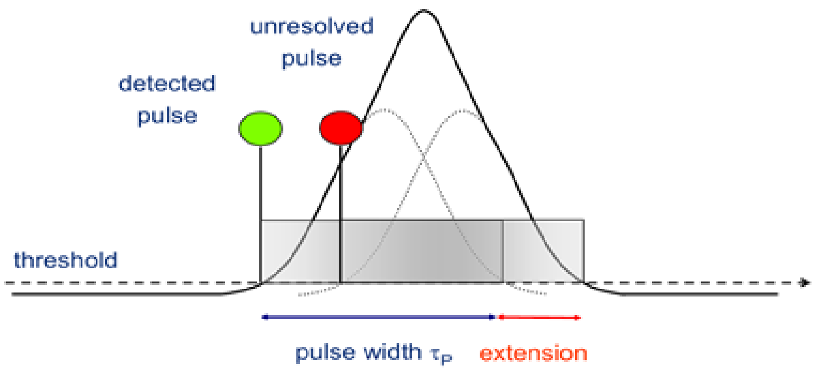
FLUKA simulations

➢ Specific PET parameters

Output unit Binary or ASCII

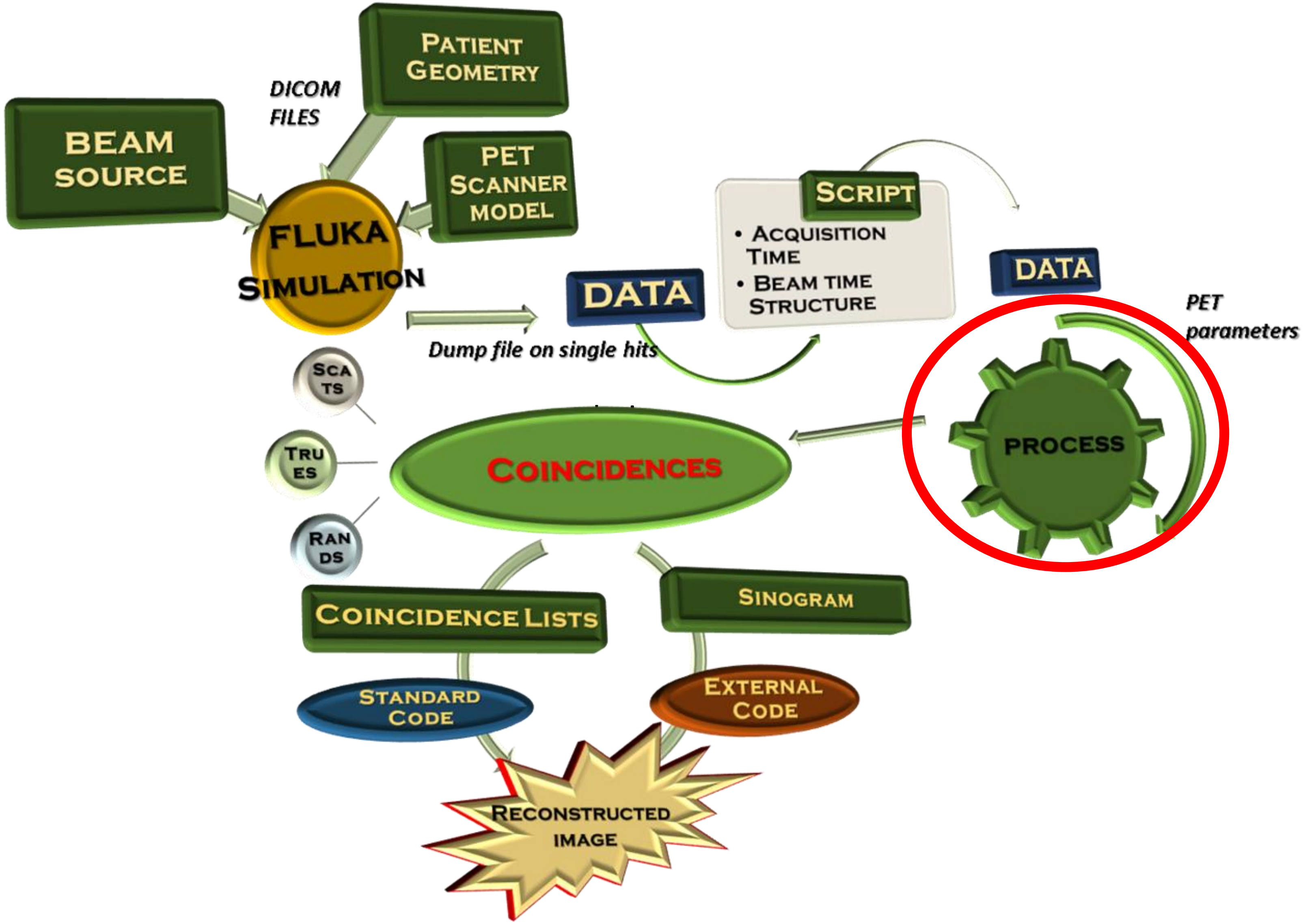
- **Energy resolution-** Energy window interval around the 511keV (min-max)
- Acquisition time interval (min-max) [s]
- Time resolution of the detector [ns]
- Pulse time of the detector [ns]
- Hit dead time of the detector [ns]



➢ 5 Specific scoring routines

- Collection of input parameters
- Collection of Energy deposited in each crystal
- Stores info of particle and parents when created.
- Dumps the buffer into an output file in list mode
- Implementation of the hit dead time and energy window

WORKFLOW



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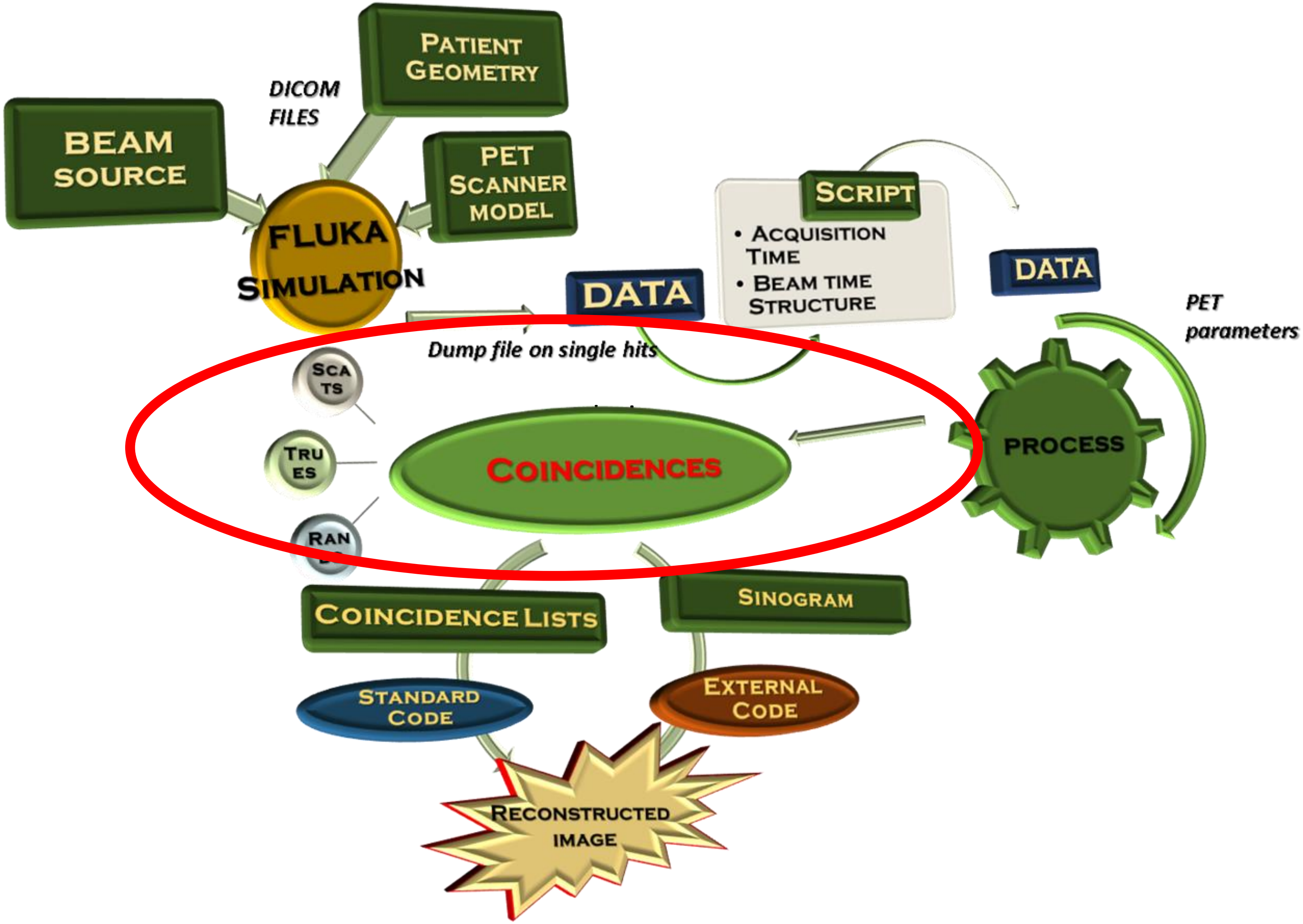

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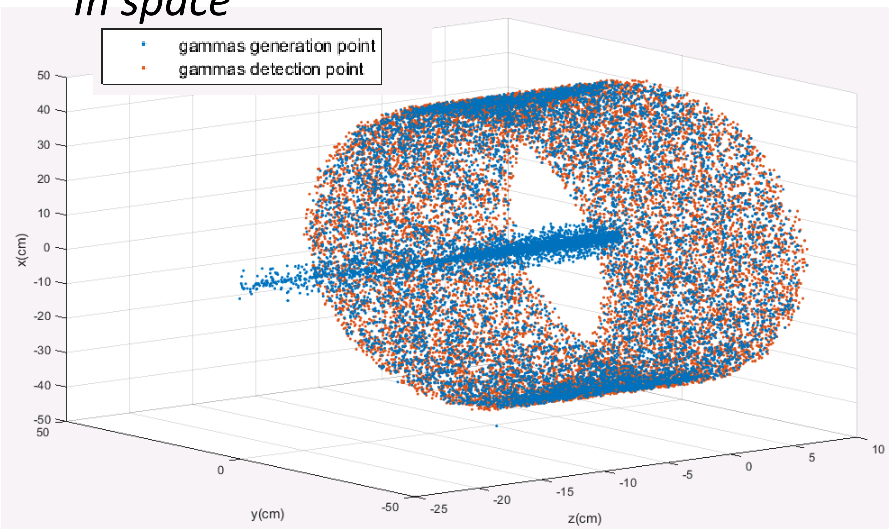
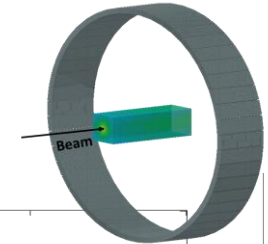
Coincidences file in list mode

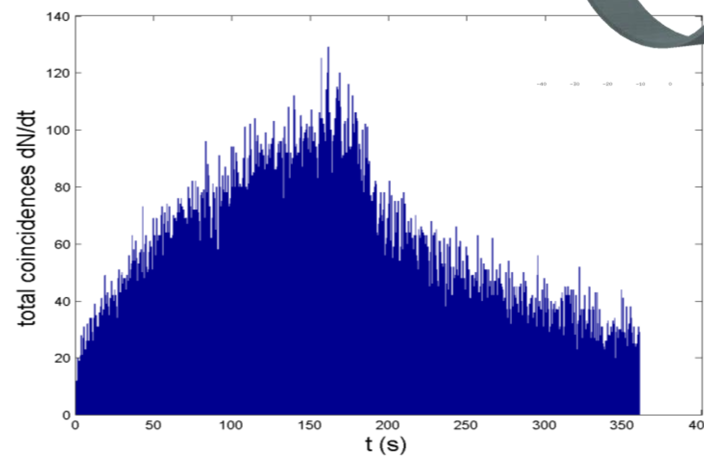
The user can perform several analysis :
Ex. For in-beam PET with a C12 ion beam

In space

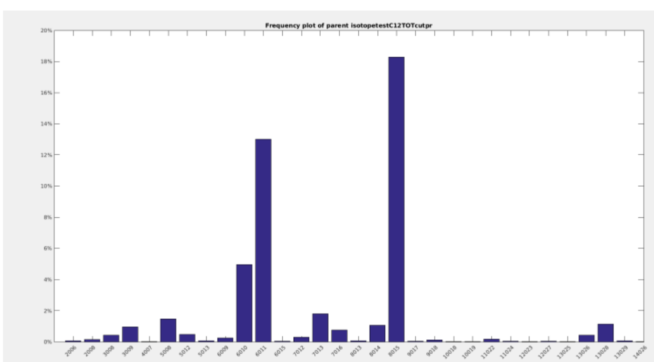


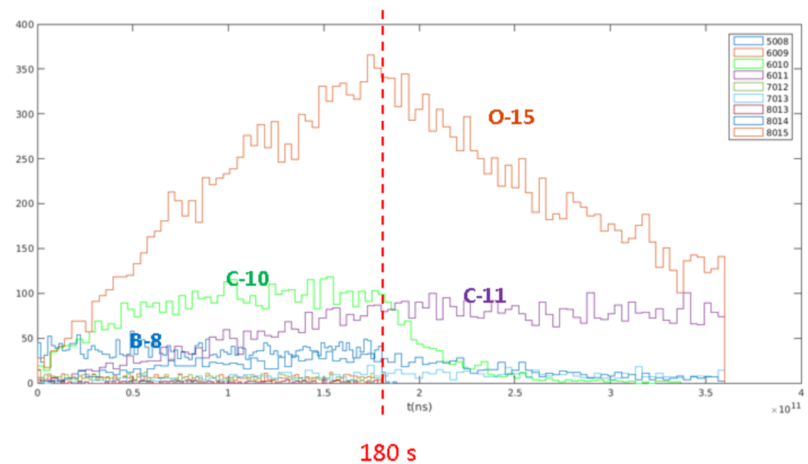
In time





Parent Isotope studies





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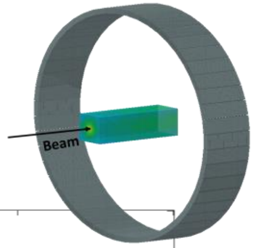

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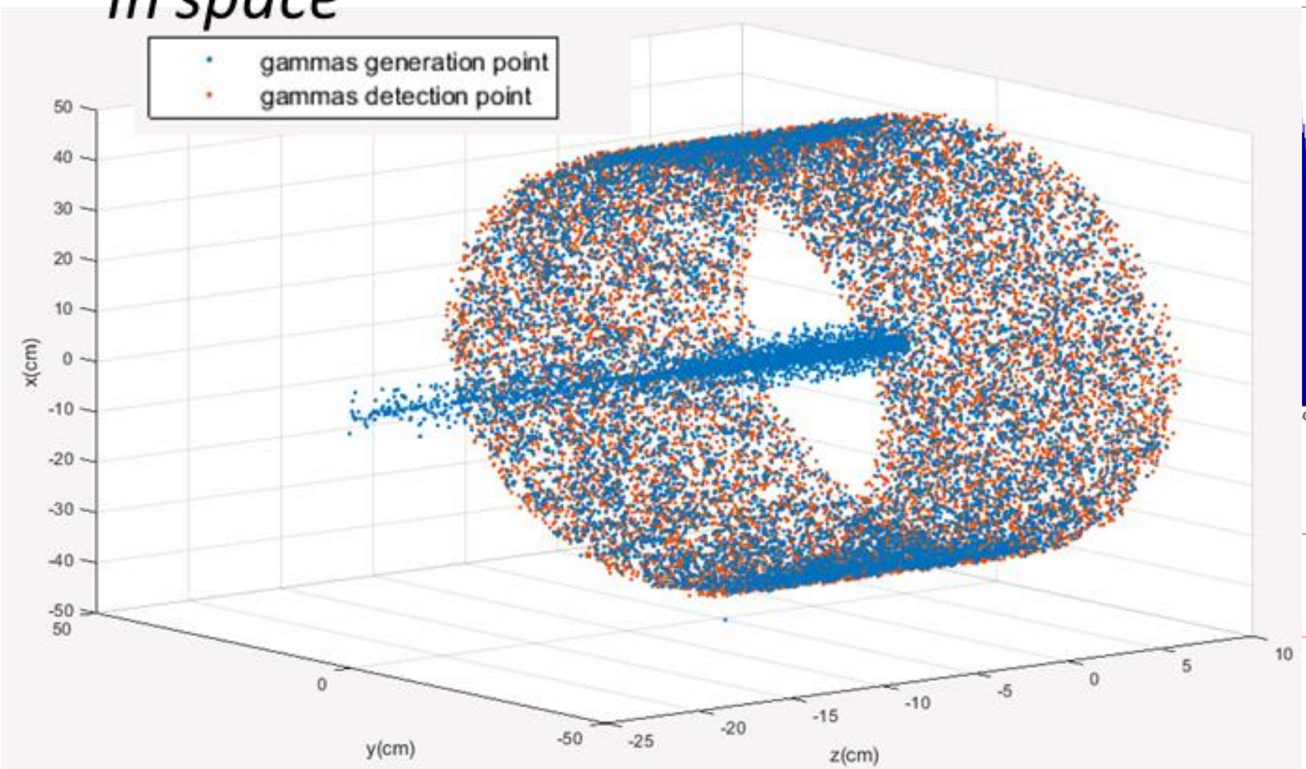

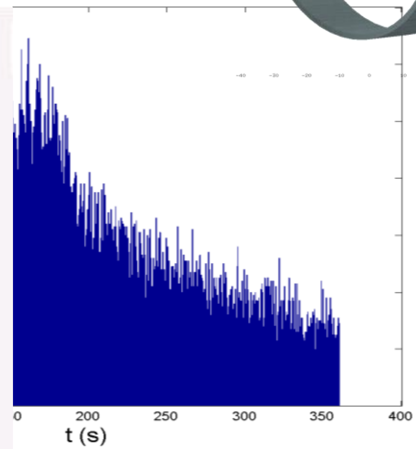

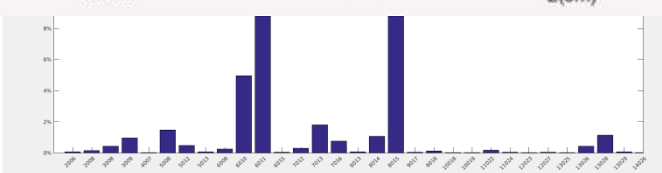

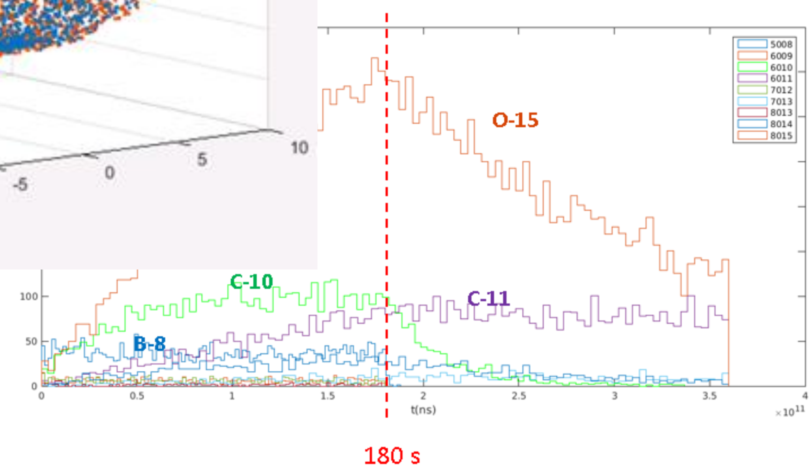

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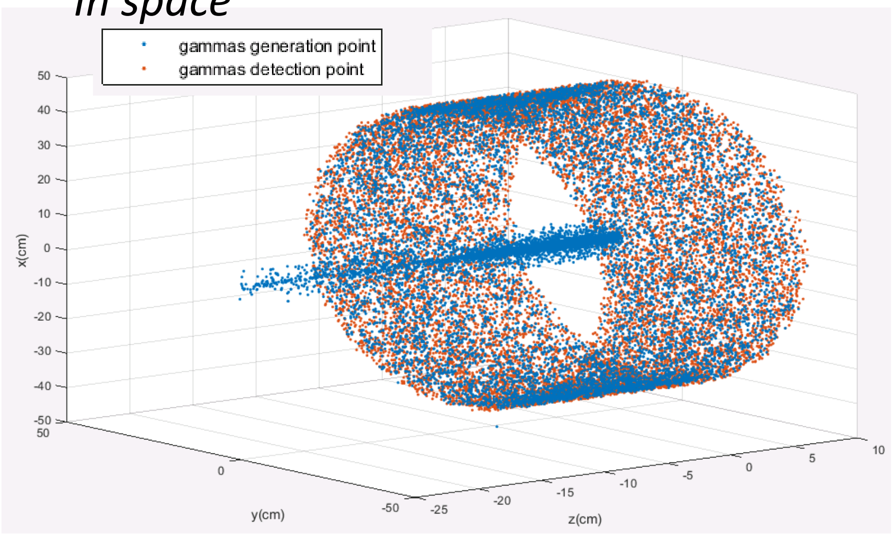

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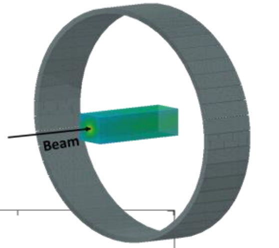
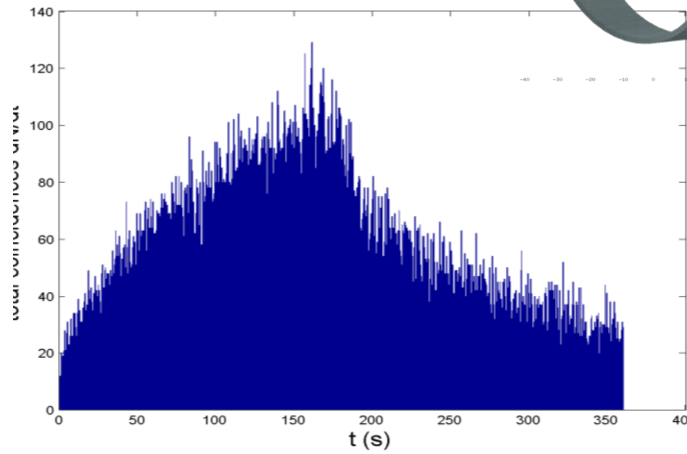
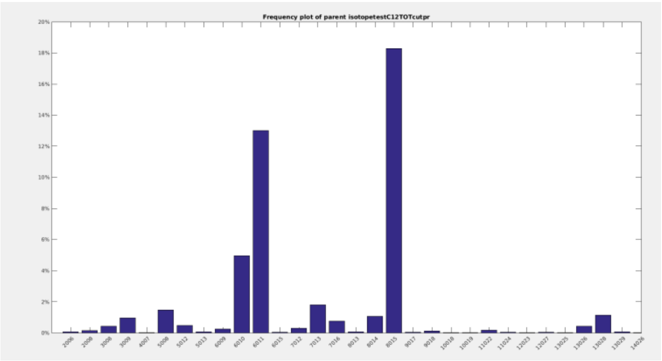
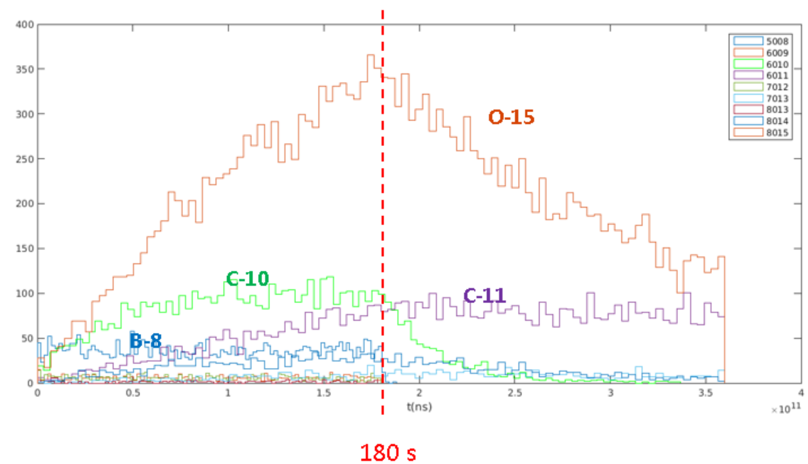




Parent Isotope studies





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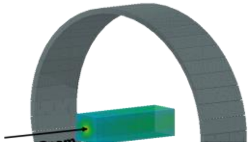

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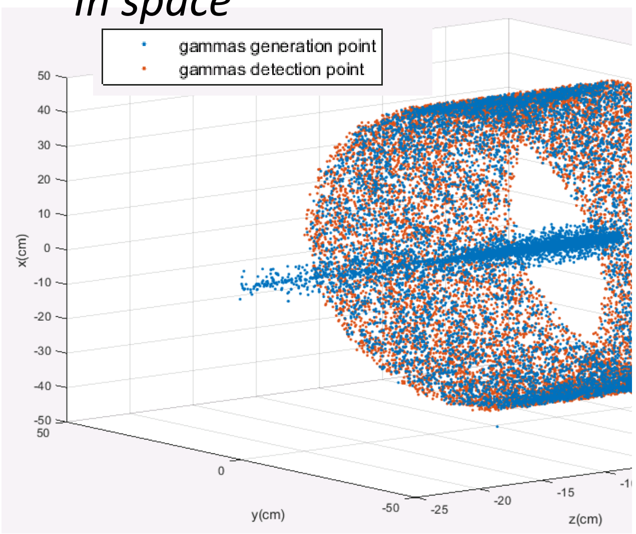

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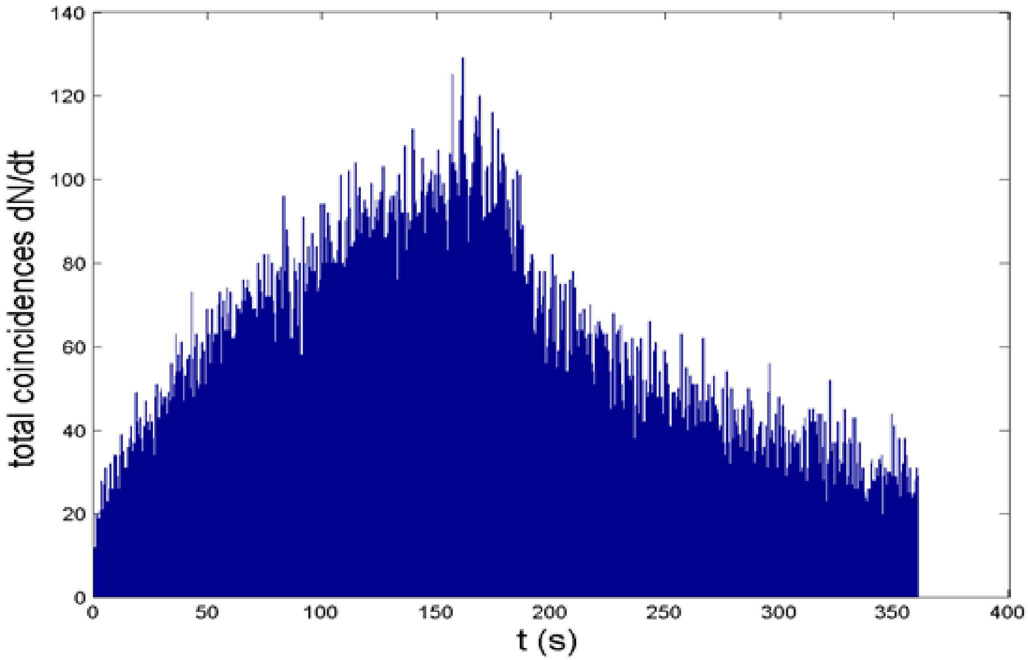

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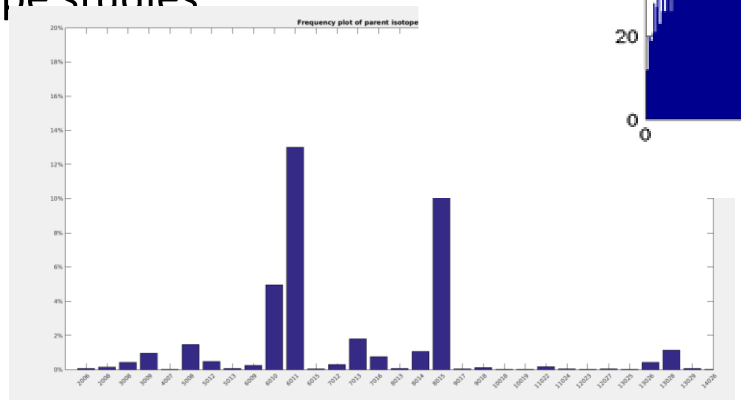

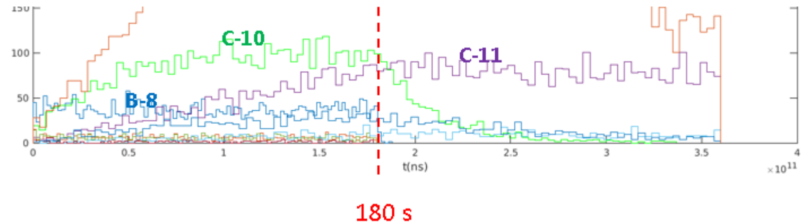

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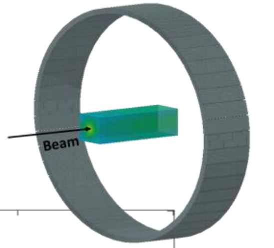

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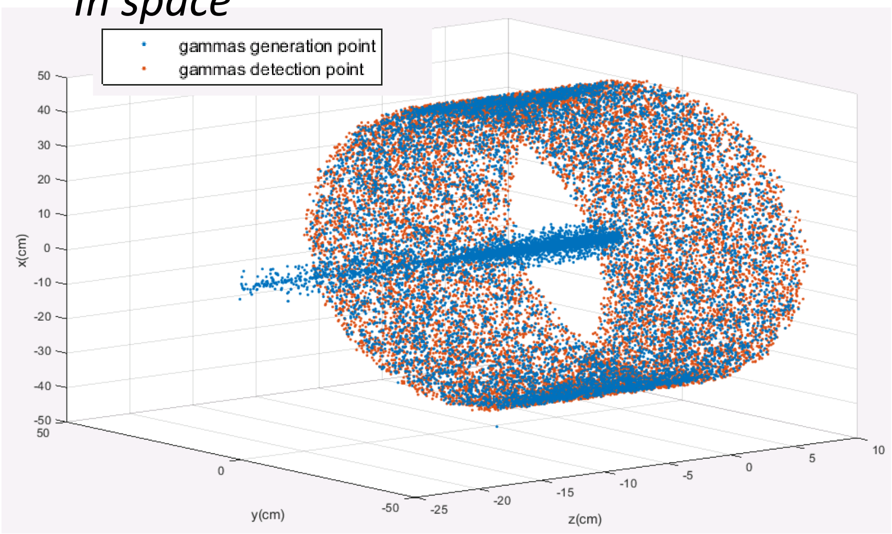

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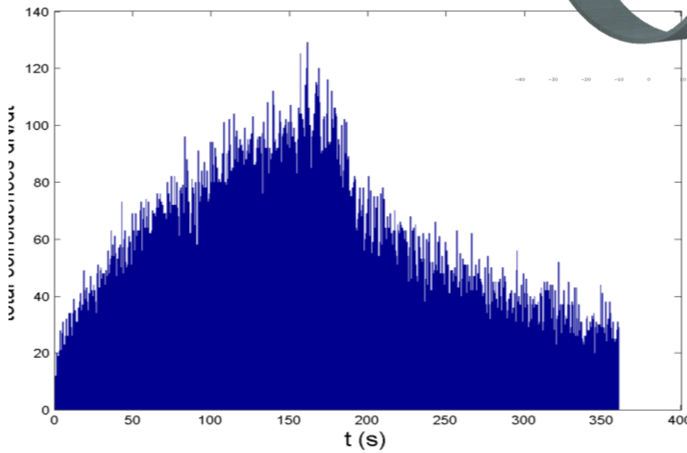

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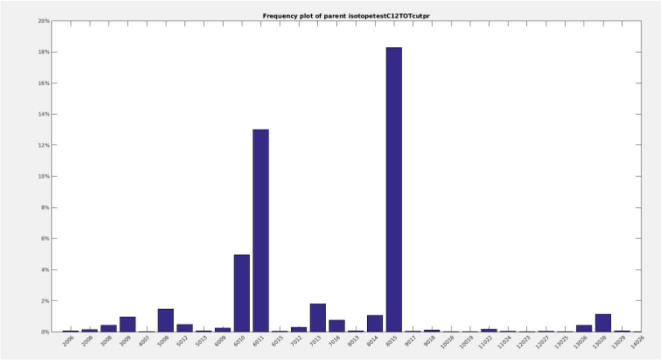

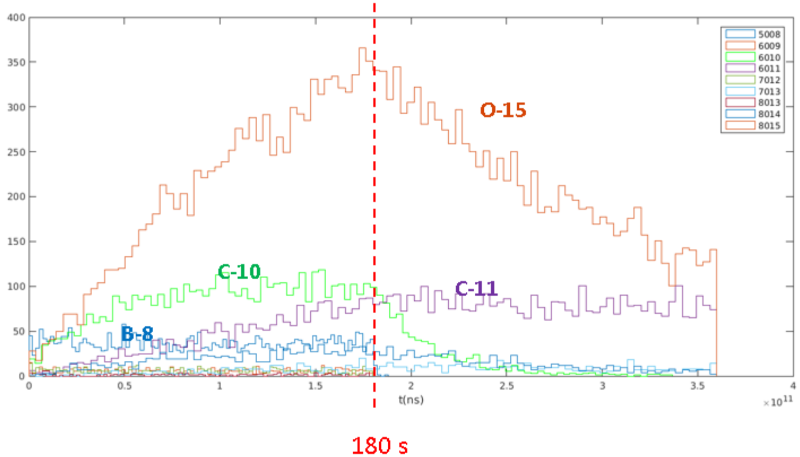

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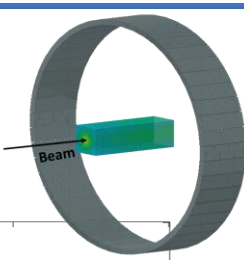

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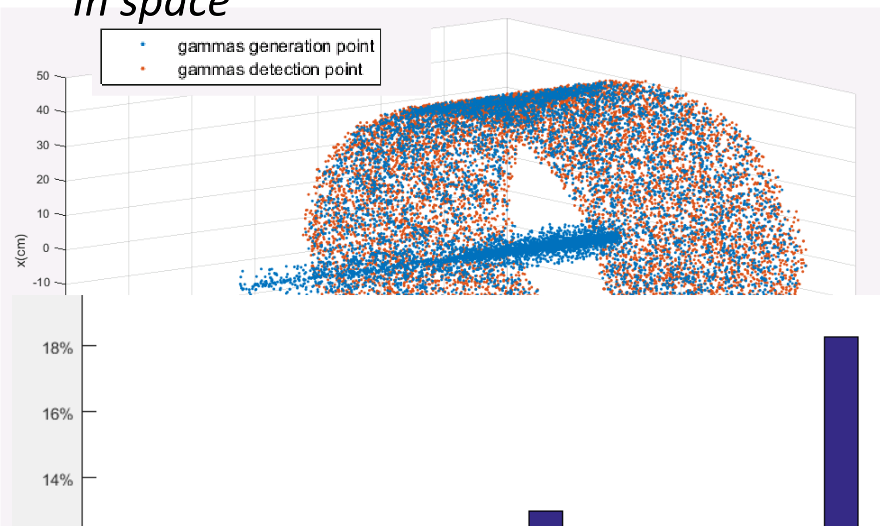

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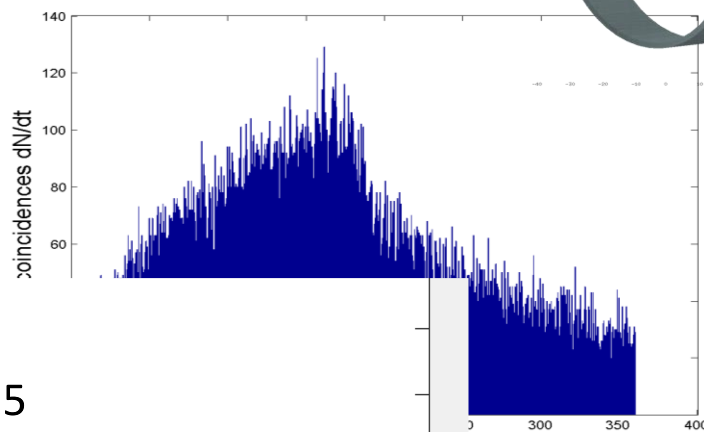

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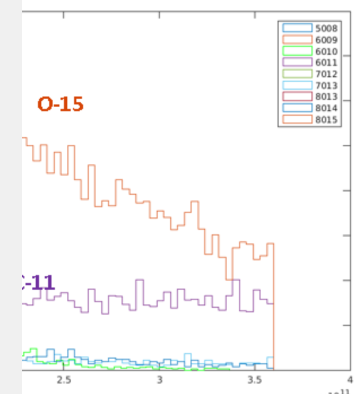

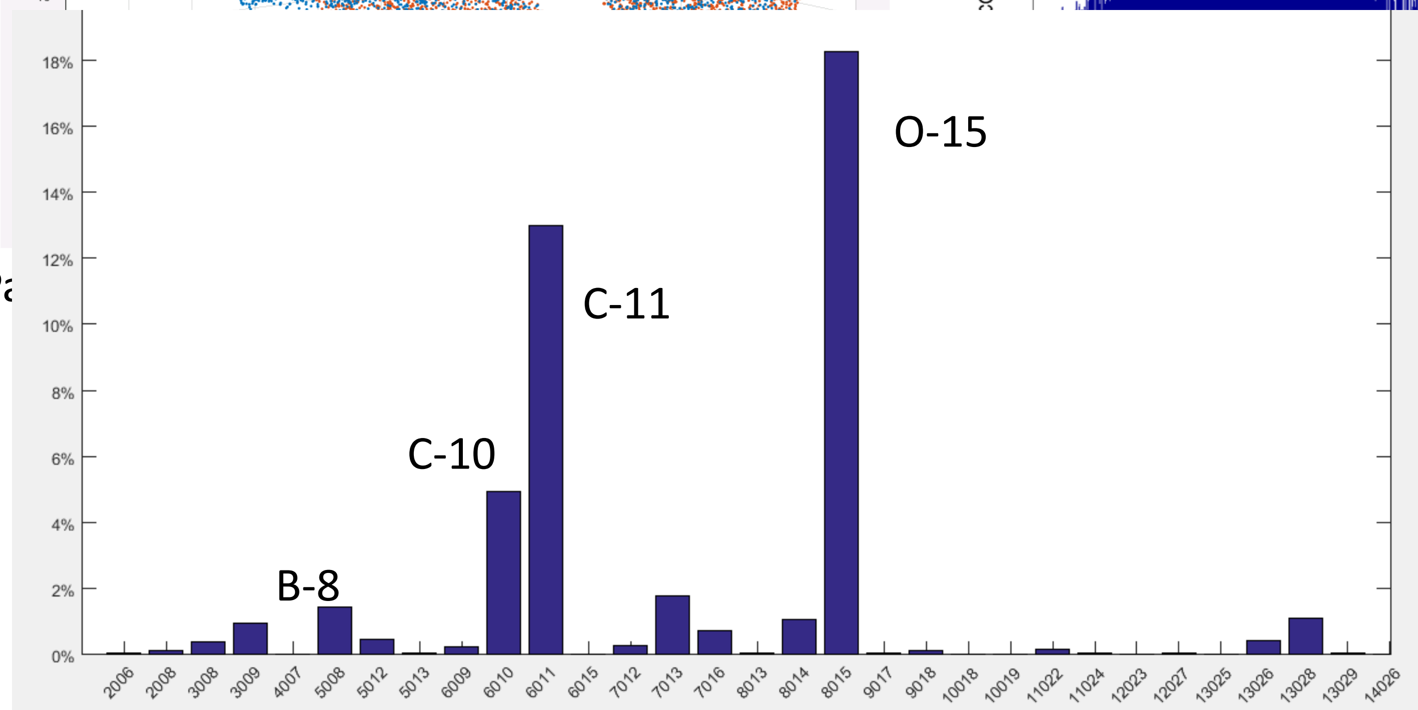

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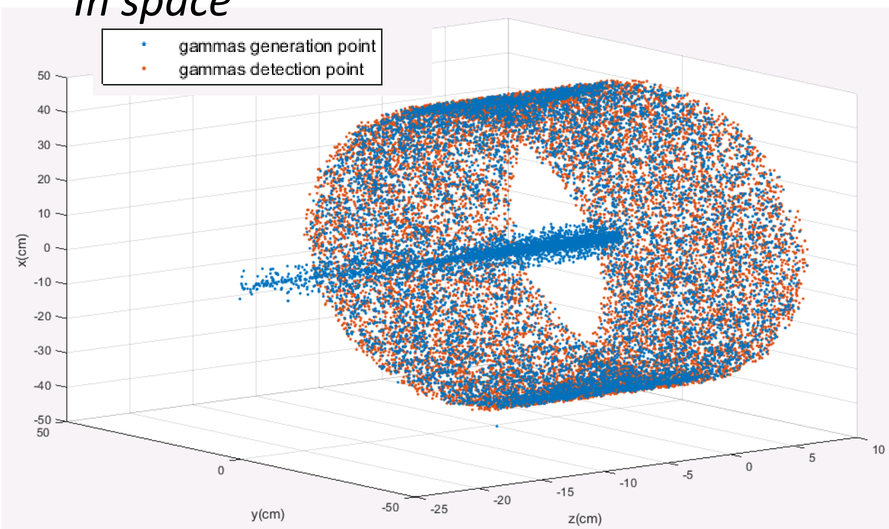
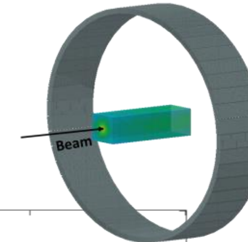
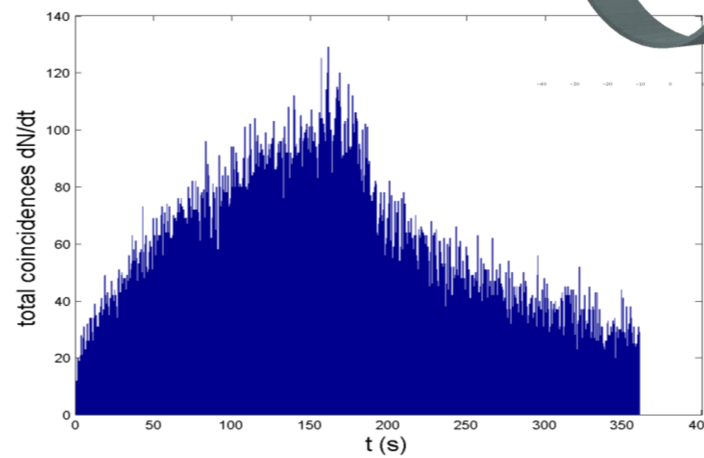
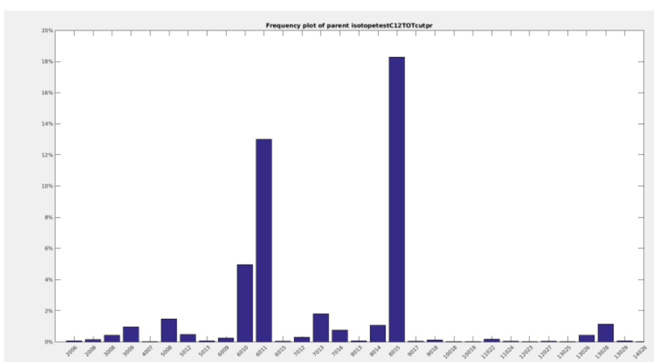


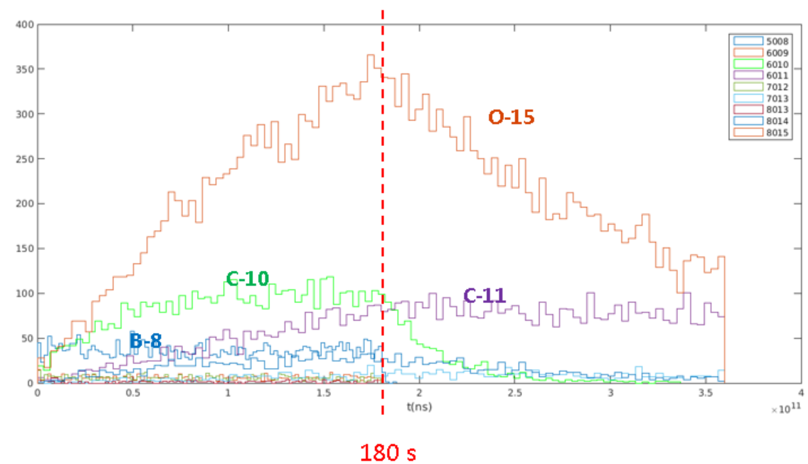
In time





Parent Isotope studies

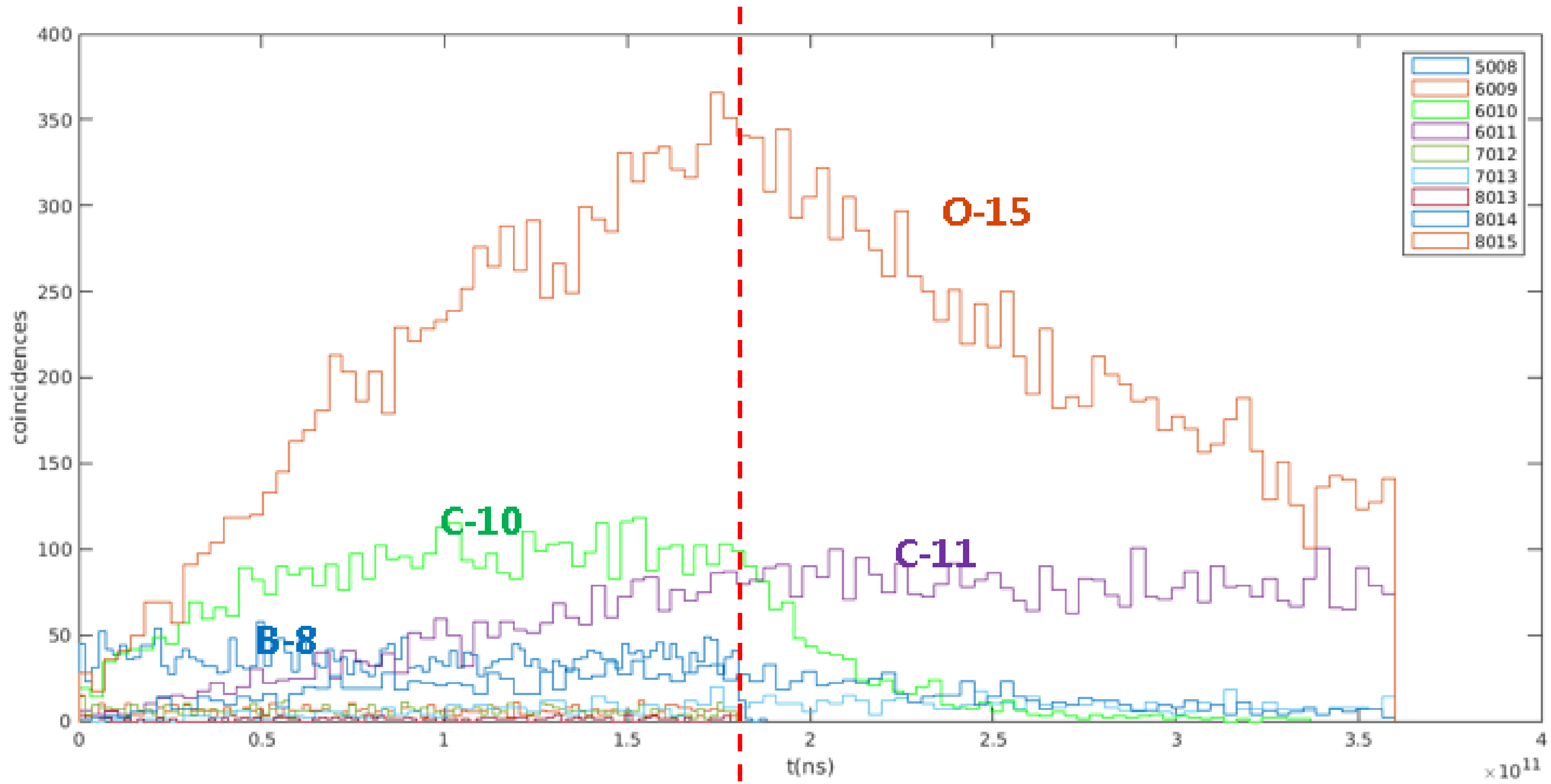




Coincidences file in list mode

The user can perform several analysis on single hit:

Ex. For in-beam PET with a C12 ion beam

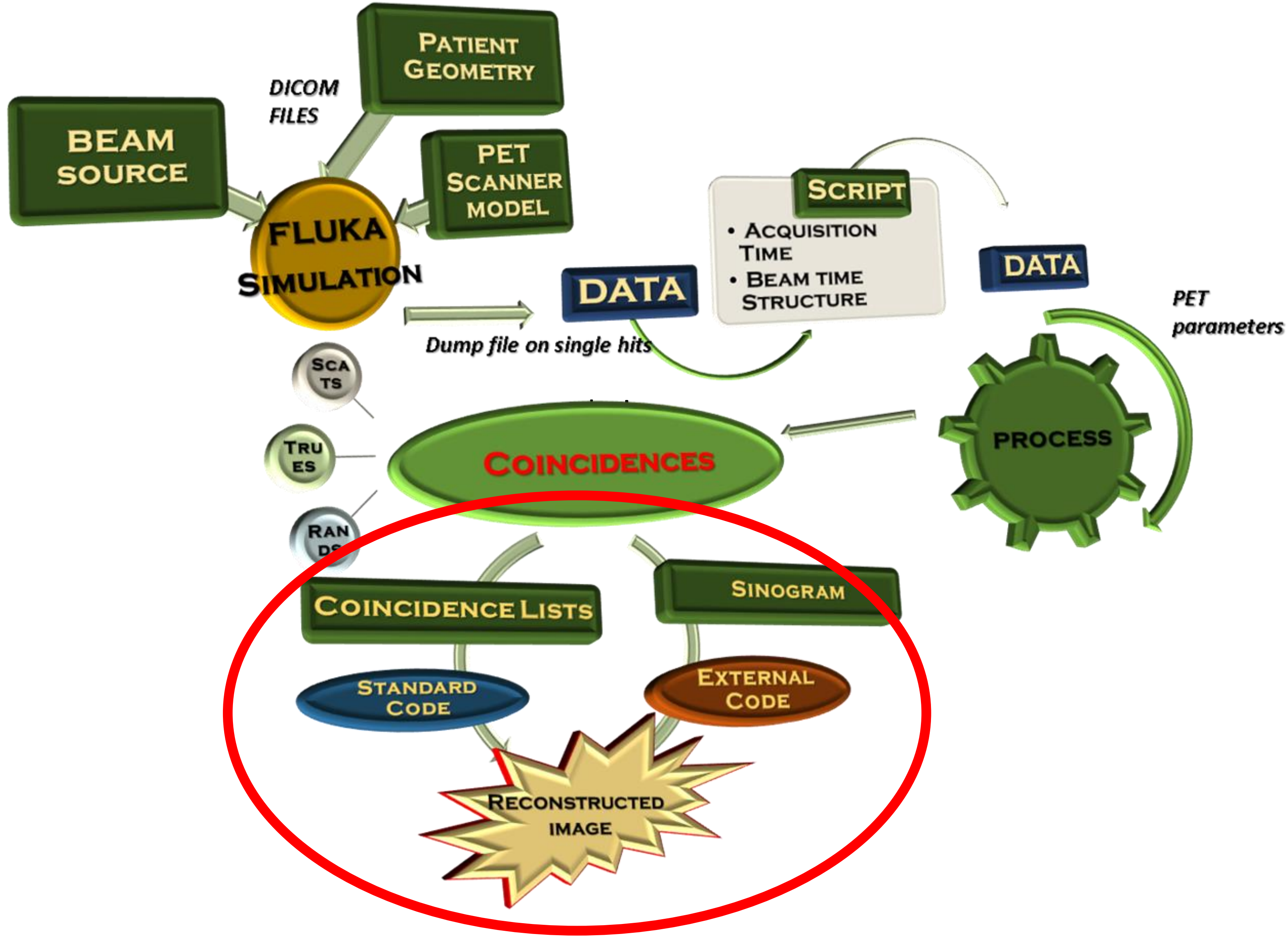


P

180 s

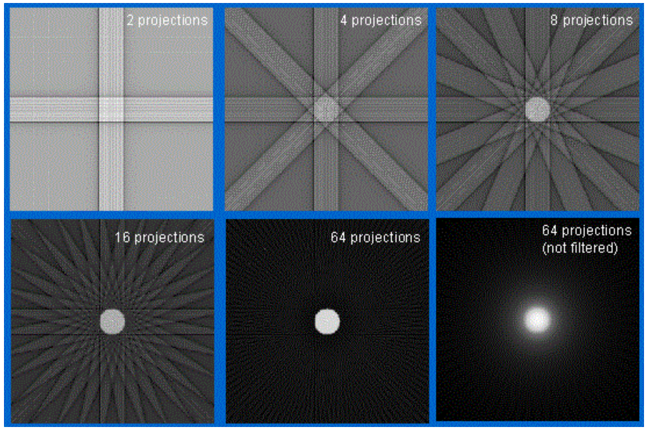
180 s

WORKFLOW


Patient Geometry
DICOM FILES
BEAM SOURCE
PET Scanner model
FLUKA Simulation
Script
• Acquisition Time
• Beam time structure
DATA
DATA
PET parameters
Dump file on single hits
Scatts
Trues
Rands
Coincidences
Process
Coincidence Lists
Sinogram
Standard Code
External Code
Reconstructed image

Reconstruction codes

➢ FBP (python) Filtered Back Projection



- Based on the **Fourier slice theorem**.
- Simple, fast… not accurate enough
- Available in **scikit-image** Python package.

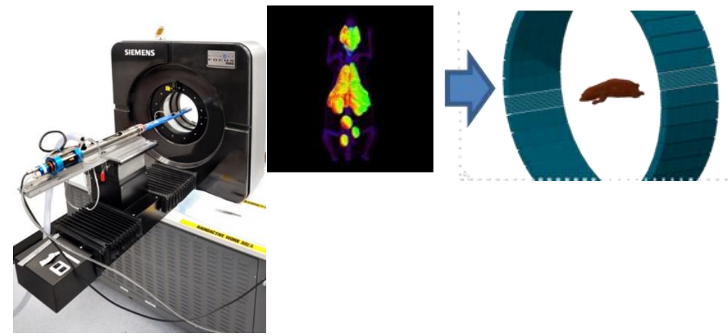
➢ MLEM Maximum-Likelihood Expectation-Maximization

- Best estimates the reconstruction image maximizing the *likelihood function*: Finds the mean number of radioactive disintegrations in the image that can produce the sinogram with the highest likelihood.
- Iterative, more accurate

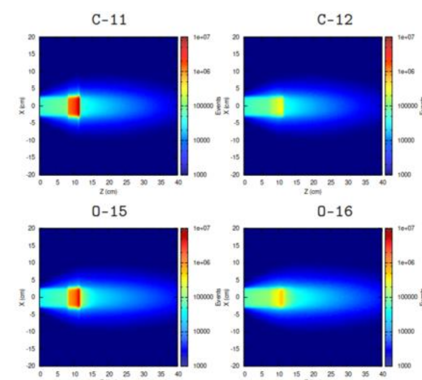
➢ Integration with STIR

- Easy to implement Sinogram outputs to STIR
- STIR Templates are ready for the users, to use different algorithms.

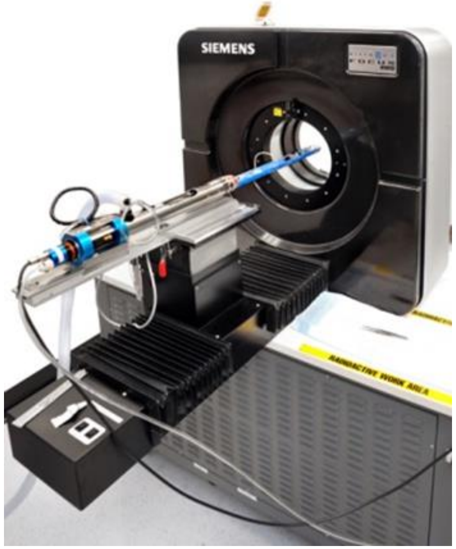
➢1. Conventional PET for small animals: Example of a commercial scanner (MicroPET P4 scanner)

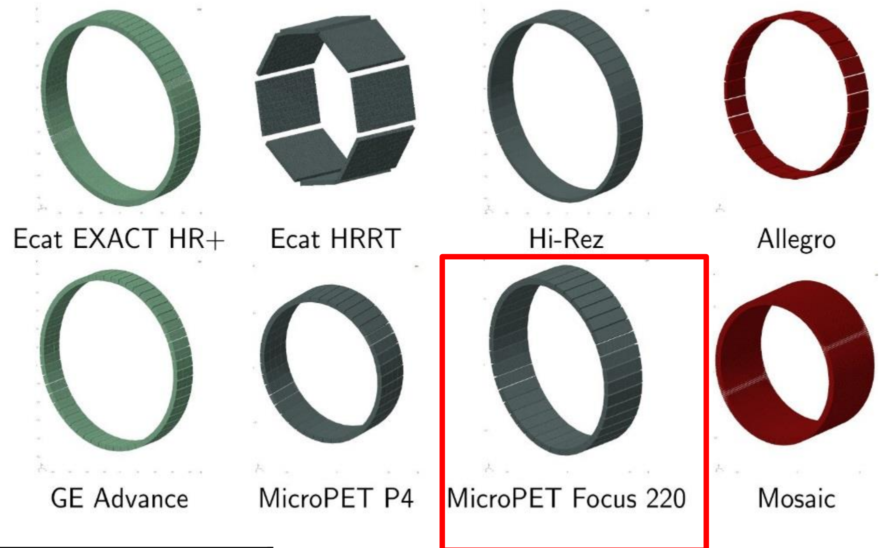


➢ 2. In beam PET in Hadrontherapy with Beta + Radioactive Ion Beams



MicroPET P4 scanner





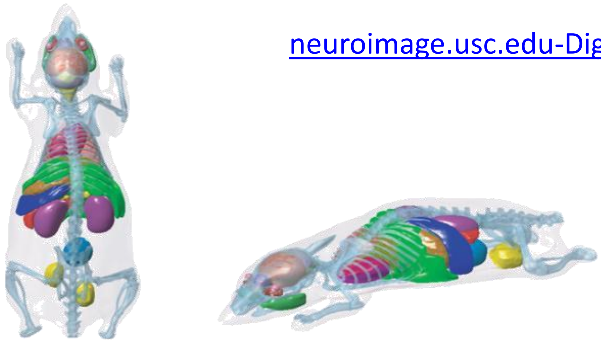
Parameters	P4 scanner
Crystal dimensions [mm^3]	2.2x2.2x10
Detector diameter (cm)	26
Transaxial Field of View (FOV in cm)	18
Axial Field of View (cm)	7.8
Number of detector blocks	168
Total number of detectors (8x8x168) (LSO)	10752

- Coincidence time window: 6 ns
- Hit dead-time: 500 ns
- Coincidence dead-time: 43 ns
- Energy window: 261-761 keV
- Acquisition time: 0-1800 ns.
- Detector resolution: 0.14 ns
- Pulse time: 50 ns

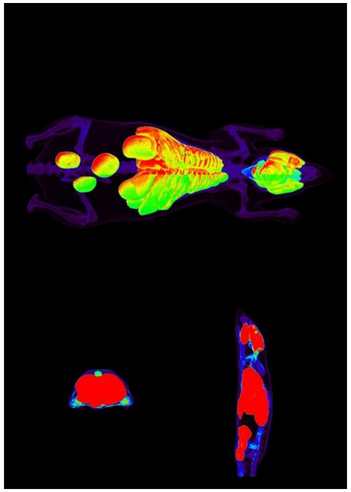
MicroPET P4 scanner

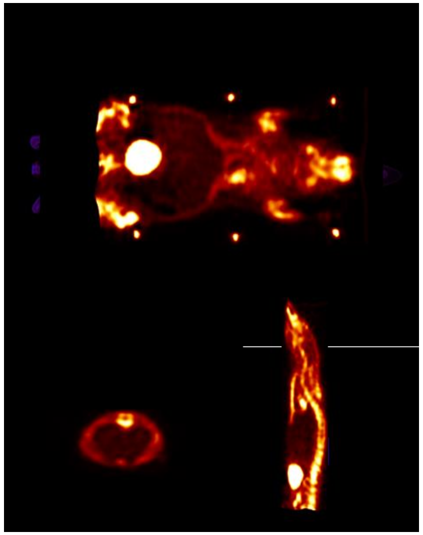
Voxelized phantom: Digimouse Atlas

neuroimage.usc.edu-Digimouse

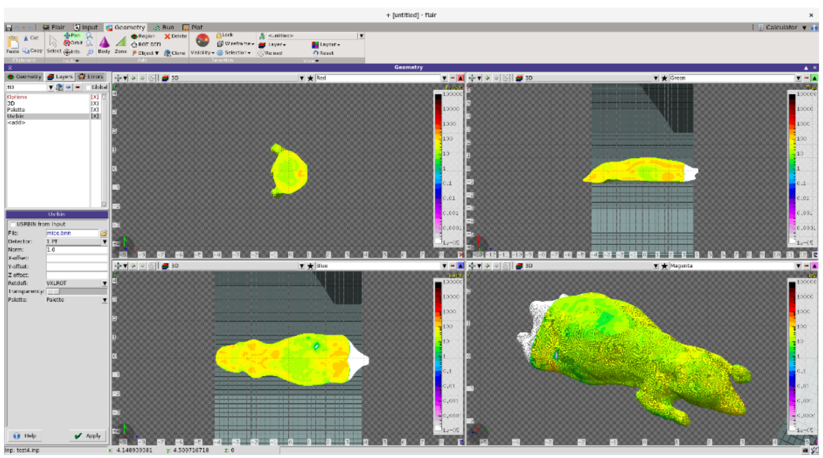


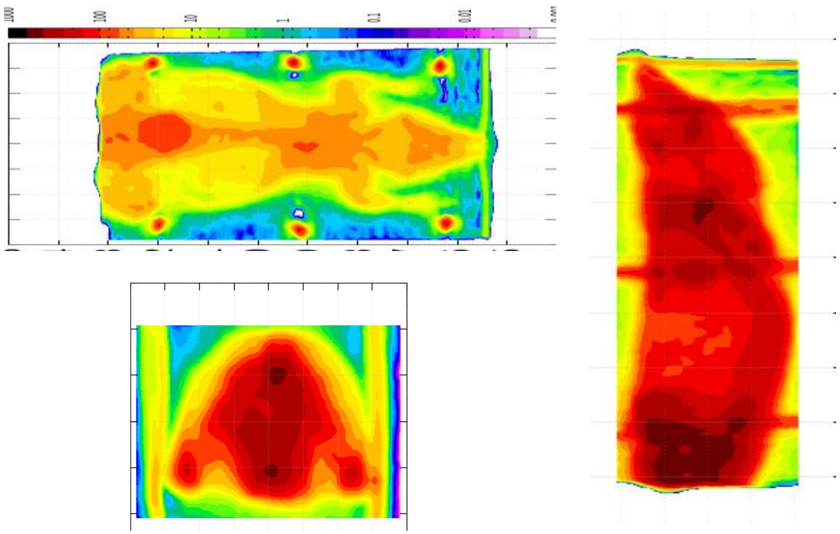
Optimization for FLUKA
courtesy of M.P.W. Chin





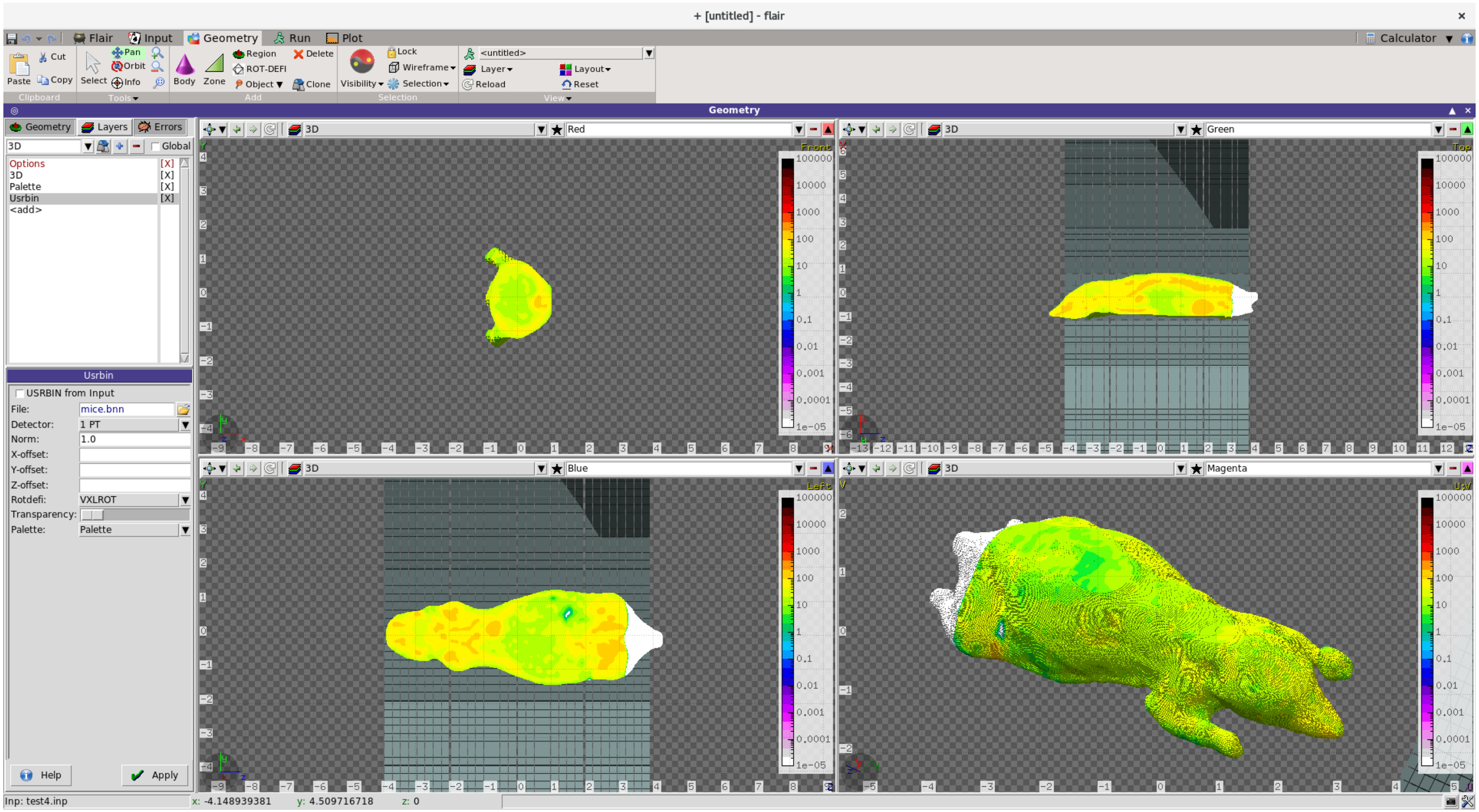
○*F-18 source*, generated from USRBIN of Mouse PET image



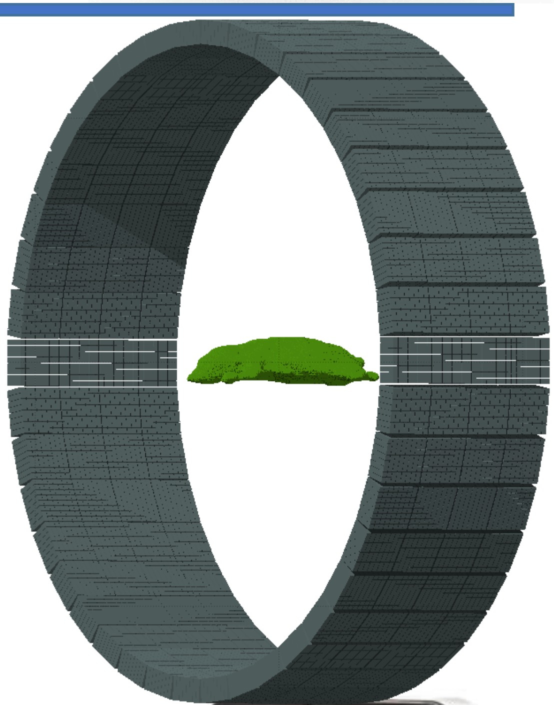


MicroPET P4 scanner

Voxelized phantom: Digimouse Atlas



MicroPET P4 scanner



- Run details:
  - Simulation ran at CERN Cluster.
  - 100 jobs, 5 cycles per job = 500 runs
  - 5 million primaries per run

- Results:
  - Average CPU time per cycle: 4.16 +- 0.09 hours
  - ~35 million Coincidences:
    - 99.998% trues
    - 0.002% scatters
    - 0% randoms

  - Trues coincidence list file is a 20Gb file...
  - Some hours to process the input files and to reconstruct MLEM up to 70 iterations

MicroPET FOCUS PET

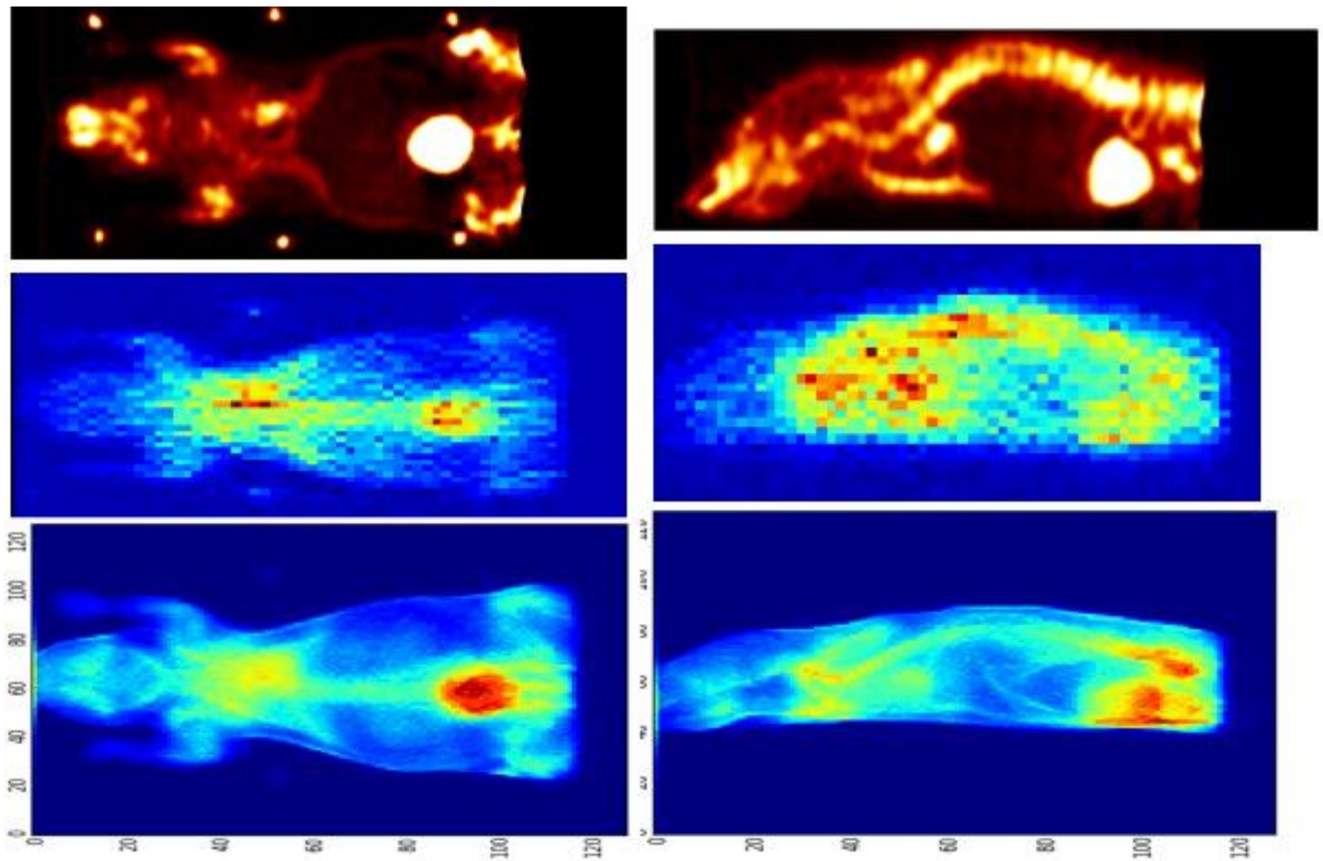
Reconstructed images

Mouse Phantom CT

neuroimage.usc.edu-Digimouse

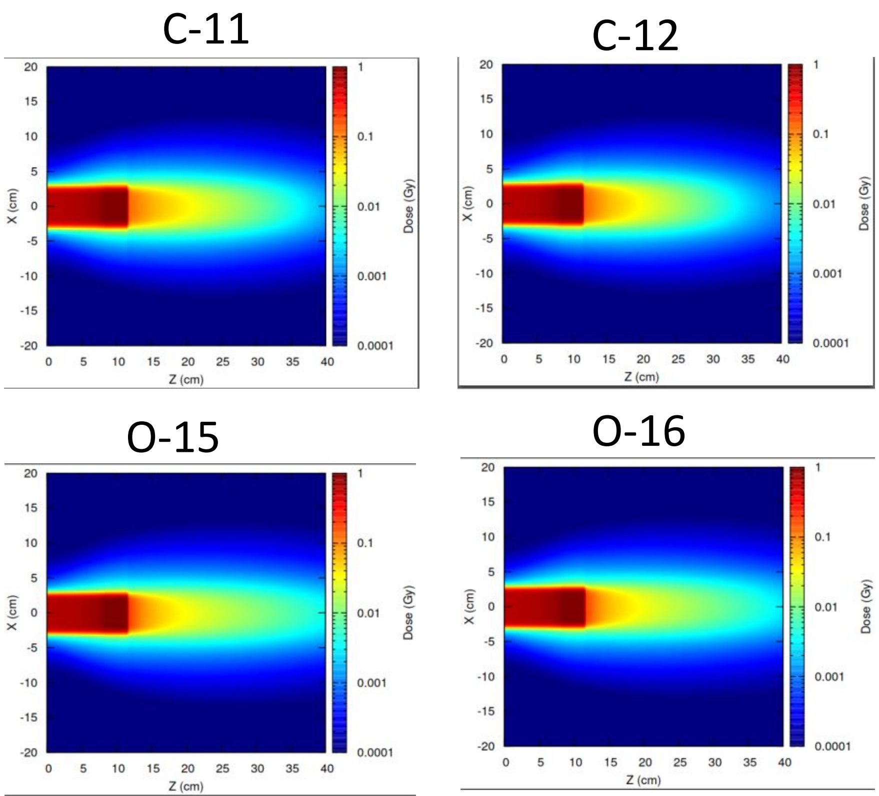
FBP (python) Filtered Back Projection

MLEM (new code!) Maximum-Likelihood Expectation-Maximization

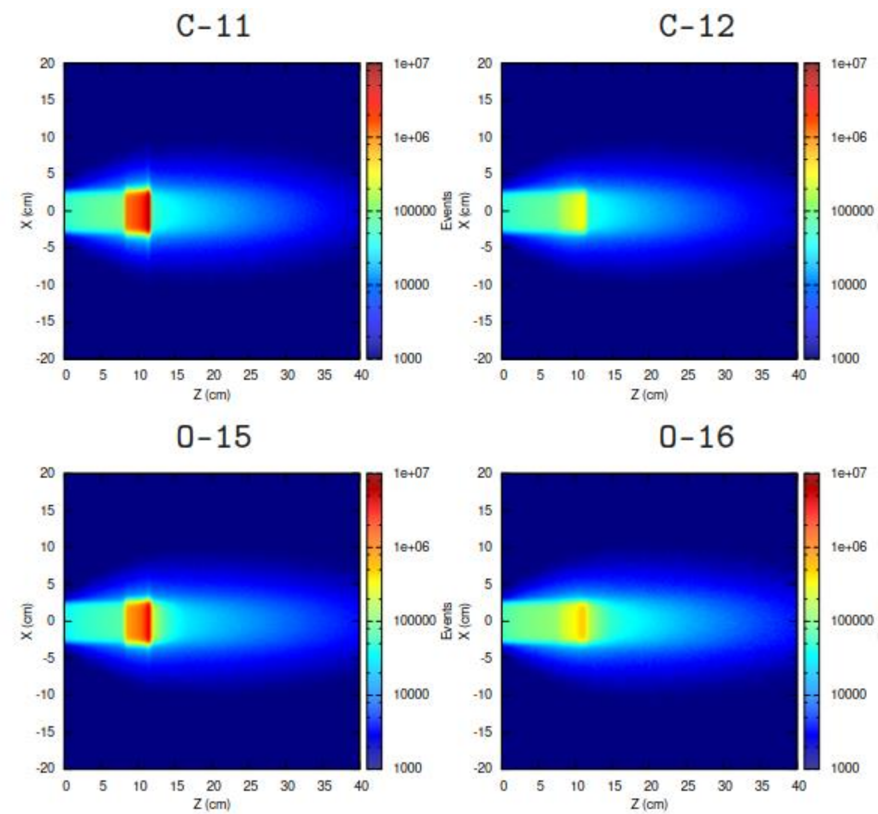


➢ Annihilations at rest results:Imaging Potential Estimator

DOSE



ANNIHILATIONS AT REST



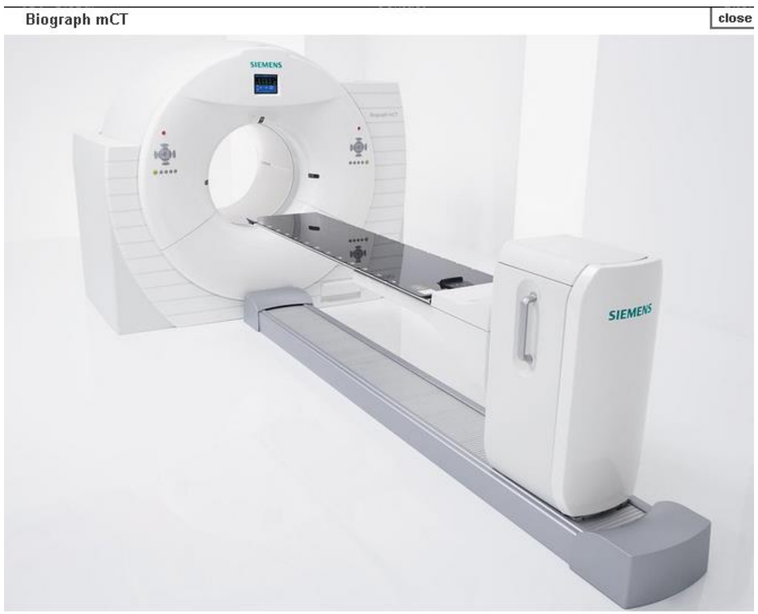
SOBP in water phantom

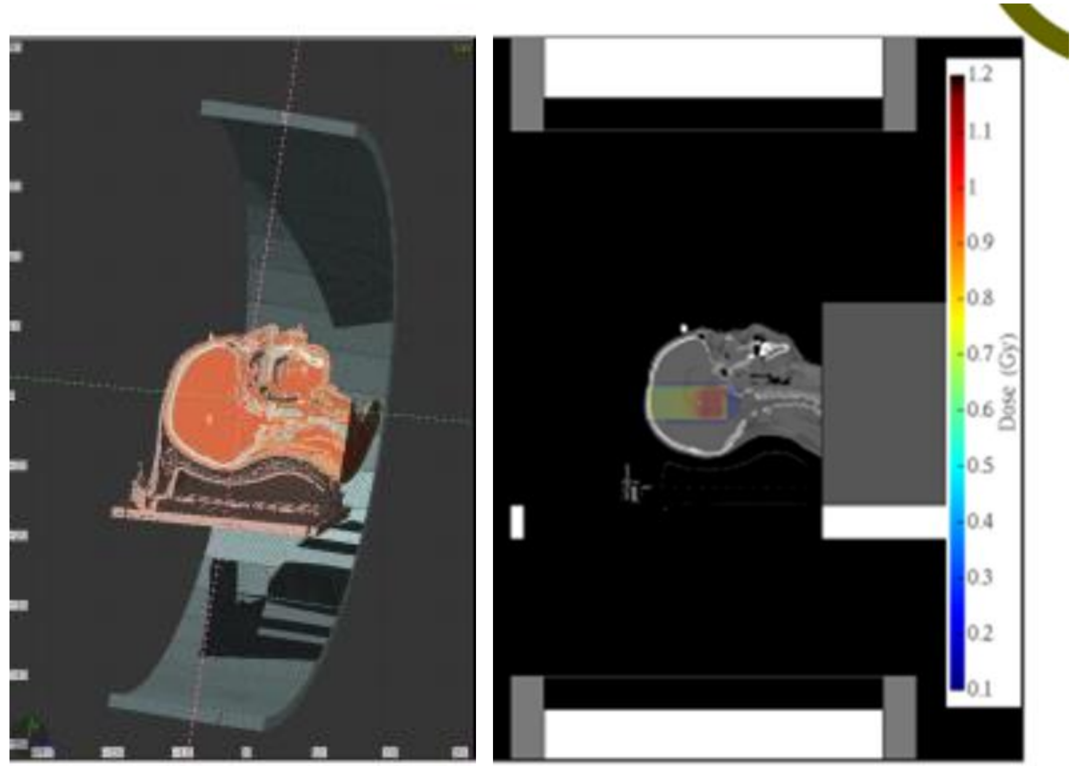
R. S. Augusto et al. ,NSS-MIC 2016, Strasbourg

➢ *Towards* a clinical in-beam PET scenario

PET scanner model

Siemens Biograph mCT as in HIT.

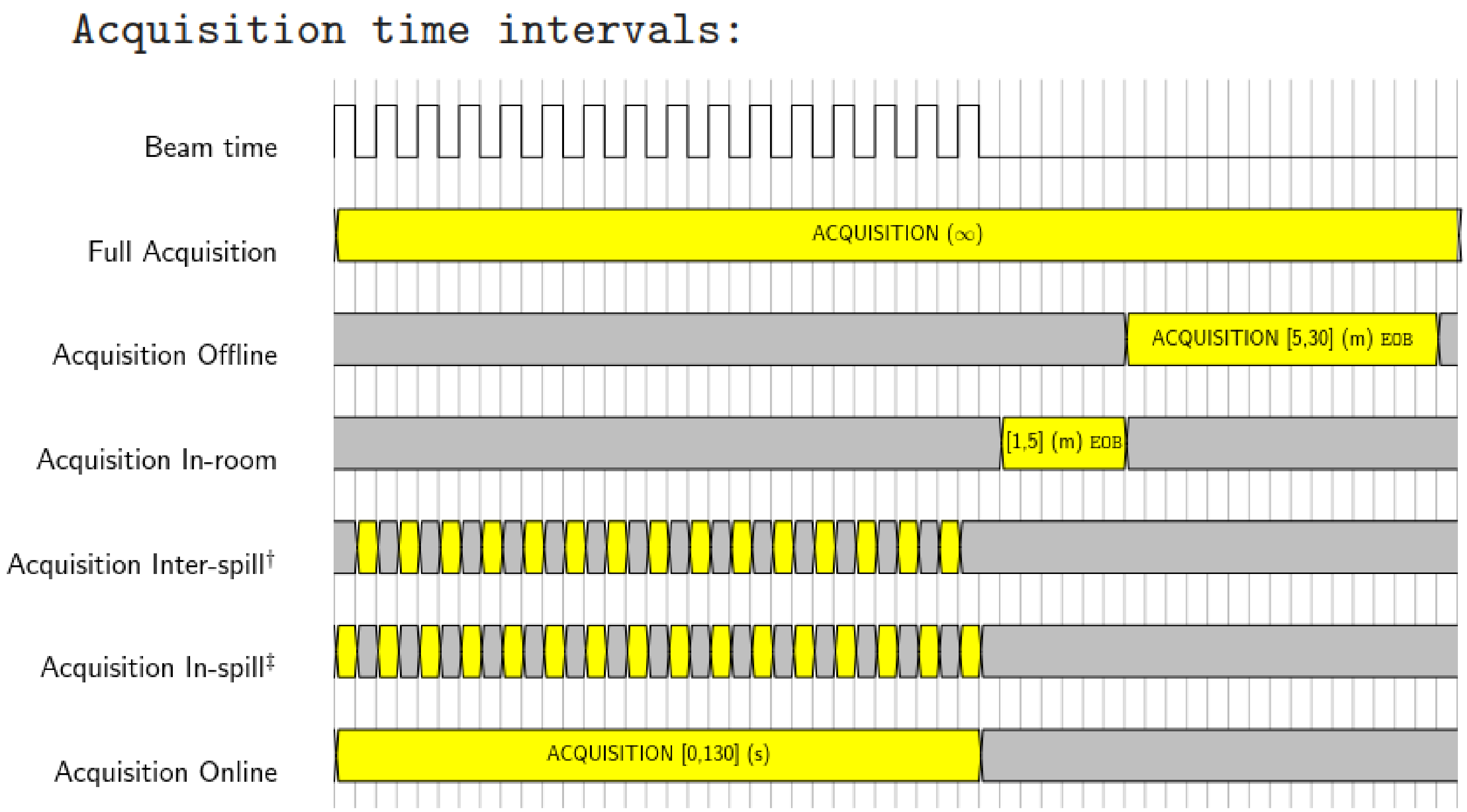




Dose delivery of 1 Gy For SOBPs ,11C beam

R. S. Augusto et al. ,PTCOG 2017 Yokohama

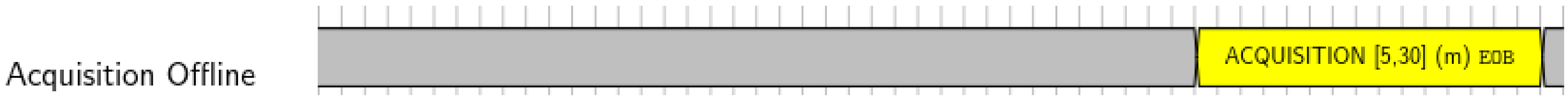
➢ *Towards* a clinical in-beam PET scenario

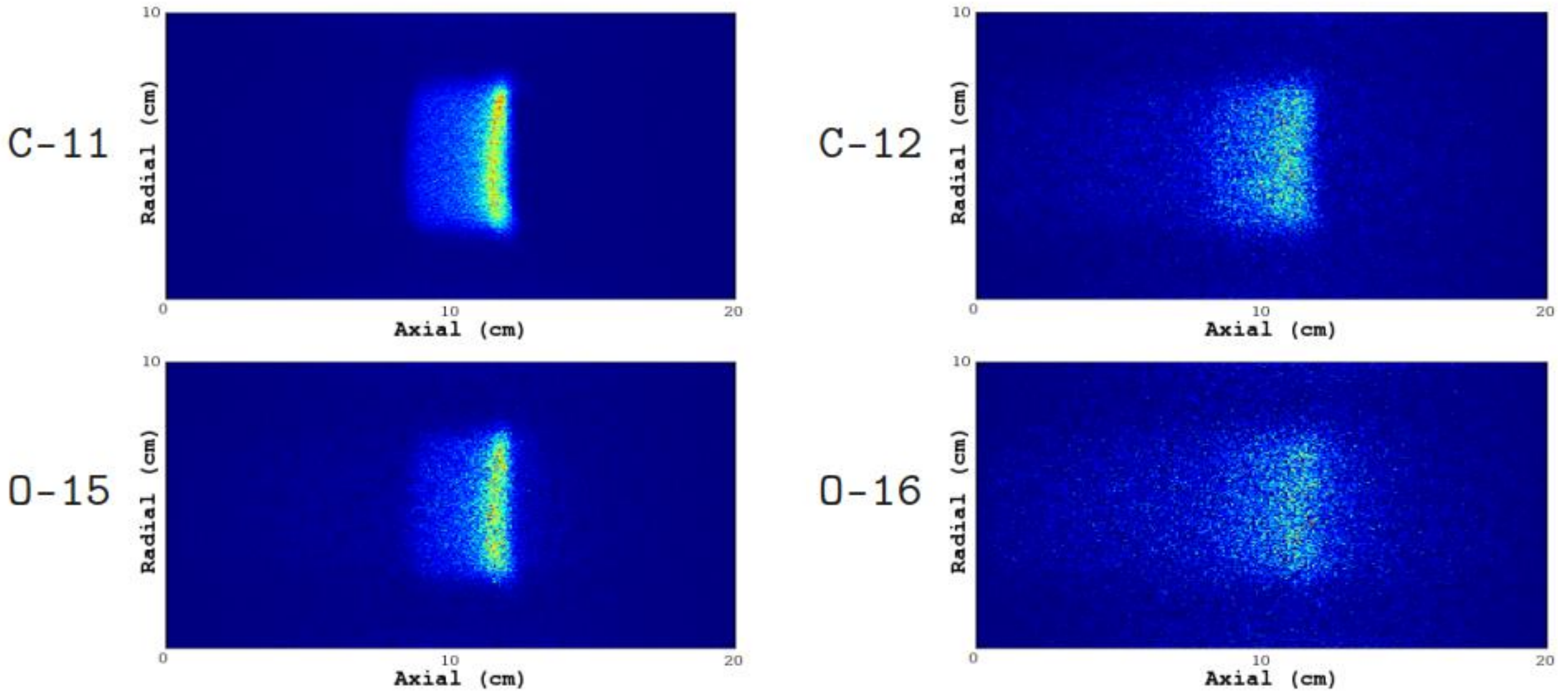


EOB:End of BEAM

In-beam PET with RIB

➢ *Towards* a clinical in-beam PET scenario : offline 25 min



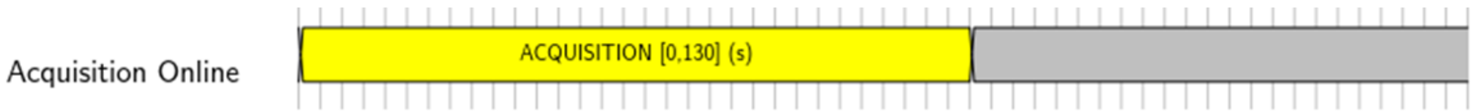


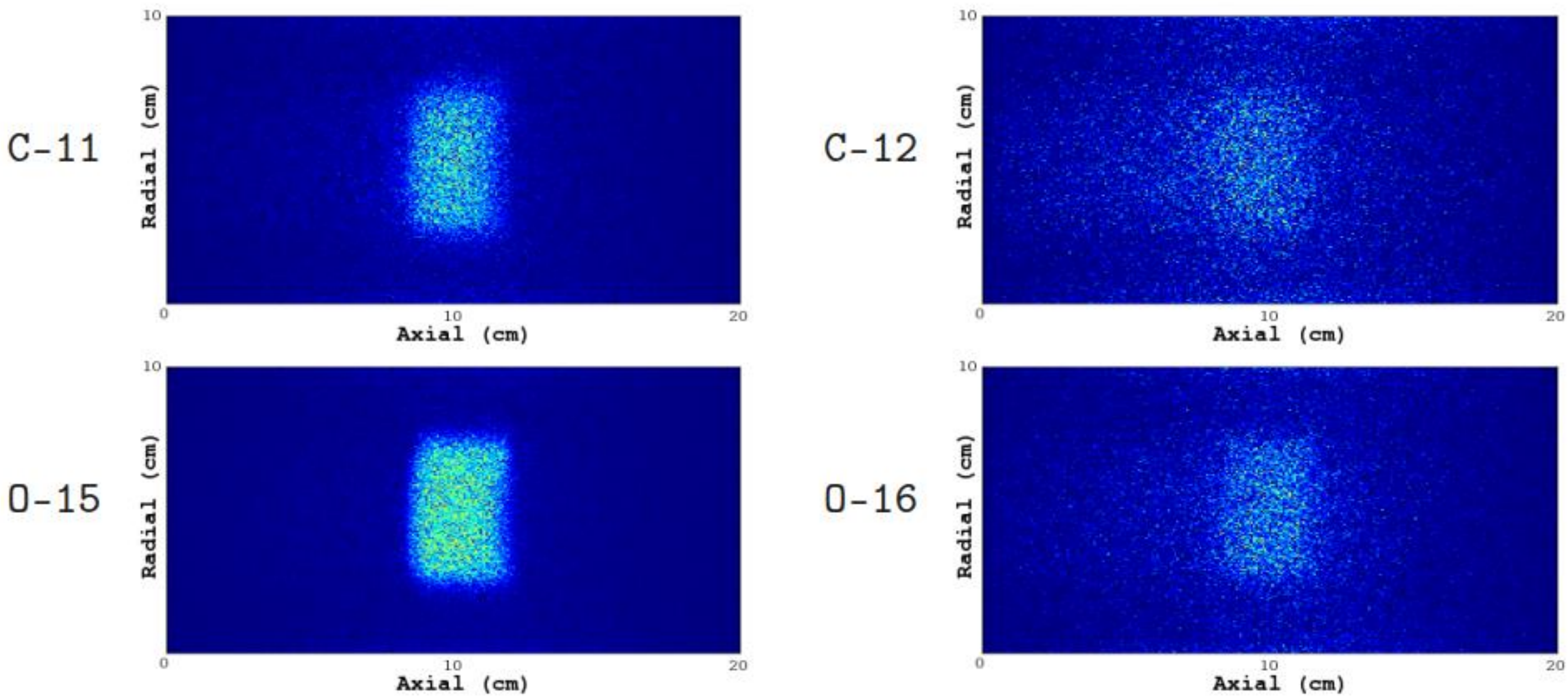
Due to the half-life difference between C-11 and O-15 (~20m & ~2m) - C-11 outperforms O-15 in longer acquisitions after irradiation.

R. S. Augusto et al. ,RAD 2017

In-beam PET with RIB

➢ *Towards* a clinical in-beam PET scenario : online 130 s

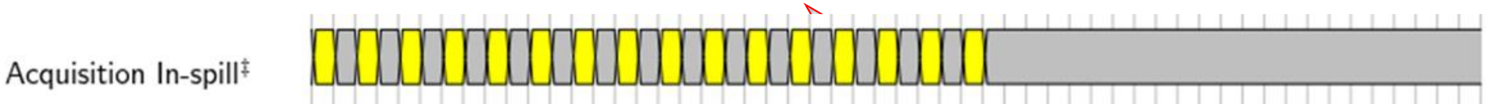


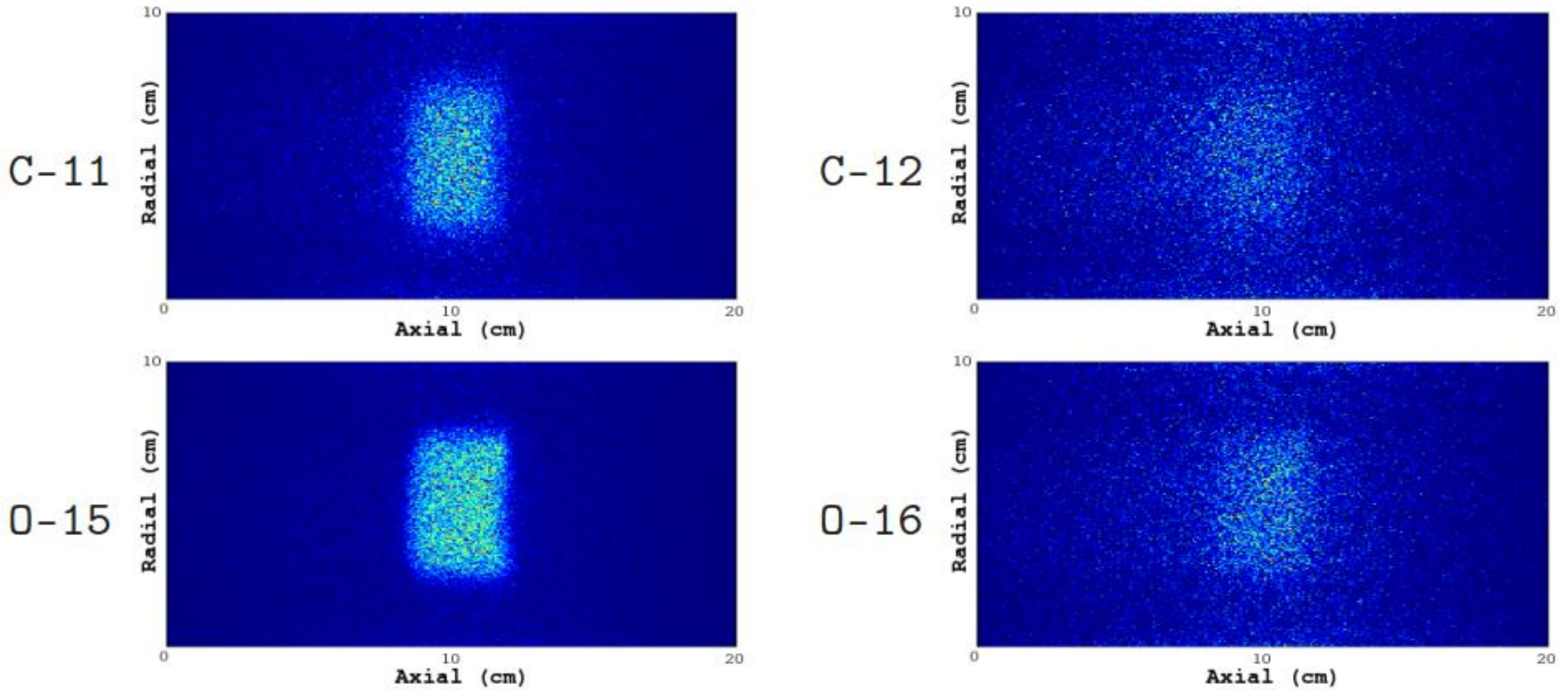


R. S. Augusto et al.
,RAD 2017

In-beam PET with RIB

➤ ***Towards*** **a clinical in-beam PET scenario : in-spill (16 spills)**

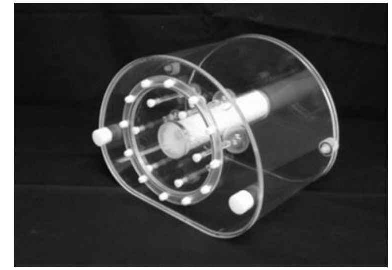




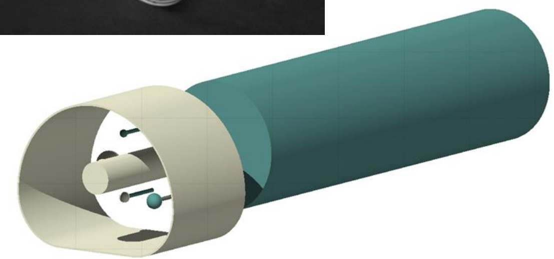
R. S. Augusto et al.
,RAD 2017

Conclusions and next steps

On going works with PET tools…..



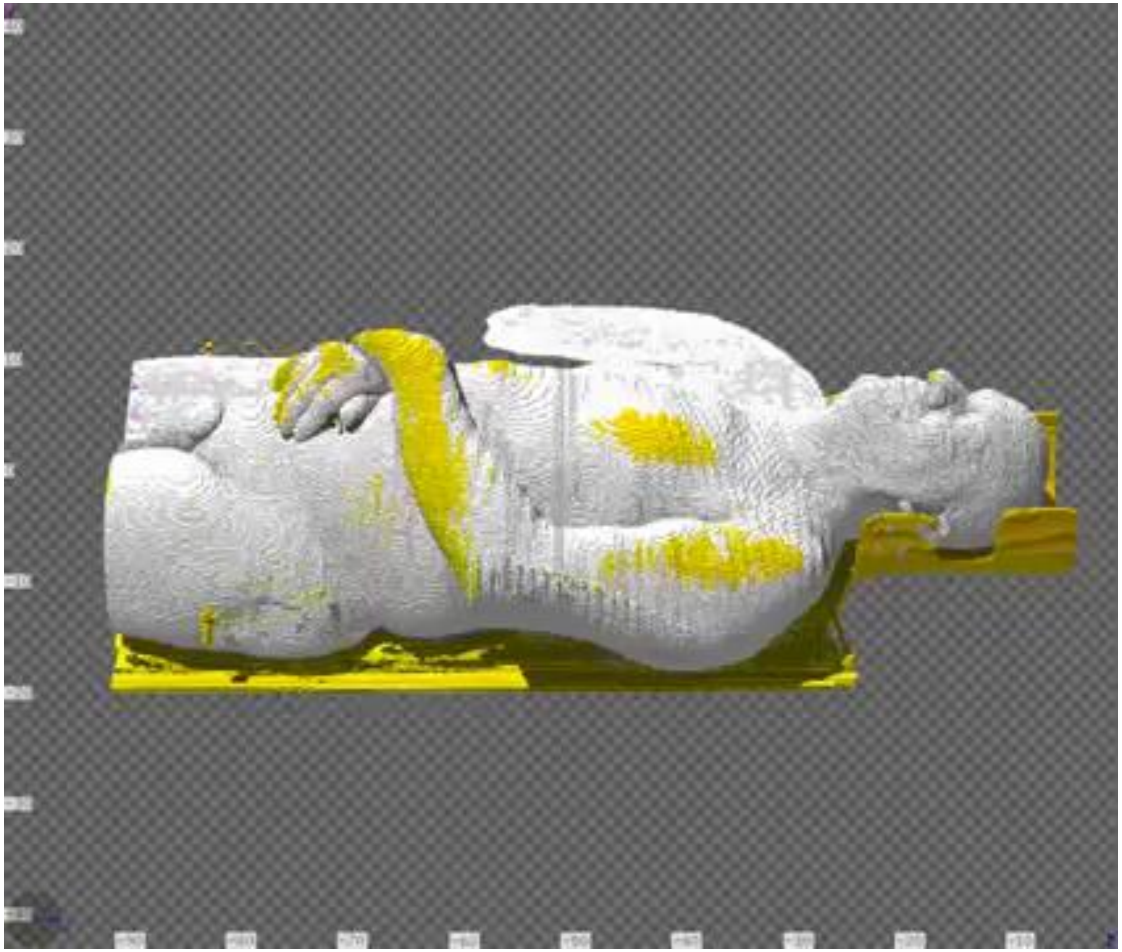
- Validation of the Clinical Biograph mCT
  - Comparison with other codes
  - NEMA Image Quality phantom validation



- Radioactive Ion beam validation with NIRS experimental results

- In-beam PET with INSIDE for ^{12}C and short acquisition time

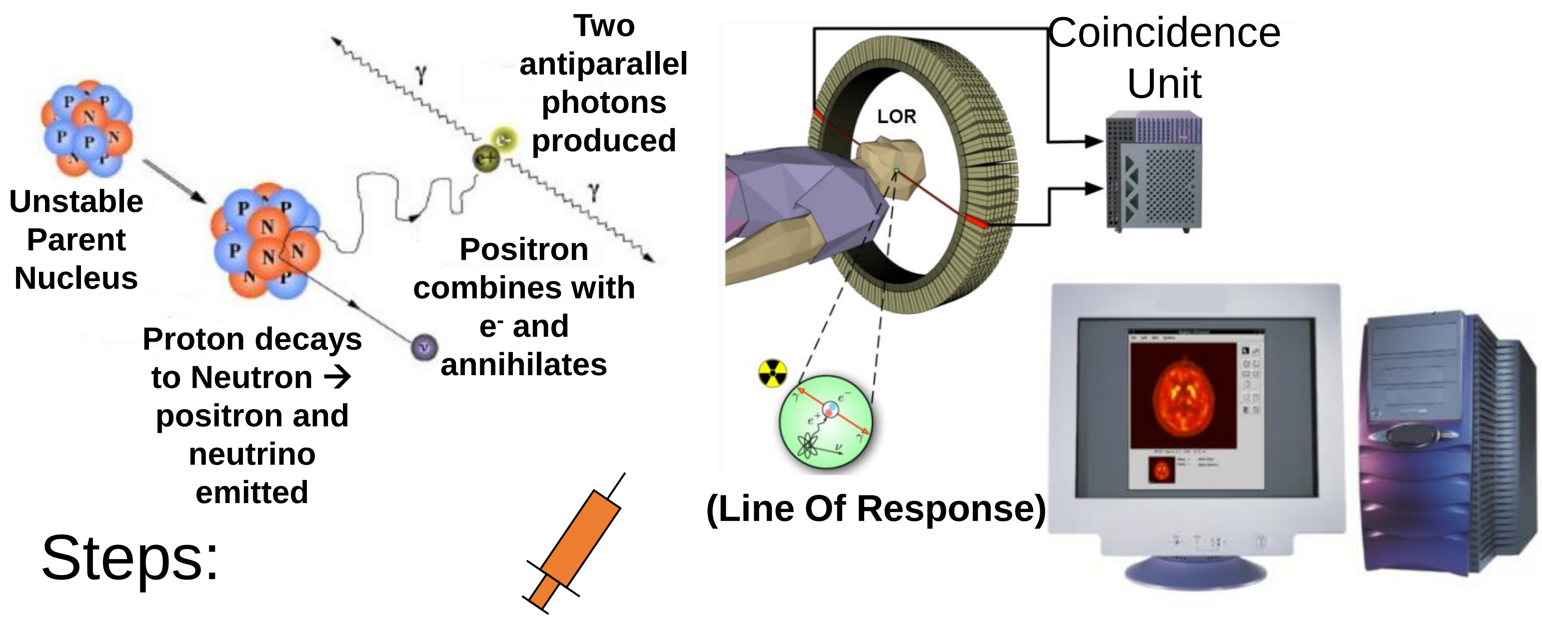
Thanks for your attention!



Back-up slides

Conventional PET

- ✓non invasive imaging modality
- ✓nuclear medicine field
- ✓provides three-dimensional (3D) tomographic images of radiotracer distribution within a living subject (molecular imaging)



Steps:

1. Radiotracer production	2. Administration of the radiotracer	3. Data Acquisition	4. Image Reconstruction

Rationale: Why FLUKA for PET

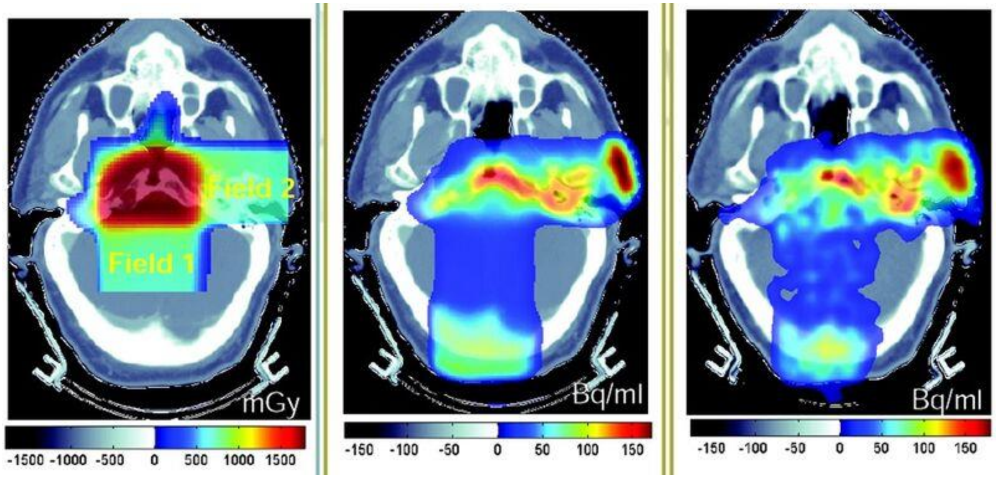
FLUKA Monte Carlo code describes b+ emitter distribution for CT-based calculations in patient using

- Planning CT (segmented into 27 material) and same CT-range calibration curve as TPS (Parodi et al MP 34, 2007, PMB 52, 2007)

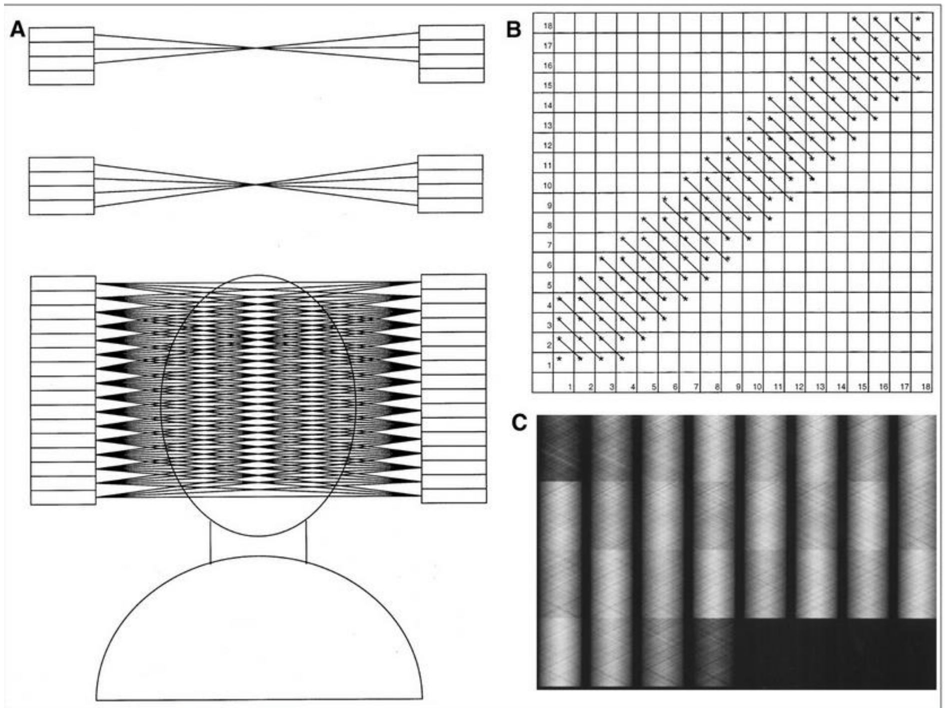
- Experimental cross-sections for b+ emitter production

- Semi-empirical biological modeling (Parodi et al IJROBP 2007)

- Convolution with 3D Gaussian kernel (7-7.5 mm FWHM)



PROCESSING

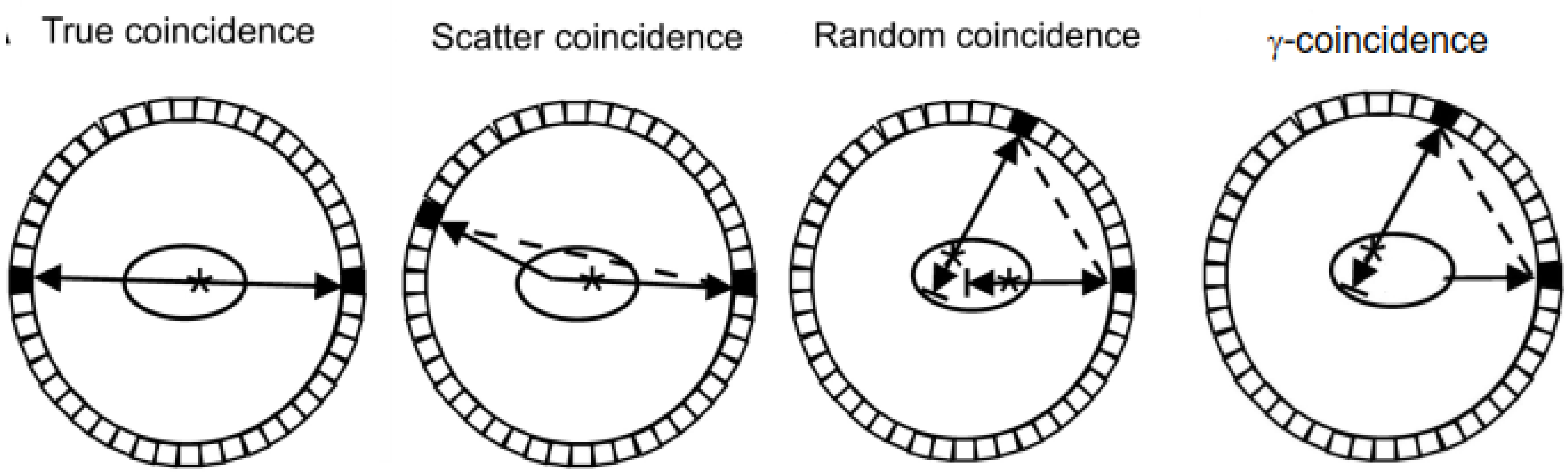


Michelogram

- *Arc correction.* The radial bin size is corrected for the circular shape of the detector.
- *Maximum Ring Difference (MRD).* The difference between two rings events can be restricted to a maximum value.
- *Span.* Extent of axial data combined. Reduces the size of the stored data.
- *Mashing factor*. Reduction of the angular sampling. Reduces the size of the stored data.
- *Number of segments.* Parameter related to MRD and span number. Defines the number of segments the cells in the Michelogram can be divided.

PROCESSING: Coincidences

- ***True coincidences***, where the line drawn between the two hit detector elements for that event passes through the point of origin
- ***Scatter coincidences***, where one or both 511-keV photons undergo Compton scatter (unwanted)
- ***Random coincidences*** occur when two distinct radionuclei contribute one detected photon (unwanted)
- ***γ-coincidences*** occur when a 511 keV photon and a γ-photon are detected (unwanted)



List-Mode ML-EM

For certain applications, as when using continuous detectors, where the spatial discretization of the measurements leads to loss of information, it is more appropriate to use a list-mode version of the ML-EM algorithm [*]. Using this method, the main summation runs through the N events in the list-mode data (l = 1, · · · ,N). The algorithm is given by:

$$f_j^{k+1} = \frac{f_j^k}{S_j} \sum_{l=1}^{N} a_{i_l j} \frac{1}{\sum_{b=1}^{J} a_{i_l b} f_b^k}.$$

Here, b = 1, · · · , J is the pixel index in the projection operation.
The system matrix $a_{i_l j}$ is the probability that a detected emission from pixel j is detected in the i_{th} detector-pair, corresponding to event l. The list-mode ML-EM algorithm is used for image reconstruction throughout this work.

[*] Barrett, H., White, T., Parra, L.: List-mode likelihood. J. Opt. Soc. Am. A 14 (1997) 2914

Scoring of PET events

•*During FLUKA simulation*: Information of the hits is stored in a buffer and dumped list mode

•Routines in scoring folder:

- Usrini.f: Collects the scoring parameters from input. Temporary...
- Mgdraw.f: Calls petsco.f if energy deposited in PET crystals, and petddt.f and petdmp.f when buffer is full. Temporary...
- stupre(f)_pet.f: Stores info of particle and parents when created.
- Petsco.f: Routine to deal with the energy depositions in PET crystals.
- Petddt.f: Routine that implements the hit dead time and energy window
- Petdmp.f: Routine that dumps the buffer information in list mode (ascii/bin)
- (PETCOM): Common with parameters and buffer definitions
- Udcdrl.f*: Direction biasing. Normally I don't use it, but it is there anyway.
- Compile: Compile script

Usrini.f (Future PET card)

- Example of FLUKA card to activate PET routines:

```
USRICALL     PET00000  PET00575       41.  3.61E-04  5.61E-04           SCORE
USRICALL           0.     1.E+99      .14       50.     -500.           SCORE2
```

- Only scoring parameters, no PET geometry involved.
- If SDUM=SCORE:
  - WHAT(1): Minimum region of PET crystals
  - WHAT(2): Maximum region of PET crystals
  - WHAT(3): Output unit (<0 binary, >0 ascii)
  - WHAT(4): Minimum energy window limit [GeV]
  - WHAT(5): Maximum energy window limit [GeV]
- If SDUM=SCORE2:
  - WHAT(1): Minimum acquisition time [s]
  - WHAT(2): Maximum acquisition time [s]
  - WHAT(3): Time resolution of the detector [ns]
  - WHAT(4): Pulse time of the detetor [ns]
  - WHAT(5): Hit dead time of the detector [ns] (<0 Paralyzable, >0 Non-paralizable, =0 not used)

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