INSIDE in-beam PET simulation

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on behalf of the Torino INSIDE group

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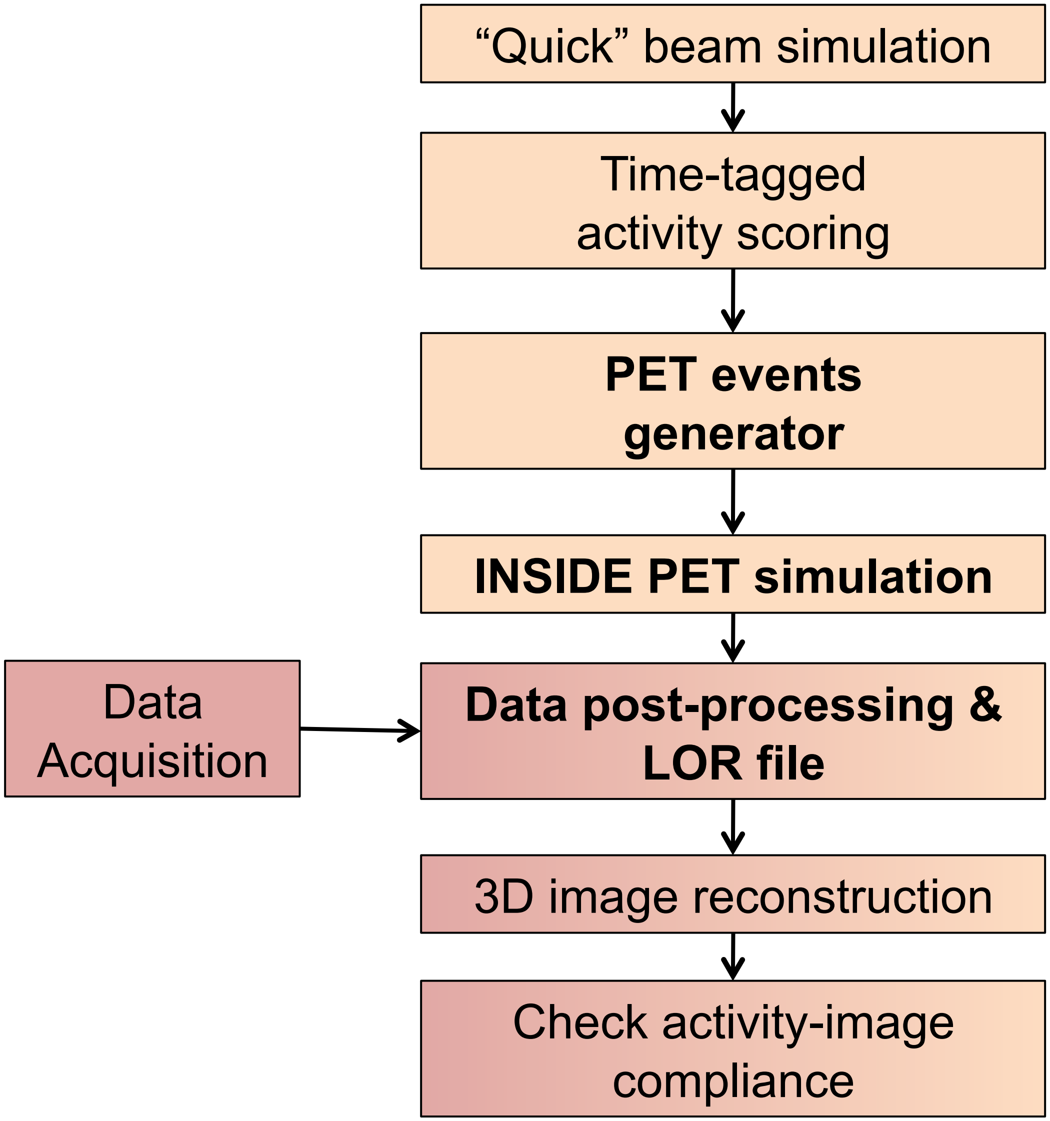
PET simulation and image reconstruction workflow



1/100 of primary hadrons are simulated (Aafke Kraan)

- Annihilation time and position
- Isotopes production time and position

Three approaches: 1) annihilation map, 2) isotopes production map and 3) isotopes production list

All the positrons are simulated

Based on MLEM algorithm (Niccolò Camarlinghi)

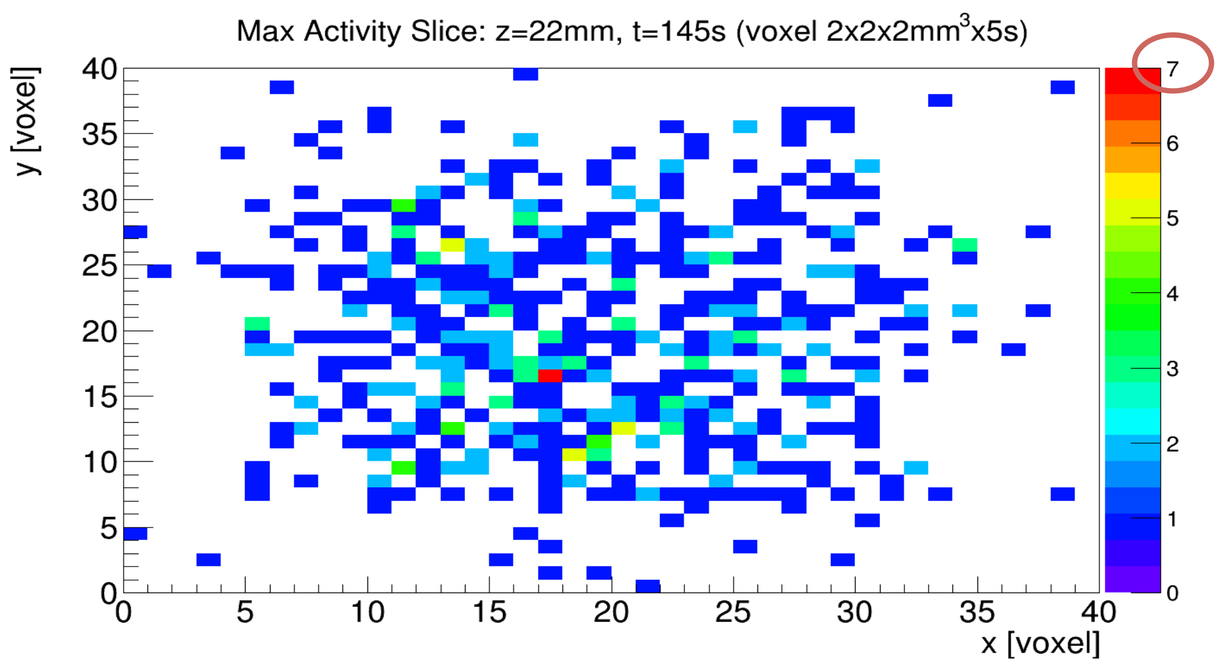
Profile analysis

PET events generator (1)

1) **Annihilation map**

- Custom source based on activity map
- All the interspill annihilations are considered
- Full treatment simulation spends 1 h with 4 cores
- Two gammas back-to-back are generated

PROBLEM:
number of annihilation not significant for generator construction (voxel with max activity has 7 annihilations)
⟶ abandoned approach

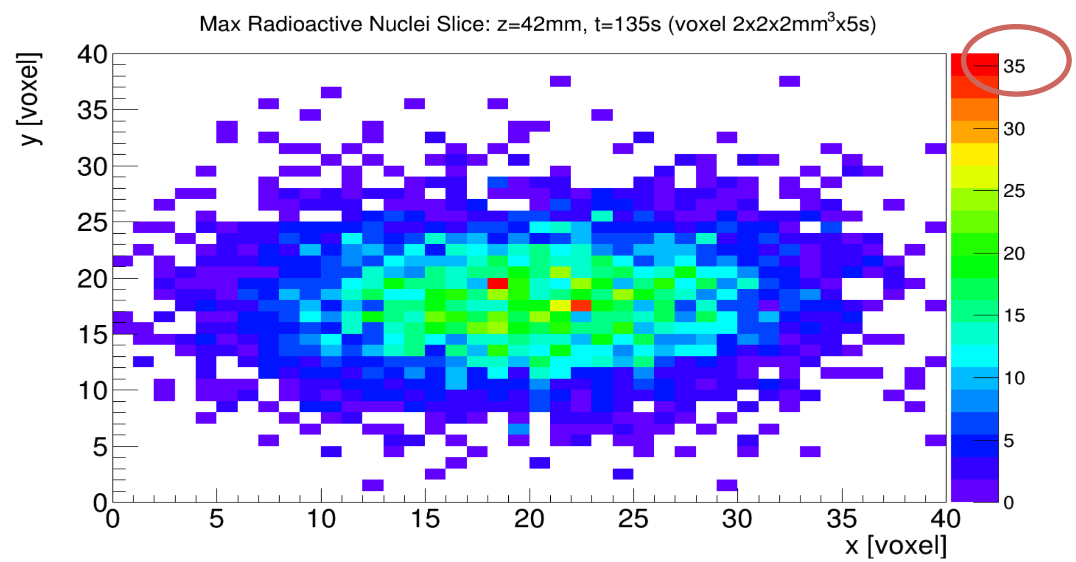


PET events generator (2)

2) **Isotopes production map**

- Custom source based on isotopes production map
- ^{11}C, ^{15}O and ^{10}C are considered (about 90% of events)
- Full treatment simulation spends 30 min with 30 cores
- Two gammas back-to-back are generated

Satisfactory statistics with voxel of 2x2x2mm^3 for each spill
⟶ sampling of isotope type, position and decay time



PET events generator (3)

3) **Isotopes production list**

- Custom source based on isotopes production list
- ^{11}C, ^{15}O and ^{10}C are considered (about 90% of events)
- Full treatment simulation spends 20 min with 25 cores
- Positrons are generated

The spatial spread is given by the positron walk.

The time spread is ensured by the decay time.

$\longrightarrow$ The simulation is faster and takes into account all physics processes.

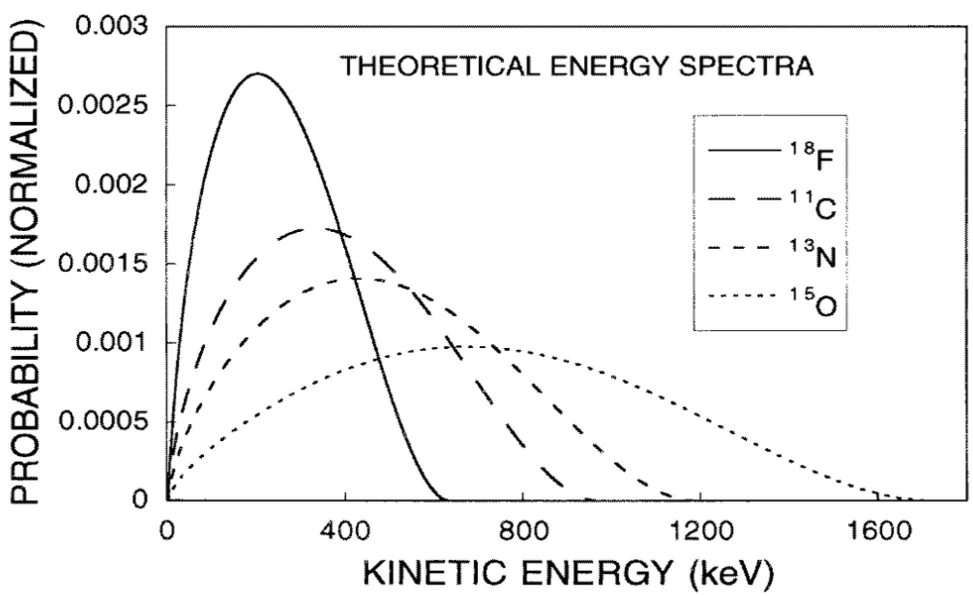
INSIDE PET Simulation (1)

INPUT: isotopes list generator (^{11}C, ^{15}O and ^{10}C)

In each position, 100 positrons are injected.

1)The annihilation position takes into account the positron walk and the decay time.

2)The positron energy is sampled.



INSIDE PET Simulation (2)

OPTIMIZATIONS:

- If the annihilation time is greater than a limit value (e.g.: 1800 s, 3600 s) the particle weight is set to 0 (not tracked): GAIN IN SIMULATION TIME

- If the initial positron energy is less than the energy cut limit (typically 100 keV), the position of the positron production is sampled into a 1x1x1 mm^3 cube to avoid artifact.
- The minimum kinetic energy to track positrons is set to 5 keV in the air and to 100 keV elsewhere to avoid border artifacts due to differences in material density.

Simulated data post processing

- Custom c++ classes
  - Simulation output sorting
  - Energy and time resolution added
  - Energy filtering around photopeak
  - Coincidences finding (true/random)
  - LOR file output (list mode)

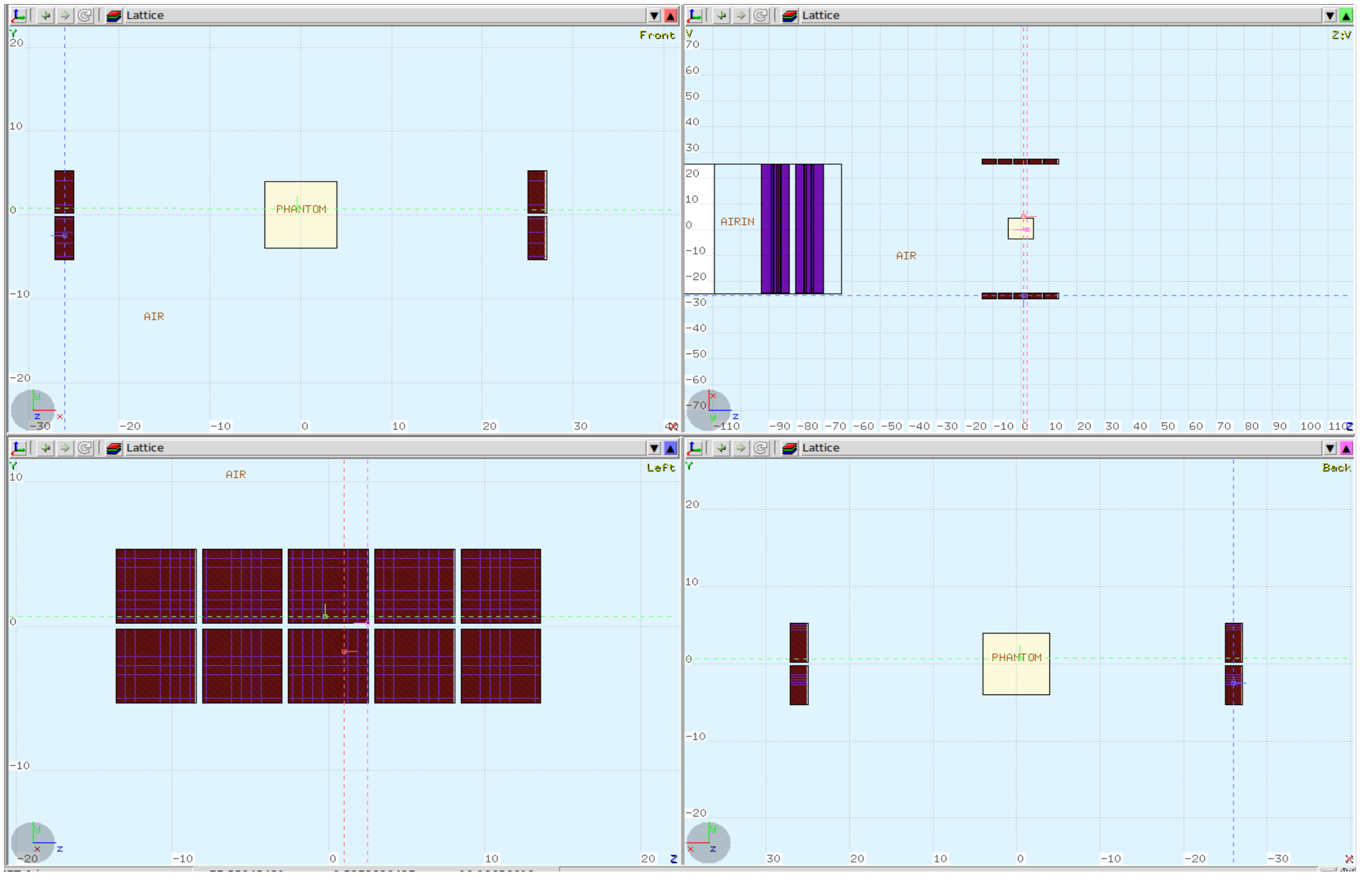
Image reconstruction

- Quantity reconstructed in images is activity relative distribution
- 1.6x1.6x1.6 mm^3 voxel, FOV 16x9.6x21.2 cm^3

Each INSIDE configuration (e.g. different distances between heads) requires a different model to perform the image reconstruction.

- Conversion from .gipl format to the NIFTI format with the ITK libraries to allow image analysis

INSIDE Simulated Set Up (1)



- Simulated detector response
- Updated geometry: 10 vs 10 modules

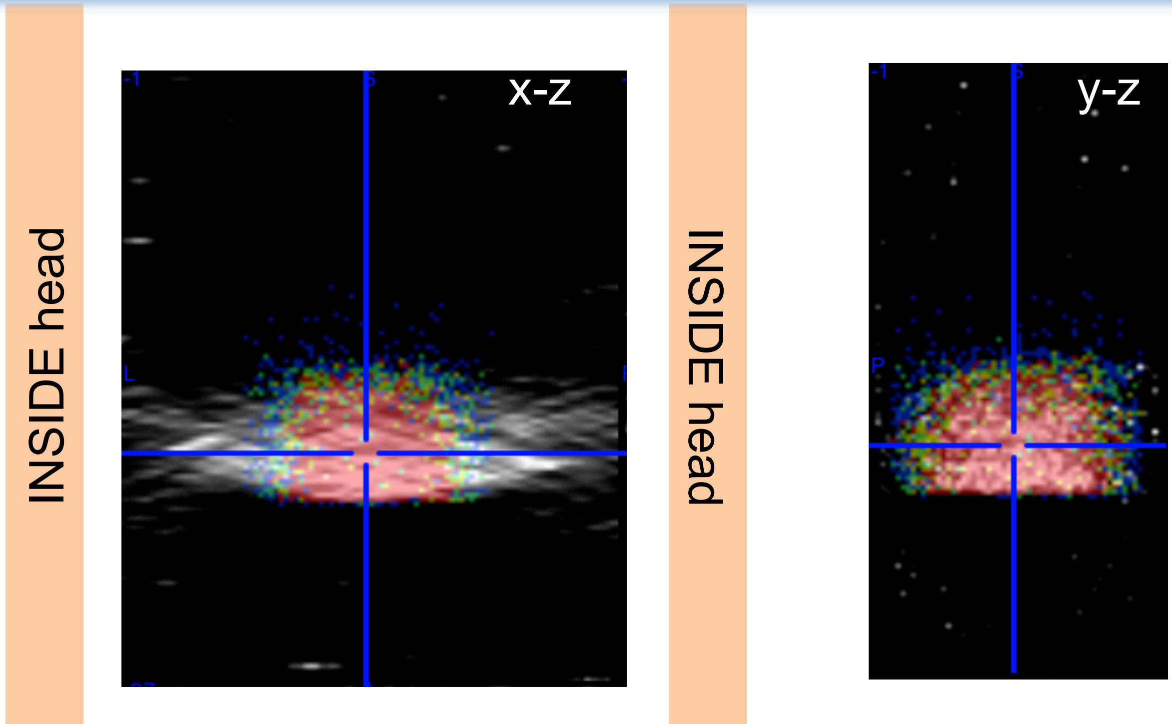
  distance between heads equal to 50 cm

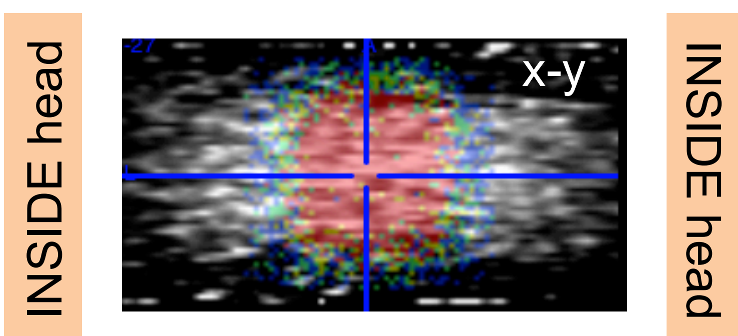
INSIDE Simulated Set Up (2)

- PMMA phantom 8x8x9 cm^3 at FOV center
- 2 Gy protons treatment, 31 spill
- Uniform irradiation of a 3x3x3cm^3 cube at z=[3,6]cm
- Nominal INSIDE geometry
- Isotopes list generator: 93.5% of annihilations are simulated
- Acquisition of inter-spill data only for the treatment duration (no after-treatment)
- Simulated 15% σ $\Delta E/E$ and 250 ps σ time resolution
- 3 ns time window[1]
- 5 iterations image reconstruction

[1]Maybe too large for the time resolution but random coincidences contribution is negligible in inter-spill

Results (1)



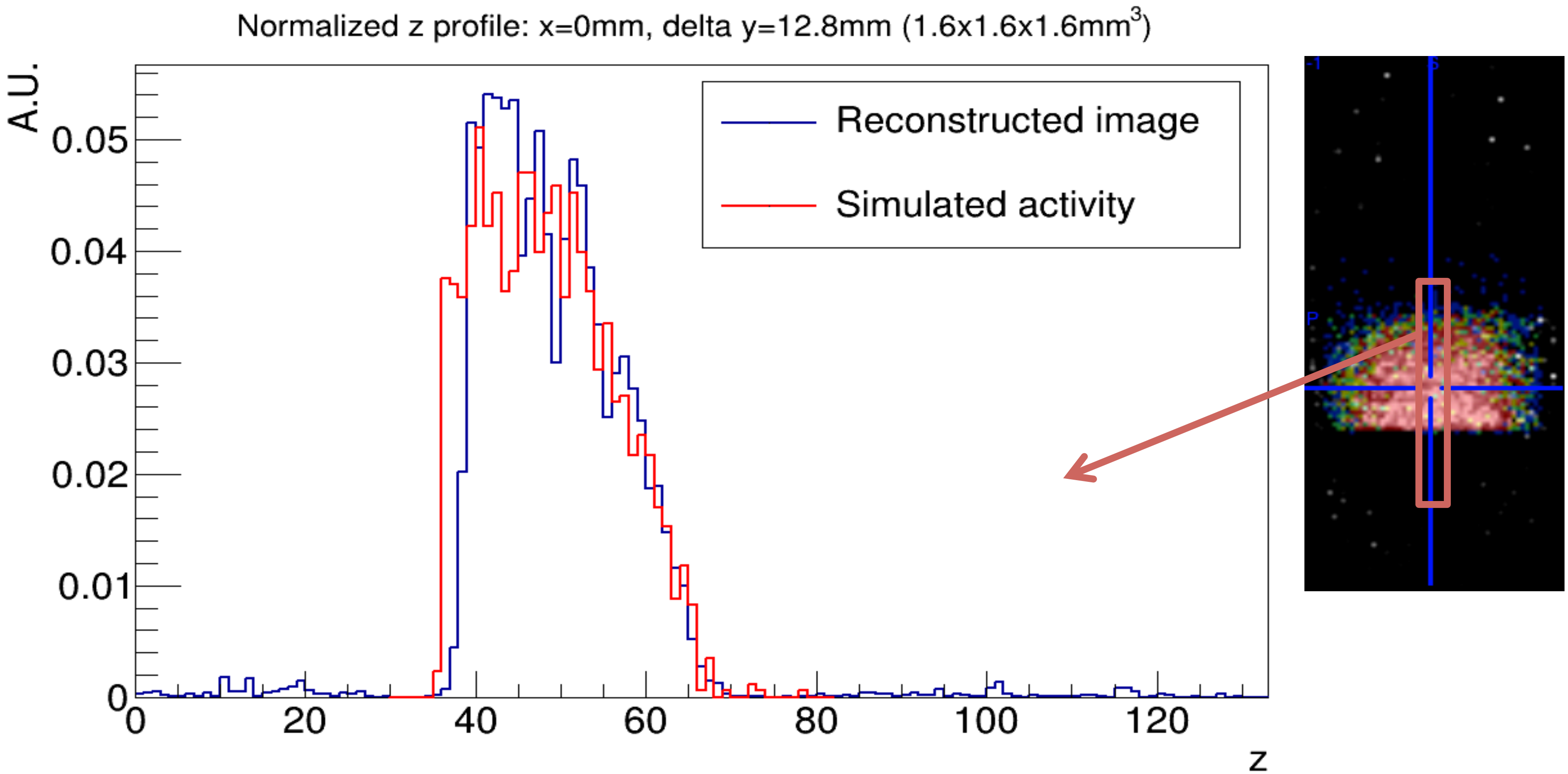


Grayscale : reconstructed PET image

- Inter-spill acquisition
- About 57000 acquired LORs
- Artifacts on the direction between heads

Colors: simulated activity

Results (2)



Blue line: reconstructed PET image Z profile at x = 0 and y from -6.4 to 6.4 mm
Red line: simulated activity Z profile at x = 0 and y from -6.4 to 6.4 mm

Conclusions

1) PET simulation and image reconstruction workflow works both for simulated and real data

2) Upgraded simulation:

- more reliable physics (positron walk, positron energy spectrum, positron production and transport energy cuts)

- faster (isotopes production list generator, decay time cut)

3) The distal falls off of the reconstructed image and simulated activity are compatible

Proposed next steps

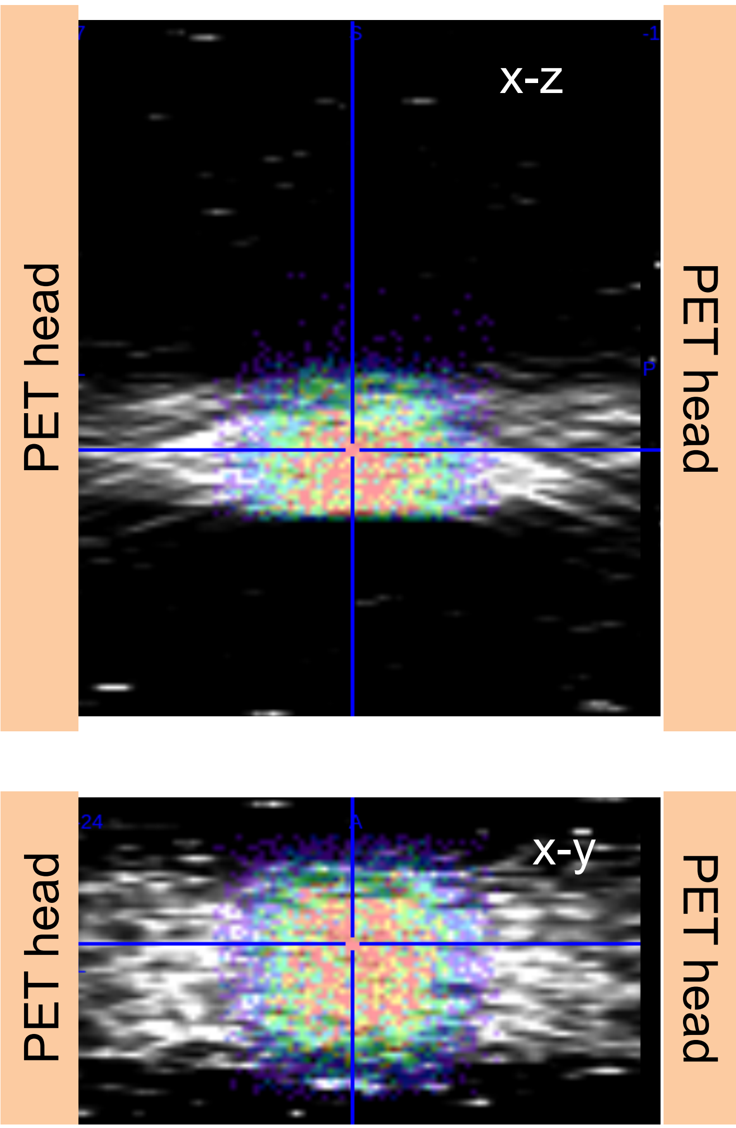
- Simulations of the next beam test acquisition
- Directional bias
- Validation with dedicated acquisitions during next beam test (INSIDE 1vs1 set up)
- Spill after spill (tentative) image reconstruction
- Image uniformity and distortion evaluation
- Carbon ions
- Integration with tracker

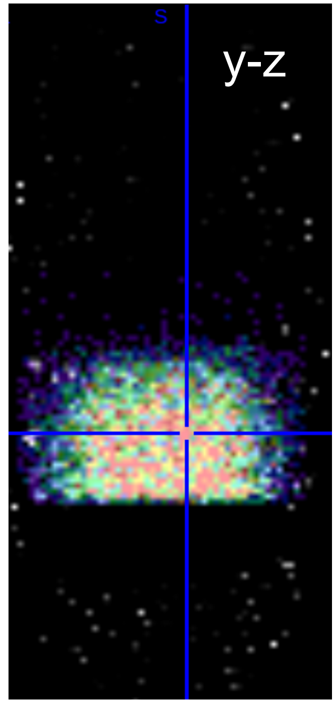
Back Up

^{11}C, ^{10}C and ^{15}O isotopes

	^{11}C	^{10}C	^{15}O
Half life	1220.04 s	19.290 s	122.4 s
% of tot. ann.	69%	2%	23%
% of interspill ann.	4%	75%	30%

Results: isotopes map based simulation (1)



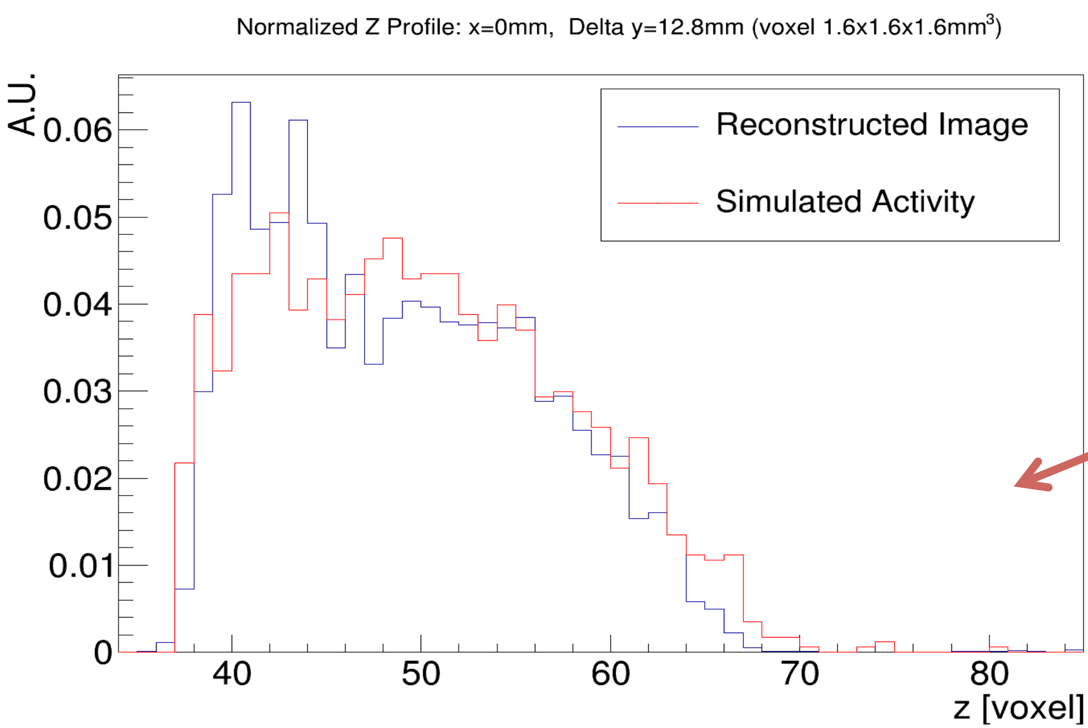


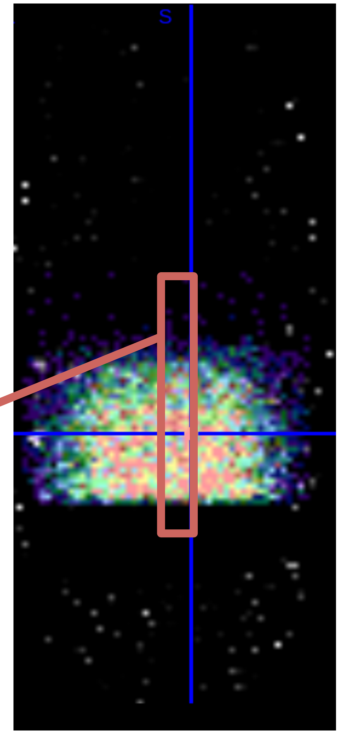
Grayscale : reconstructed PET image

- Inter-spill acquisition
- 45000 acquired LORs
- Artifacts on the direction between heads

Colors: simulated activity

Results: isotopes map based simulation (2)





Blue line : reconstructed PET image Z profile at x = 0 and y from -6.4 to 6.4 mm
Red: simulated activity Z profile
Normalized profiles between z=56 and z=136 mm