

Fast MC simulations for J-PET

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**Symposium on Positron Emission Tomography
Kraków, September 19th - 22nd, 2013**

Motivation

- Input data for testing of reconstruction algorithms:
 - geometry setups
 - different phantoms
 - detector response
- "Feed-back" for the experimental group to provide estimates and tests for:
 - geometry setups
 - time parameters

Developed tools

We developed several tools:

- event display for detector geometry and track visualization with the graphical user interface
- fast MC simulations
- simple image reconstruction algorithms
- application to compare the quality of the reconstructed images

Reconstruction methods

We use several reconstruction algorithms:

- simple but fast summation algorithm (can be treated as a backprojection from the projection space, $1/r$ smearing effect remains)
- summation algorithm + TOF techniques (two versions)
- 3-D MLEM algorithm (Z. Rudy and A.Słomski implementation)

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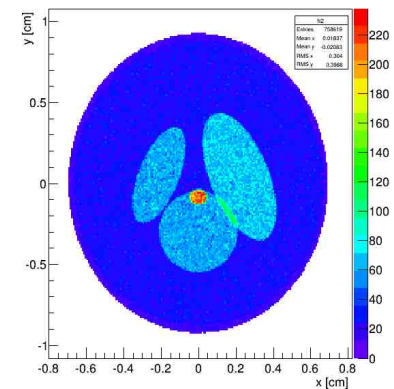
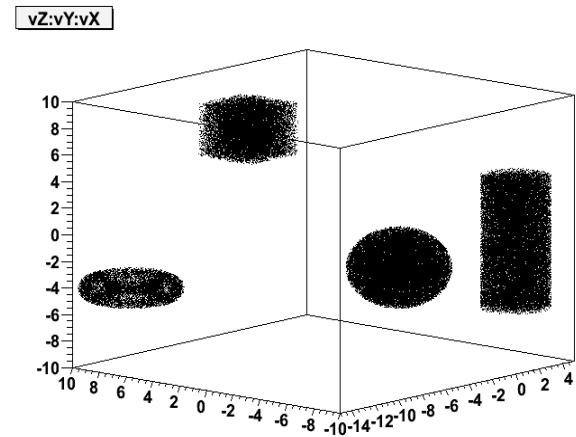
M. Bała's talk „Simple image reconstruction with TOF” , Sunday 12:50

- 3-D MLEM algorithm (Z. Rudy and A. Słomski implementation)

Z. Rudy, and A. Słomski's talk
"3D PET reconstruction based on the MLEM algorithm" , Saturday 11:10

Phantoms

- geometrical shapes with uniform distribution of points:
 - point sources
 - spheres,
 - cylinders.
 - ellipsoids
 -
- phantom generator (M. Bała)



M. Bała's talk „Simple image reconstruction with TOF” , Sunday 12:50

Image metrics

$$\text{MSE}(X, Y) = \frac{1}{N} \cdot \sum_{k=1}^N (x_k - y_k)^2$$

$$\text{PSNR}(X, Y) = 10 \cdot \log_{10} \left(\frac{L(Y)^2}{\text{MSE}(X, Y)} \right)$$

$$\text{NRMSE}(X, Y) = \frac{\sum_{k=1}^N (x_k - y_k)^2}{\sum_{k=1}^N x_k^2}$$

$$L(X) = \max(X) - \min(X)$$

$$\text{NRMSE}(X, Y) = \frac{\sum_{k=1}^N (x_k - \alpha \cdot y_k)^2}{\sum_{k=1}^N x_k^2}$$

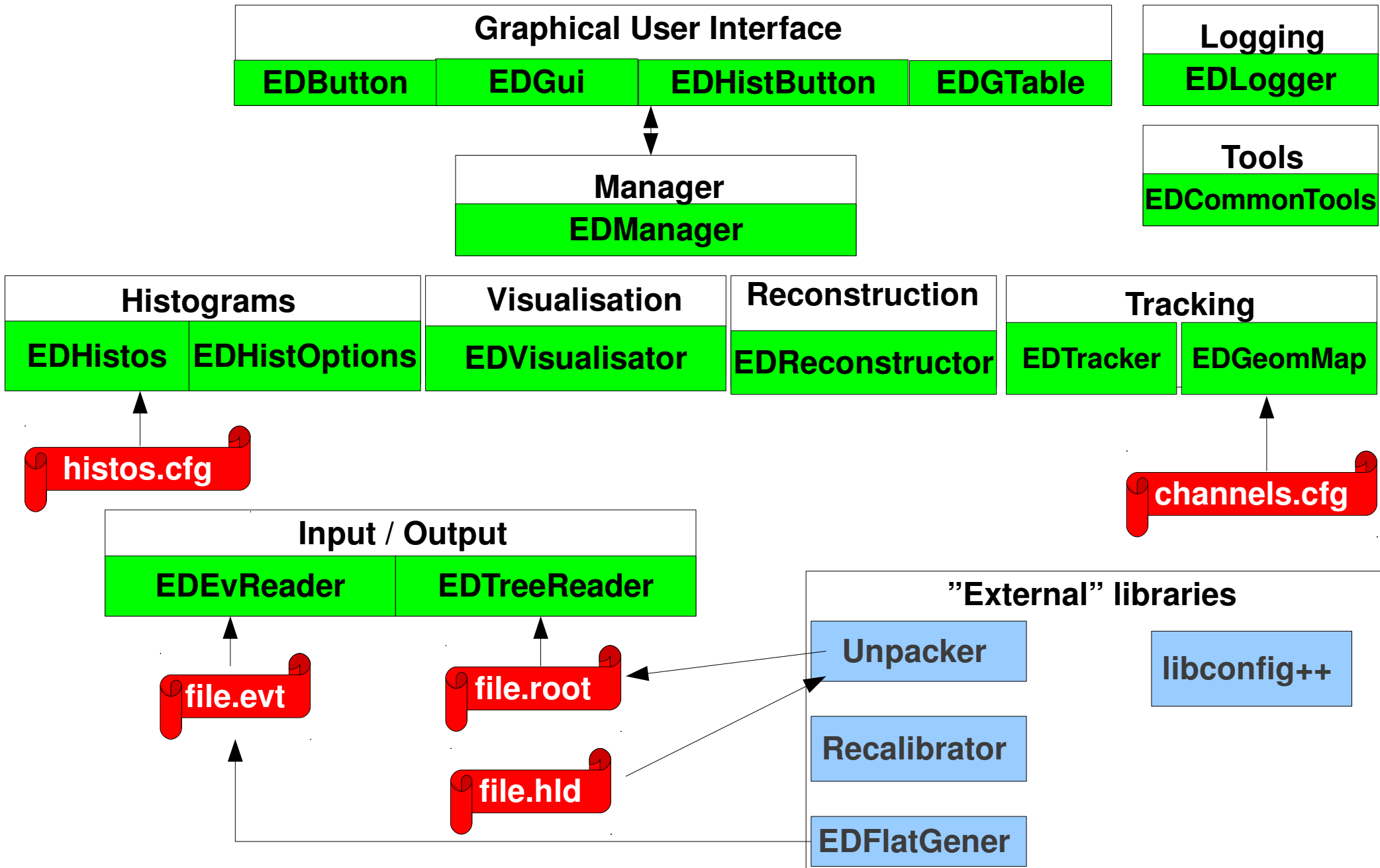
$$\text{SSIM}(x, y) = \frac{2\bar{x}\bar{y} + c_1}{\bar{x}^2 + \bar{y}^2 + c_1} \cdot \frac{2\sigma_x\sigma_y + c_2}{\sigma_x^2 + \sigma_y^2 + c_2} \cdot \frac{\sigma_{xy} + c_3}{\sigma_x + \sigma_y + c_3}$$

$$\alpha = \sum_{k=1}^N \frac{x_k \cdot y_k}{\sum_{k=1}^N y_k^2}$$

Fast MC simulations

- Independent application based on the ROOT geometry package.
- Included effects:
 - Penetration depth of gamma quanta in the material
 - Smearing of the time measurement in the photomultipliers
- Not included:
 - energy dependence
 - propagation of light in the scintillator

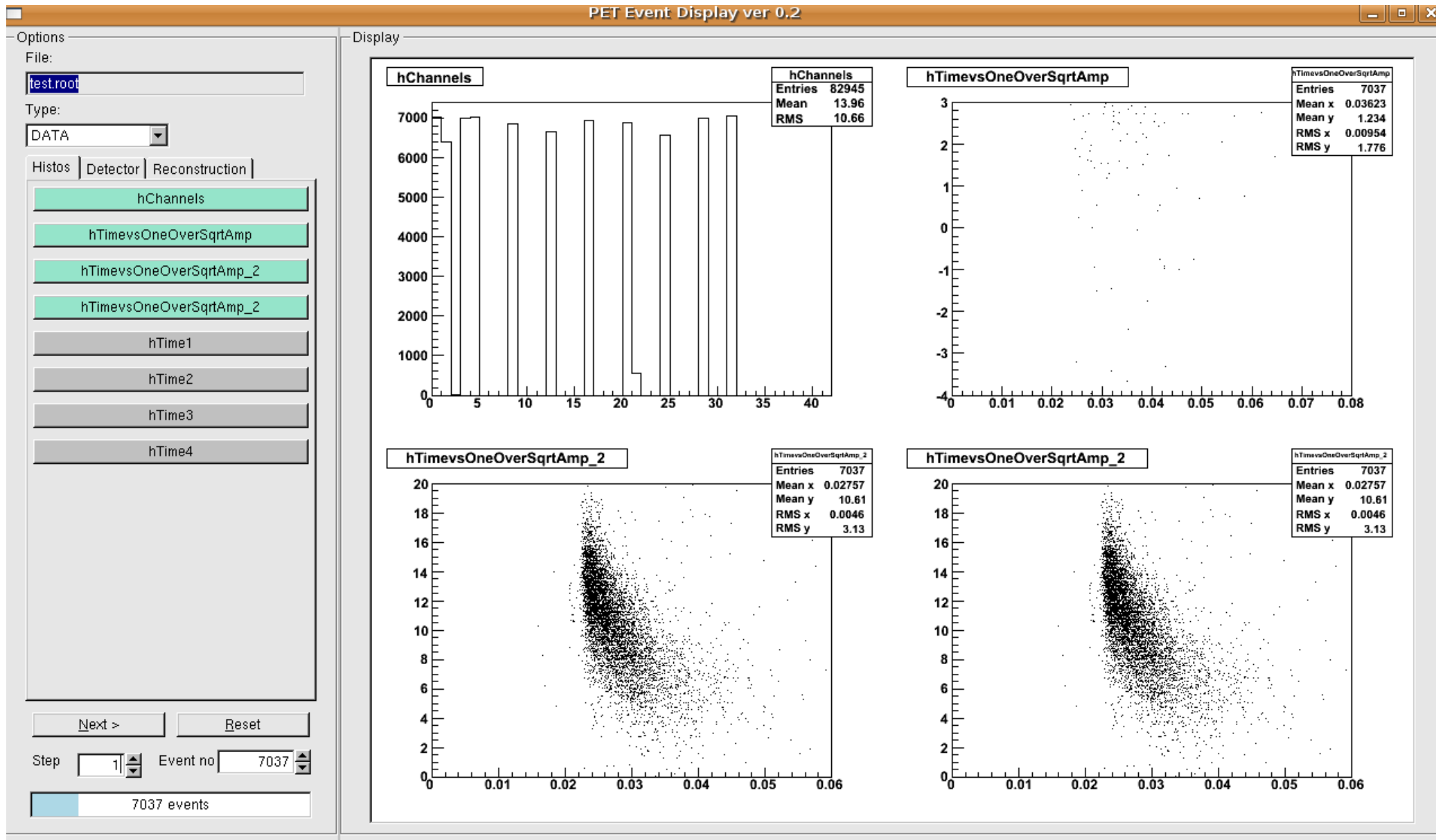
Internal architecture



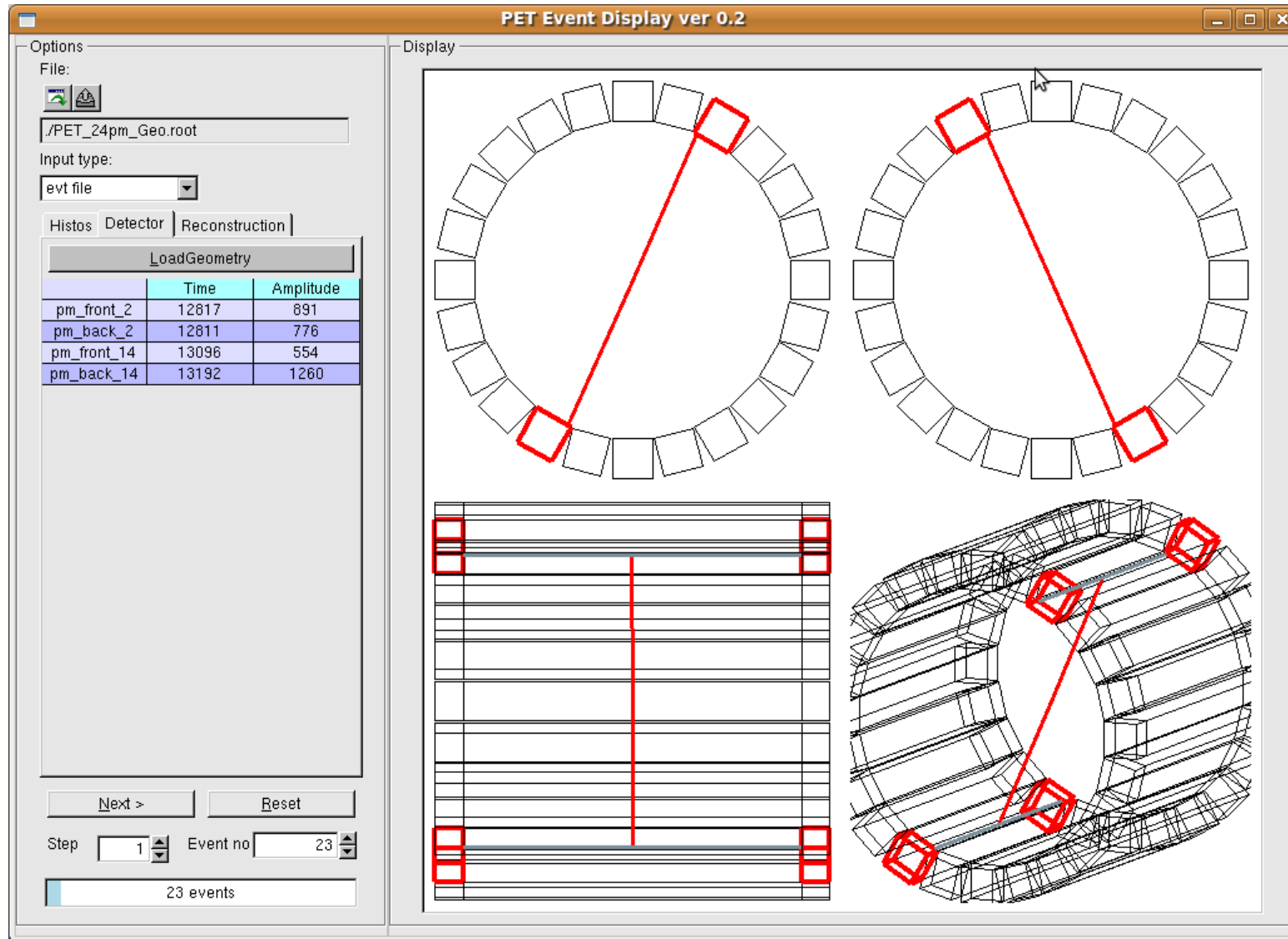
Technical details

- Developed in C++, STL.
- Modularity - possibility to add independent modules (analysis, recalibration, ...) in the future.
- Graphical User Interface based on WIN95 widgets (external library from ROOT).
- Signal-slot mechanism (like in Qt).
- HTML/Latex documentation of the whole code (Doxygen).

Graphical user interface



Detector visualization



24 x rectangular-shape: 5 cm x 5 cm x 30 cm

Phantoms visualization

PET Event Display ver 0.2

Options

File:
PET_CUBE_Geometry.root

Input type:
evt file

Add Vertices

Histos | Detector | Reconstruction

LoadGeometry

| | Amplitude | Time |
|----------------|-----------|----------|
| pm_front_10_10 | 50 | 0.974341 |
| pm_back_10_10 | 50 | 0.141999 |
| pm_front_22_22 | 50 | 0.220655 |
| pm_back_22_22 | 50 | 0.884992 |

Next > Reset >

Step 1000 Event no 2000

2000 events

Display

The visualization displays four views of a PET scanner phantom. The top-left and top-right views are top-down projections showing a circular arrangement of detector elements (red squares) around a central blue cluster. A green line (line of response) connects two detector elements. The bottom-left view is a side projection showing the detector elements as horizontal lines, with the green line and blue cluster visible. The bottom-right view is a 3D perspective view of the detector assembly, showing the green line and blue cluster within the structure.

Phantoms visualization

PET Event Display ver 0.2

Options

File:

PET_CUBE_Geometry.root

Input type:

evt file

Add Vertices

Histos | **Detector** | Reconstruction

LoadGeometry

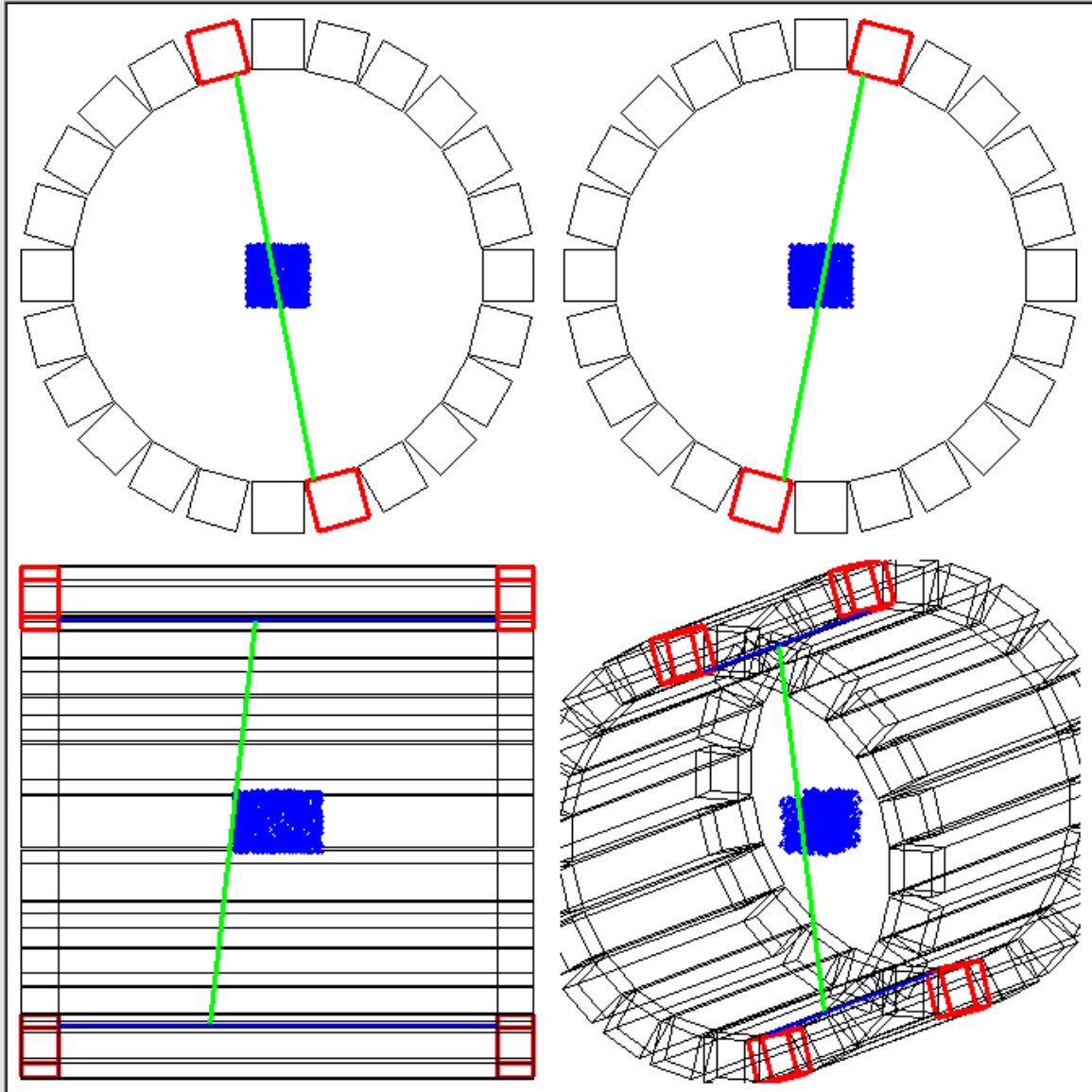
| | Amplitude | Time |
|----------------|-----------|----------|
| pm_front_11_11 | 50 | 0.354549 |
| pm_back_11_11 | 50 | 0.672765 |
| pm_front_23_23 | 50 | 0.464612 |
| pm_back_23_23 | 50 | 0.589137 |

Next > Reset >

Step 2000 Event no 2000

2000 events

Display



Detector response simulation

- Propagation of light in the scintillator treated as a straight line
- Ideal propagation times smeared under the assumption that the time error follows a Gaussian distribution



$\text{time1}' = \text{Gauss}(\text{time1})$

$\text{time2}' = \text{Gauss}(\text{time2})$

- Interaction point reconstructed from the time difference

Detector response simulation

PET Event Display ver 0.2

Options

File:

PET_CUBE_Geometry.root

Input type:

tree

Add Vertices

Histos | **Detector** | Reconstruction

LoadGeometry

| | Amplitude | Time |
|----------------|-----------|----------|
| pm_front_0_0 | 50 | 0.711483 |
| pm_back_0_0 | 50 | 0.403438 |
| pm_front_12_12 | 50 | 0.413175 |
| pm_back_12_12 | 50 | 0.634101 |

Next > Reset >

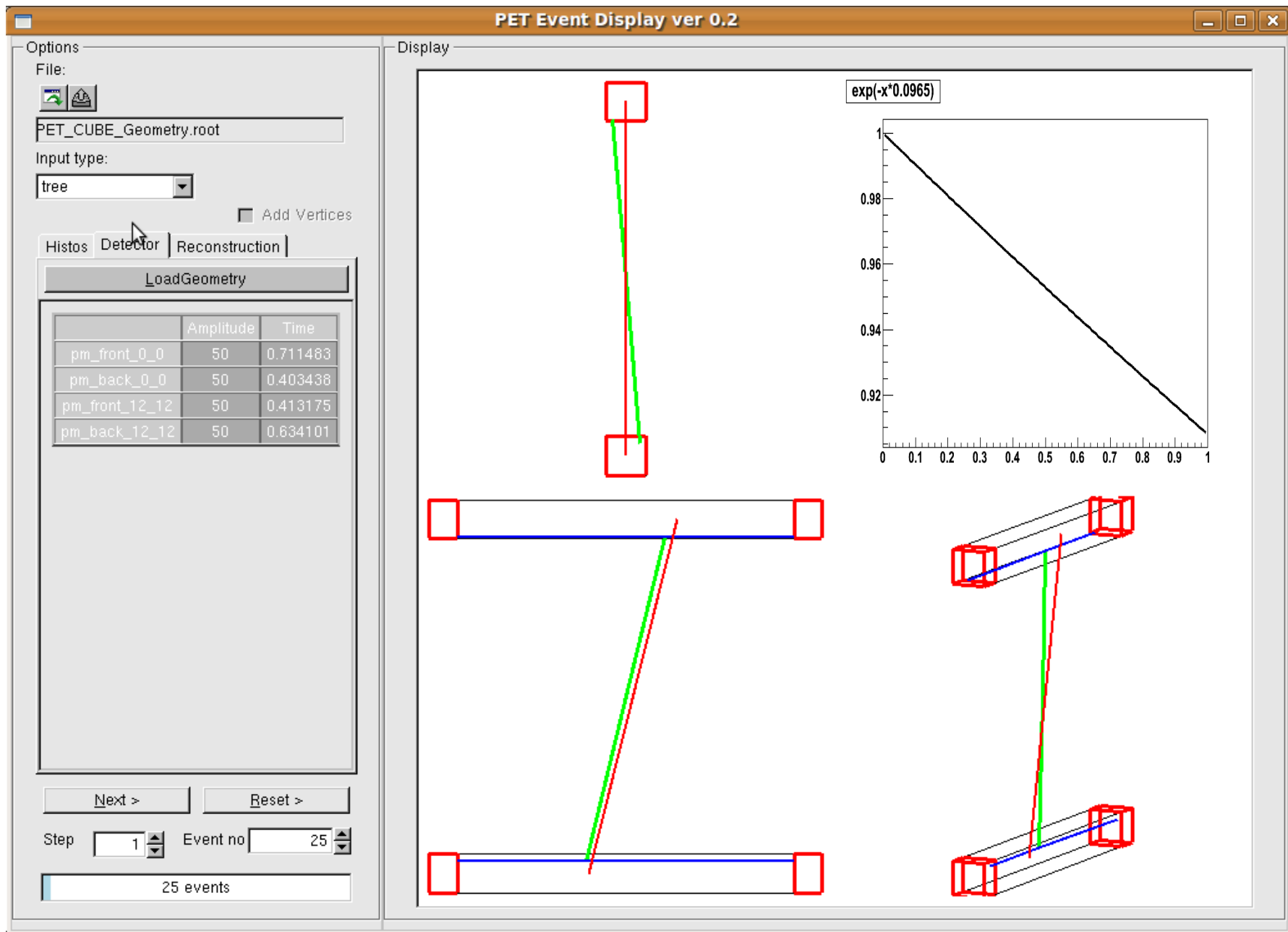
Step Event no

25 events

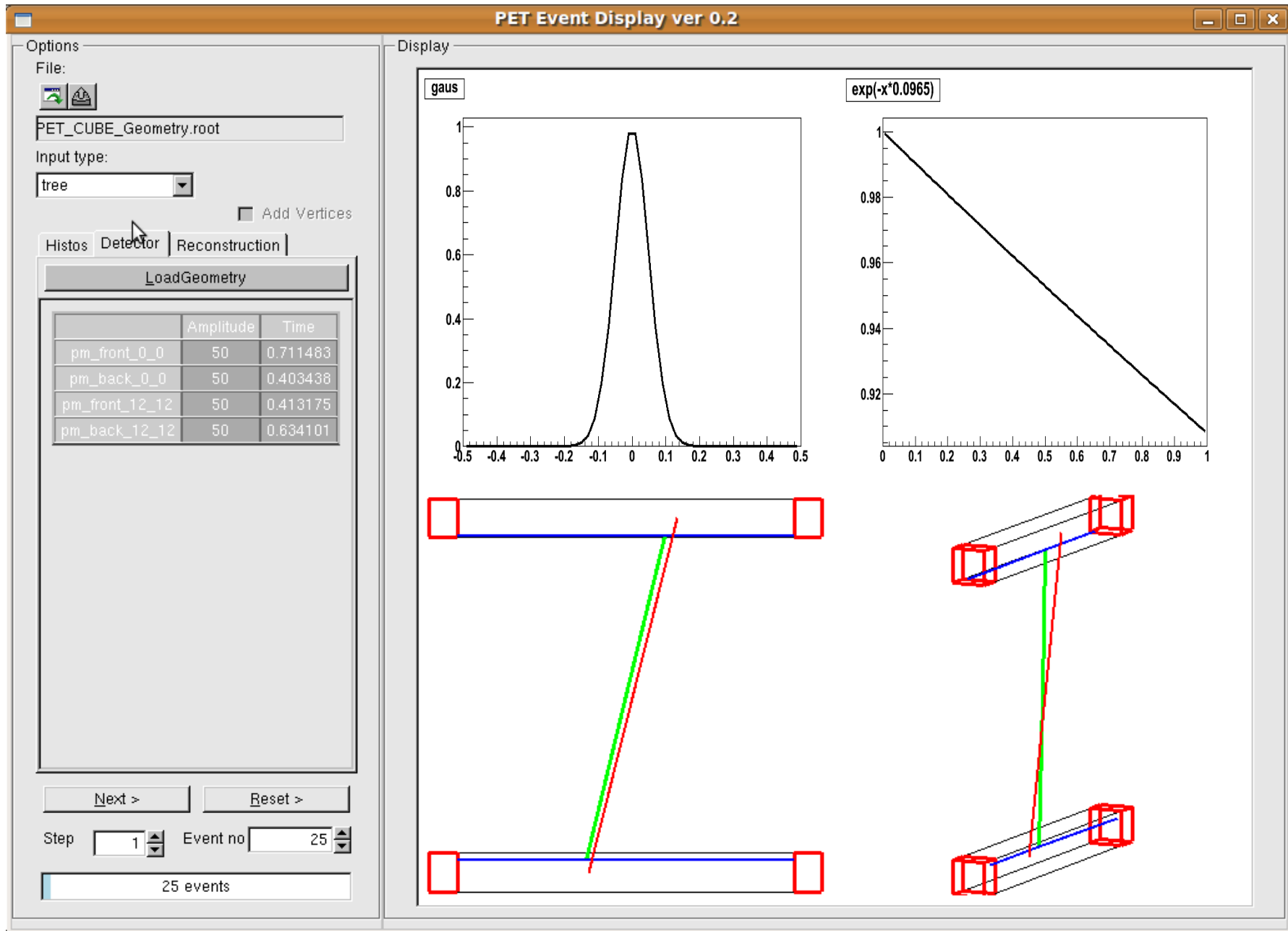
Display

The Display window shows two views of the detector geometry. The left view is a 2D projection showing a central horizontal bar (blue) and two vertical bars (green) extending from it. The right view is a 3D perspective showing the same geometry with red boxes at the ends of the bars. A green line and a red line represent the paths of particles or photons through the detector.

Detector response simulation



Detector response simulation



Detector response simulation

PET Event Display ver 0.2

Options

File:

PET_CUBE_Geometry.root

Input type:

tree

Add Vertices

Histos | Detector | Reconstruction

LoadGeometry

| | Amplitude | Time |
|----------------|-----------|----------|
| pm_front_7_7 | 50 | 0.823925 |
| pm_back_7_7 | 50 | 0.187834 |
| pm_front_19_19 | 50 | 0.189579 |
| pm_back_19_19 | 50 | 0.838072 |

Next > | Reset >

Step 1 | Event no 42

42 events

Display

The Display panel contains four sub-views of the detector geometry and event reconstruction:

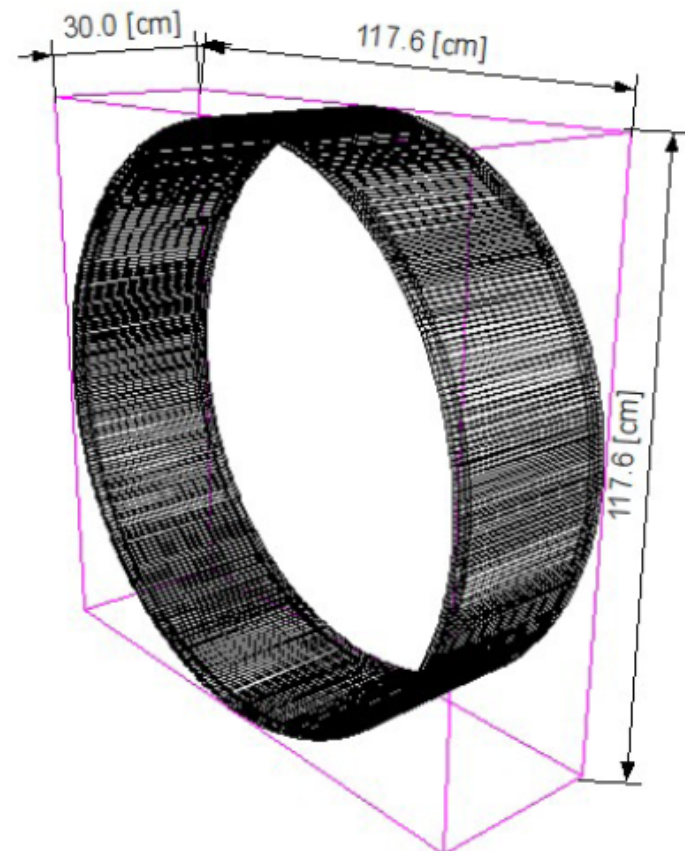
- Top-left: 2D schematic of the detector ring with two red squares marking the interaction points and a green line connecting them.
- Top-right: 2D schematic of the detector ring with two red squares marking the interaction points and a red line connecting them.
- Bottom-left: 2D schematic of the detector ring with two red squares marking the interaction points and a green line connecting them.
- Bottom-right: 3D wireframe view of the detector ring with two red squares marking the interaction points and a green line connecting them.

MC tests - QA plots

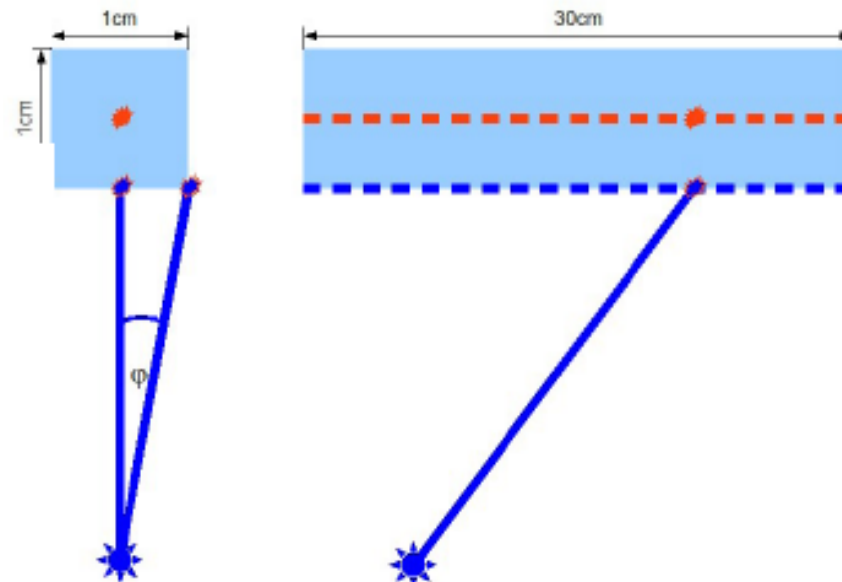
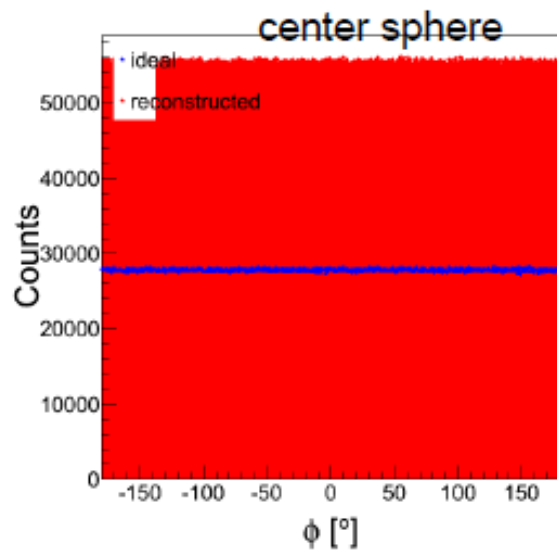
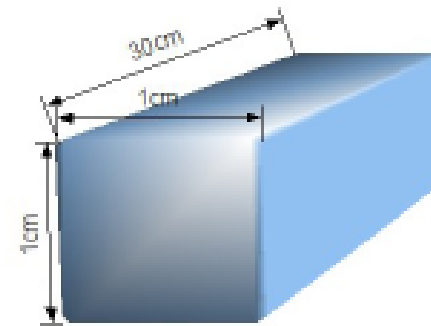
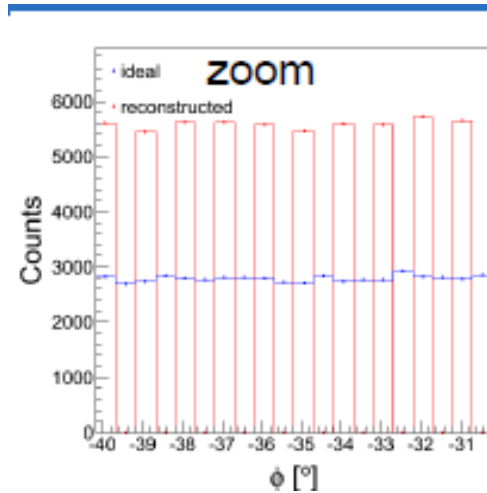
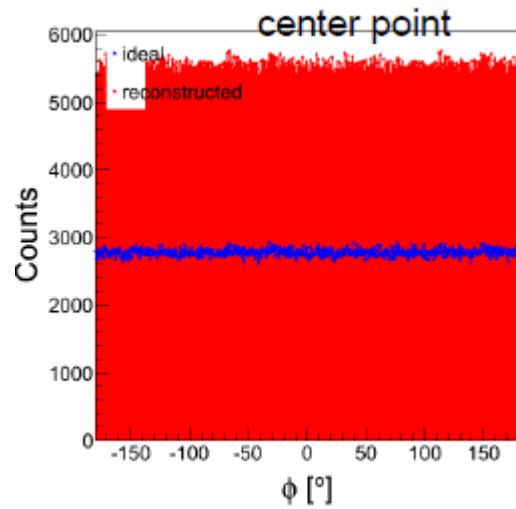
toy detector:

- 360 strip scintillators distributed symmetrically on a circle ($R = 57$ cm)
- Module dimensions $1 \times 1 \times 30$ cm

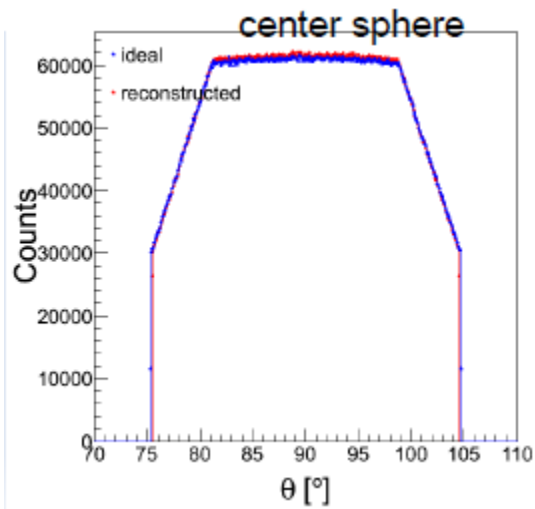
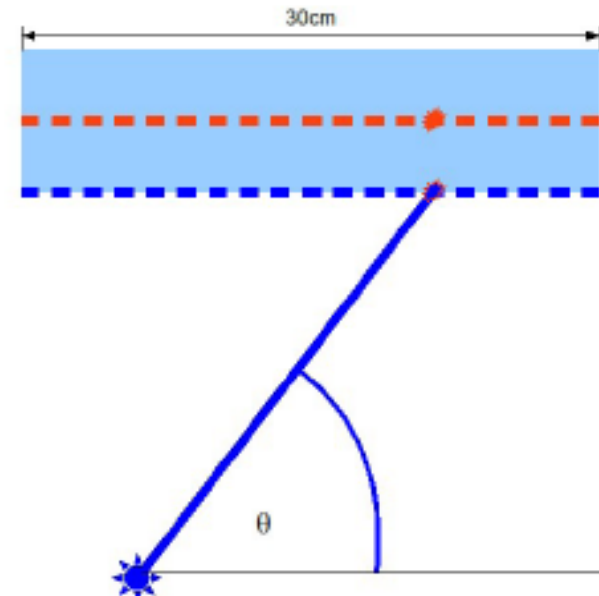
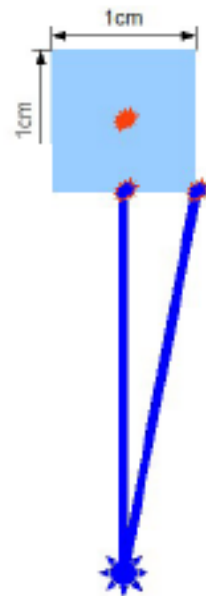
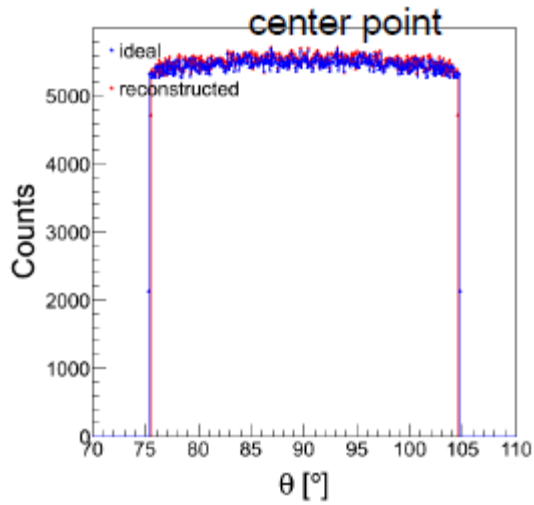
- Two simple phantoms:
Emitting point $(0,0,0)$
Sphere $(0,0,0)$ $R=3$ cm



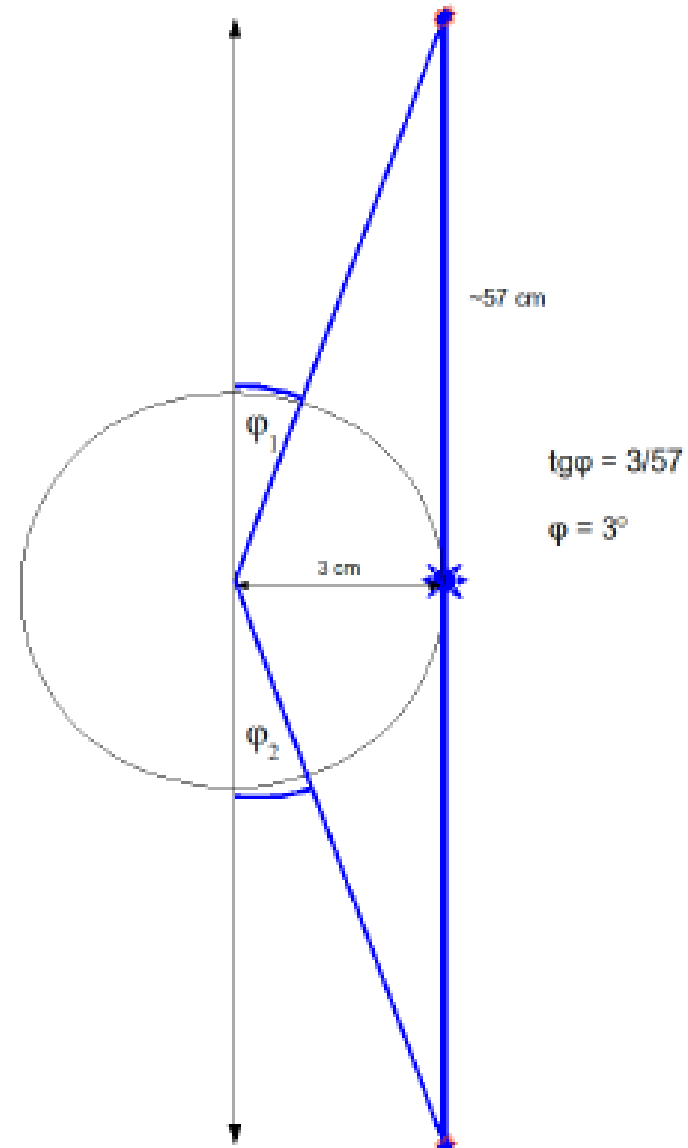
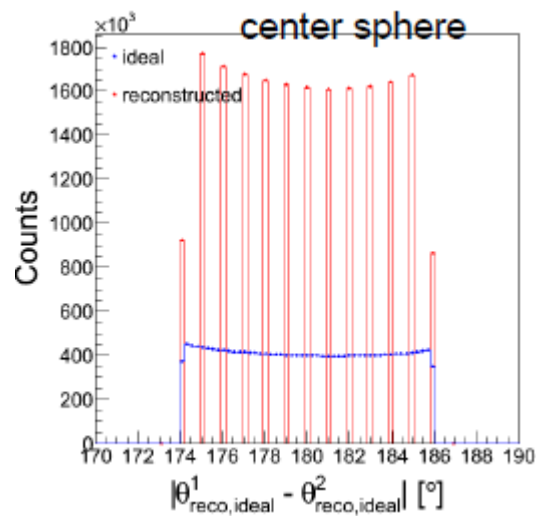
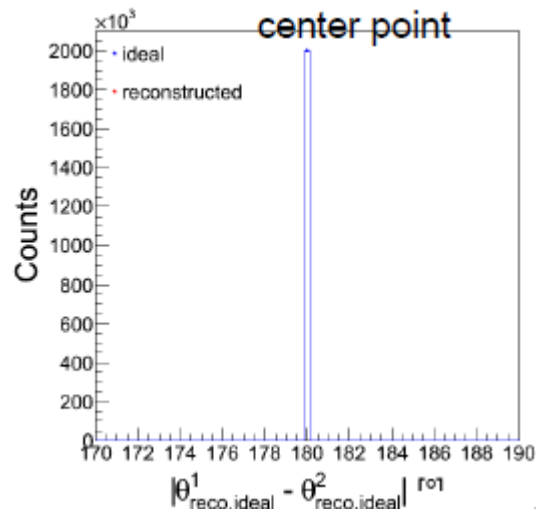
MC tests - QA plots



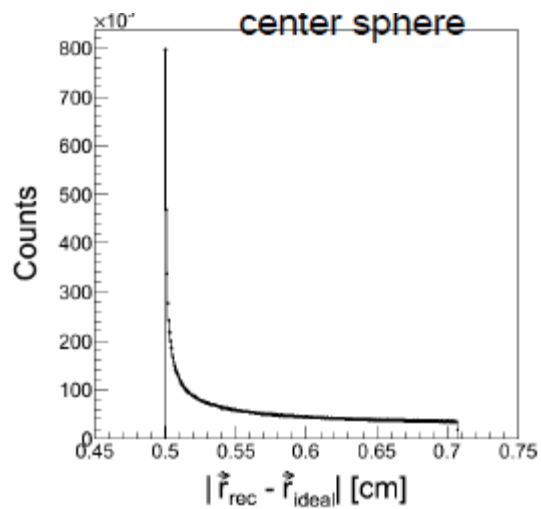
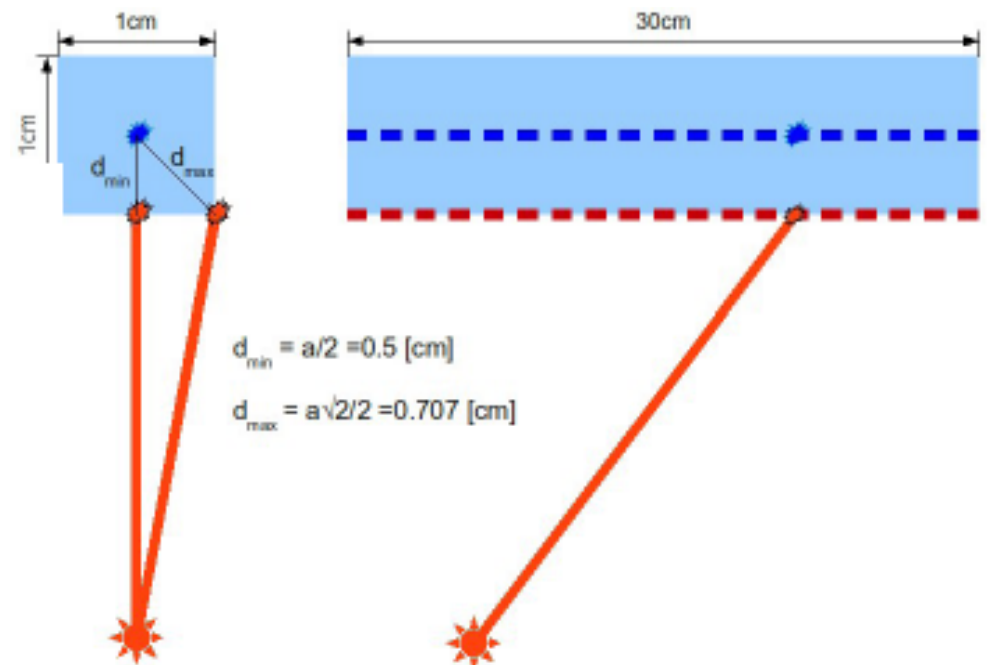
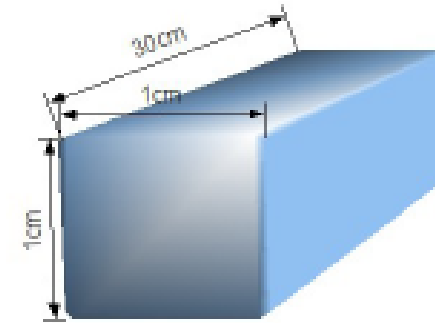
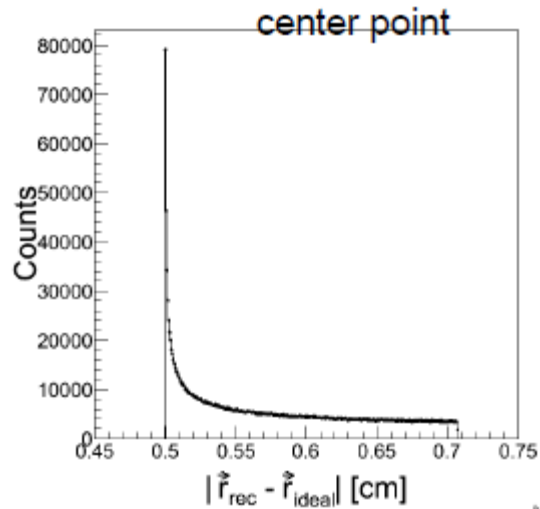
MC tests - QA plots



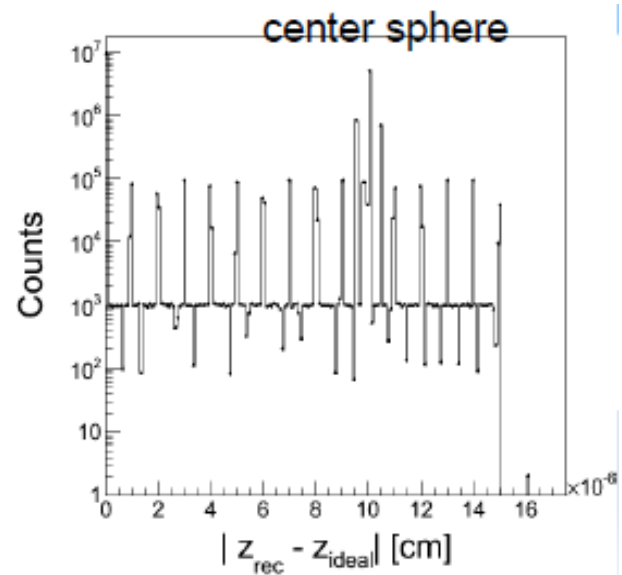
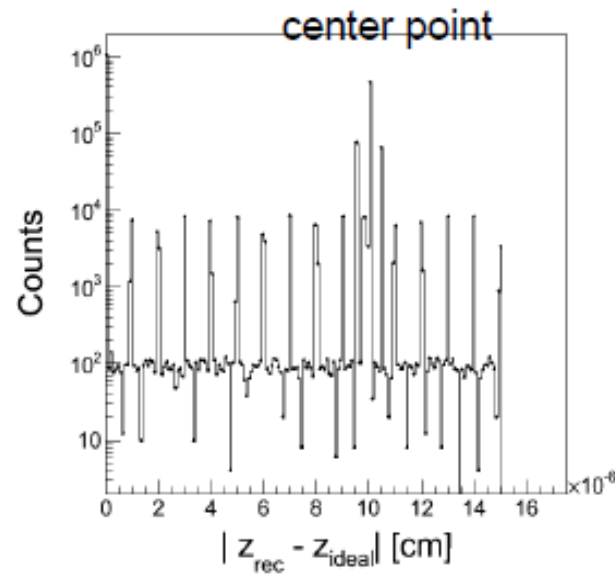
MC tests - QA plots



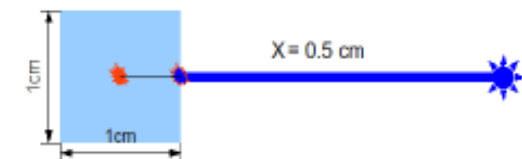
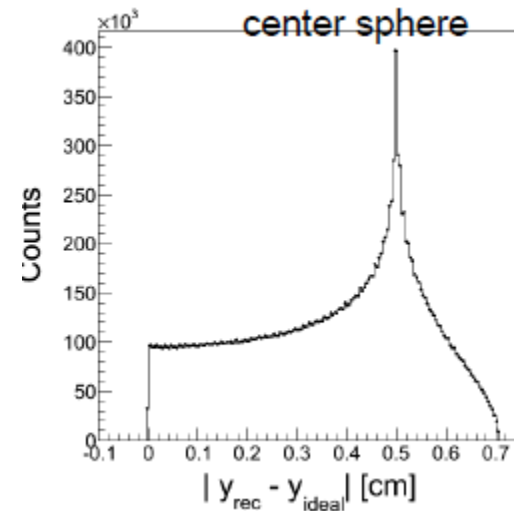
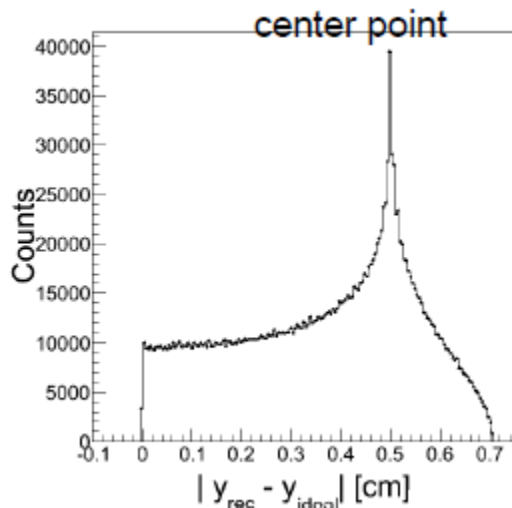
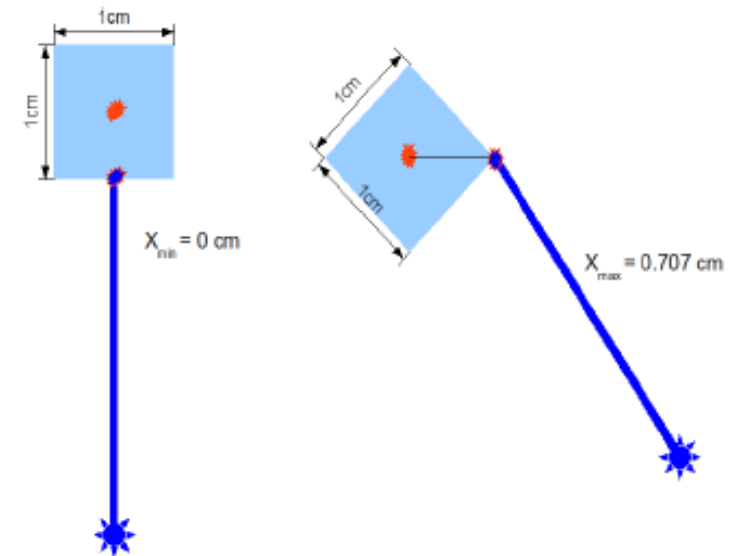
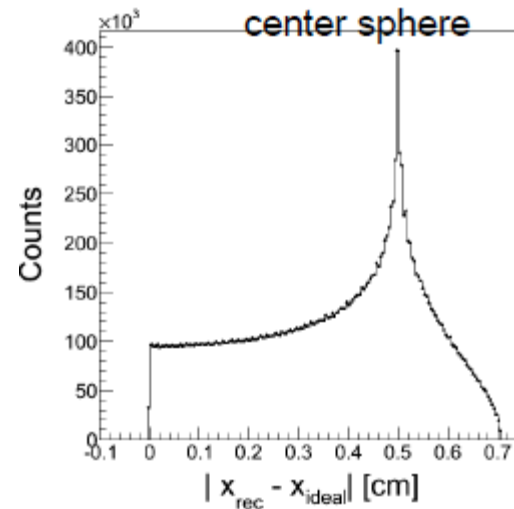
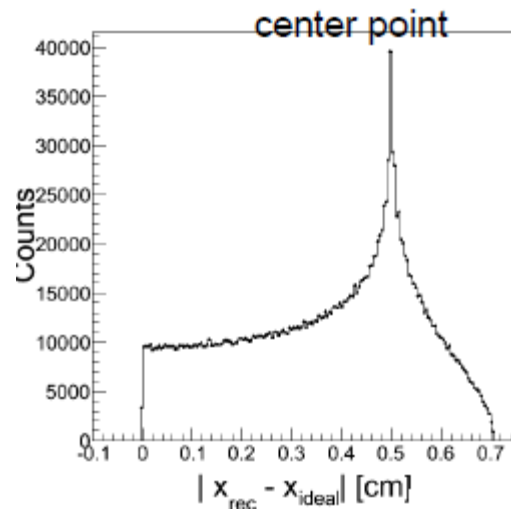
MC tests - QA plots



MC tests - QA plots



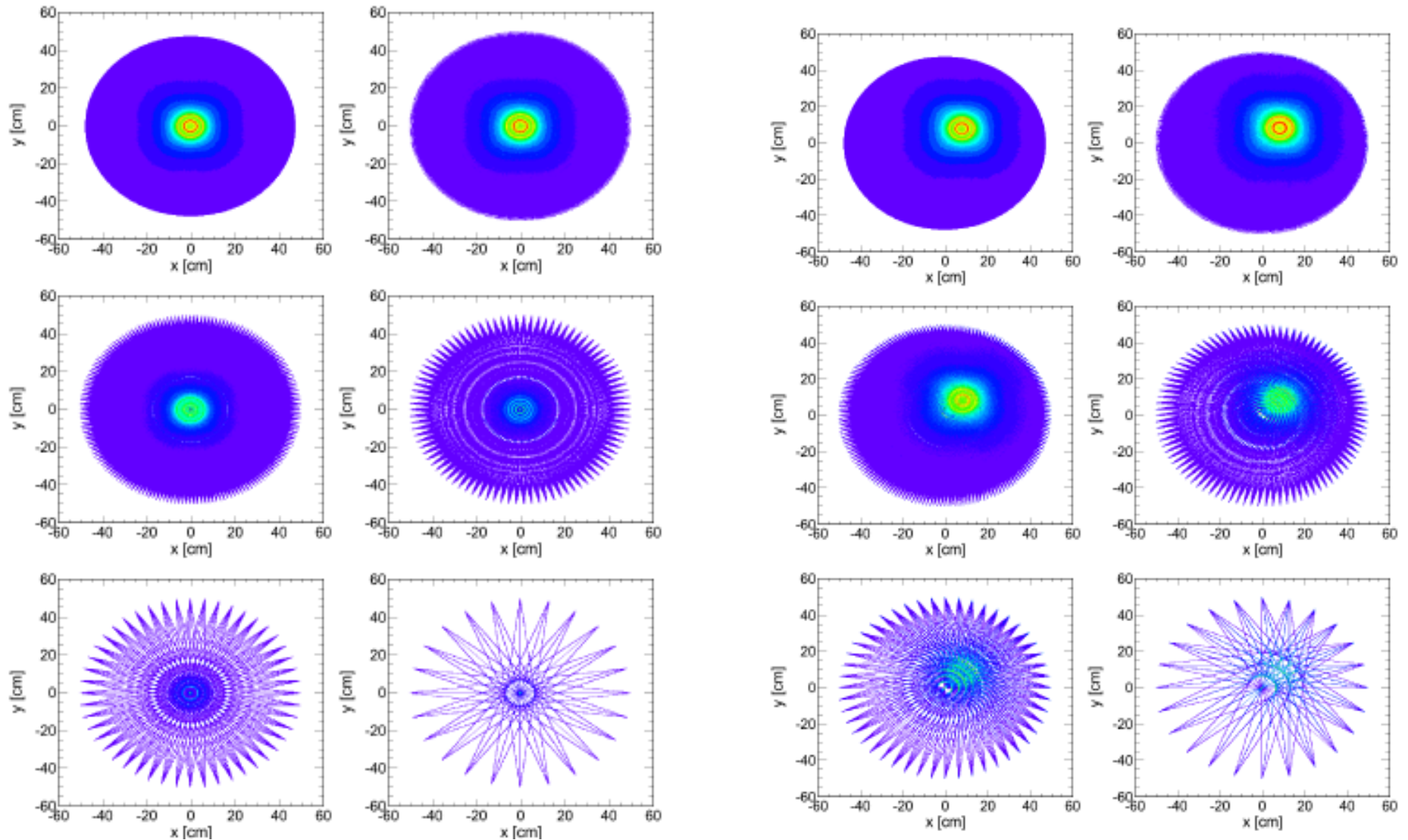
MC tests - QA plots



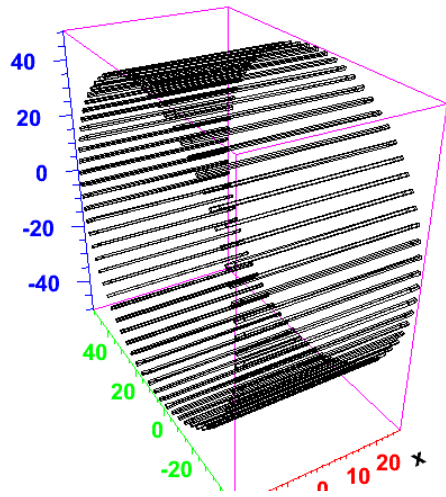
Simple reconstruction example

- Uniformly distributed sphere within a sphere ($r_1 = 3$ cm, $r_2 = 6$ cm).
- Two cases:
 - position of the center: in $(0,0,0)$
 - position of the center: in $(8,8,8)$ cm.
- Detector is a cylindrical barrel with strip modules distributed symmetrically on the circle ($R = 50$ cm).
- Dimensions: 50 cm x 2,5 x 2 cm
- We change the number of modules in the detector:

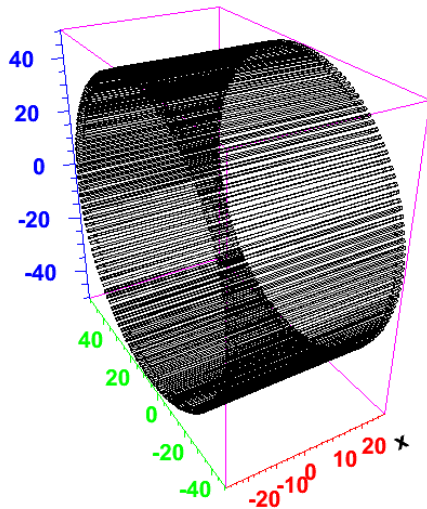
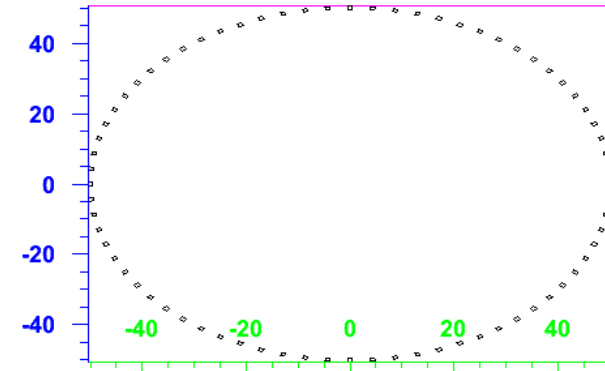
Examples of reco (cross-sections $z = 0$, 5 mln events registered)



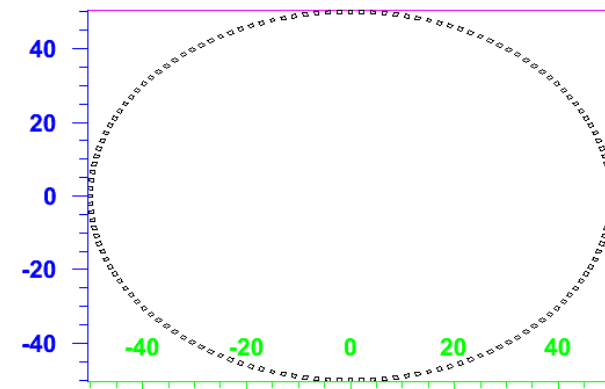
Different number of detectors (uniformly distributed 20% -100%) ($R=50\text{cm}$, $L=50\text{cm}$)



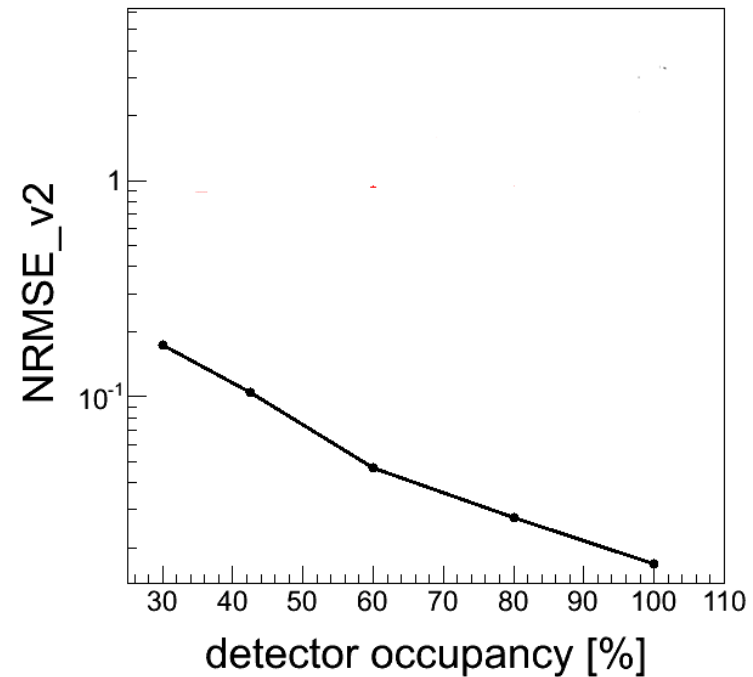
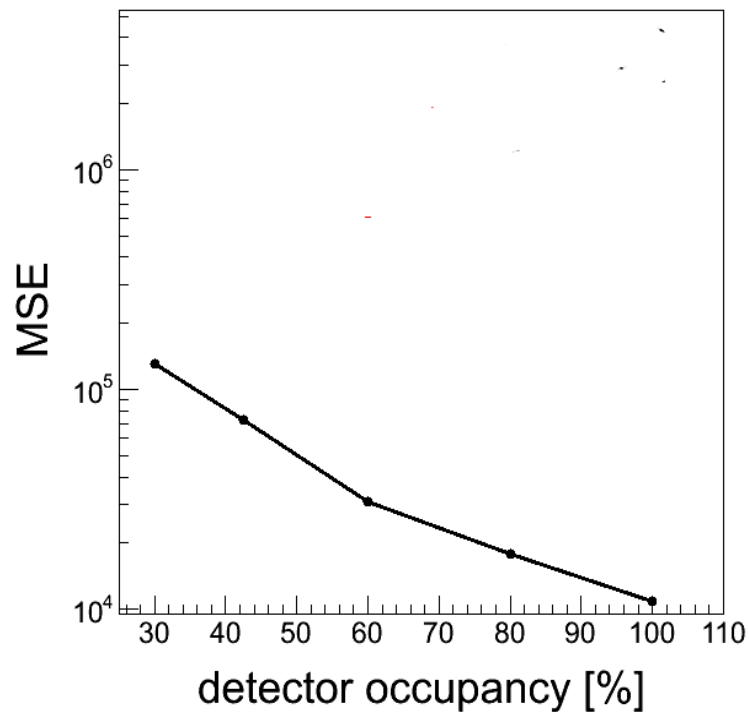
20%



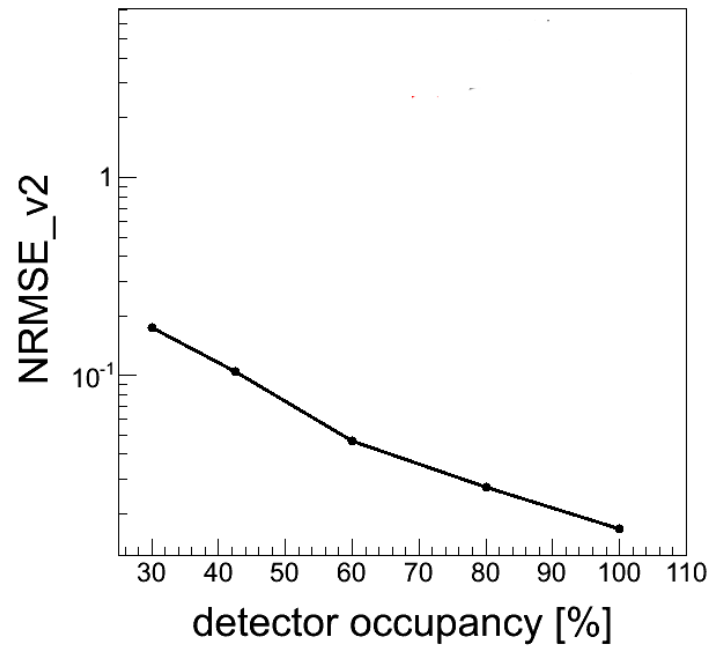
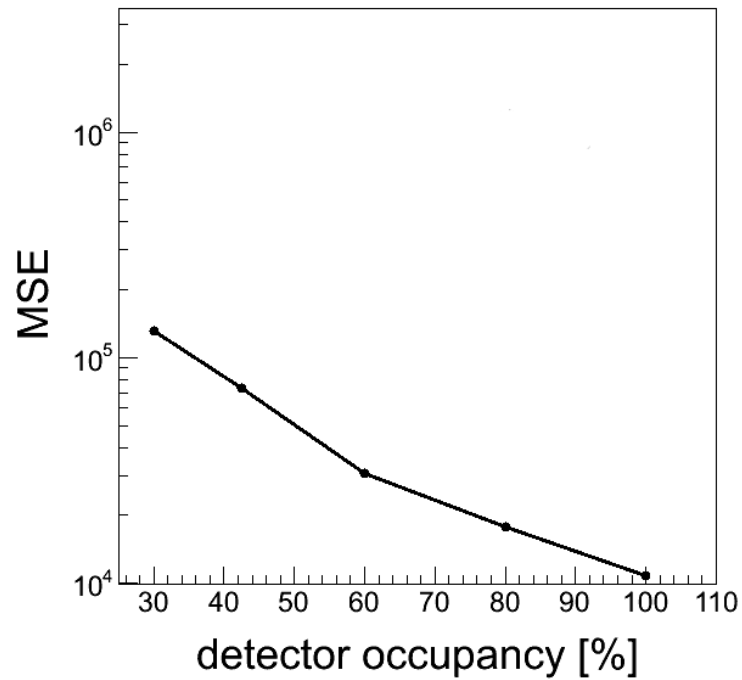
40%



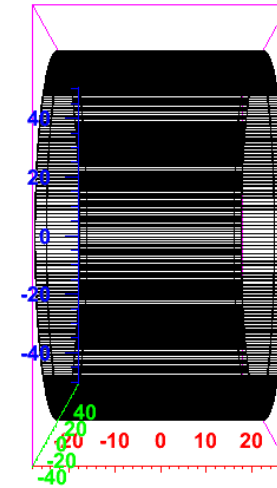
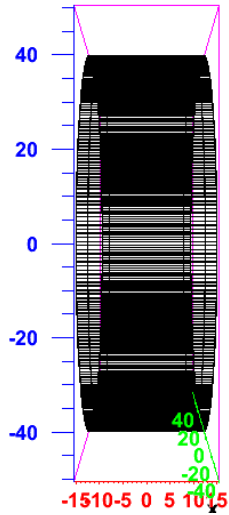
Same number of LORs accepted (same # of LORs for every case)



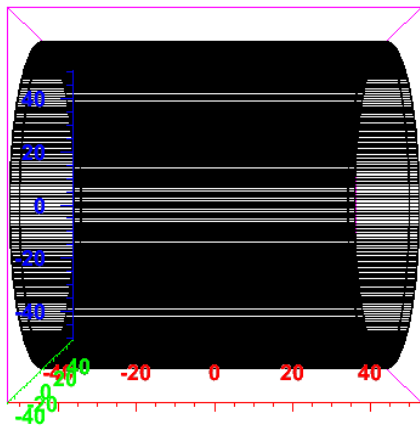
Same number of LORs emitted (different # of LORs due to acceptance)



Different detector length ($R=50$ cm, $L = 25, 50, 100$ cm)

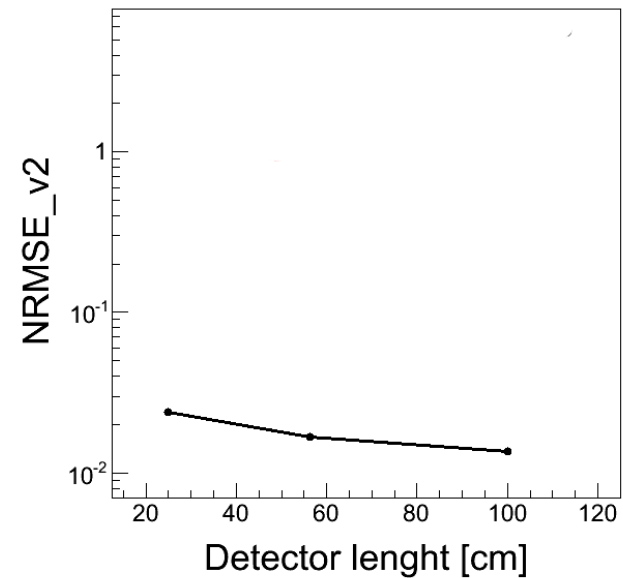
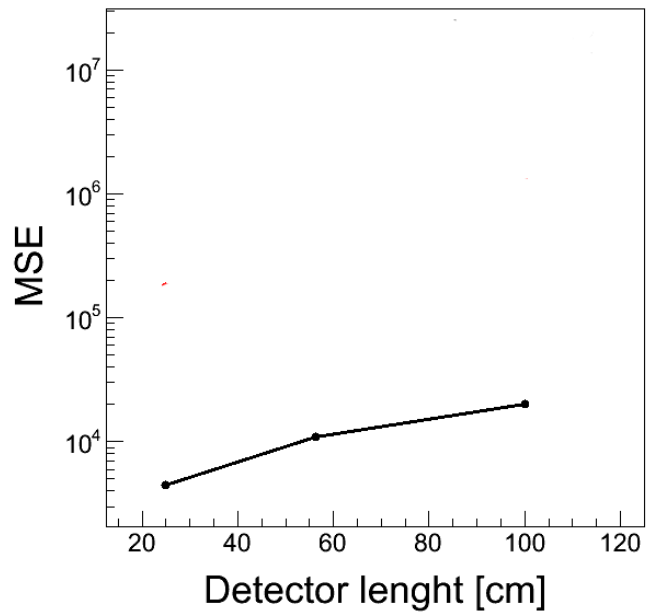


x



x

Different detector length ($L = 25, 50, 100$ cm)



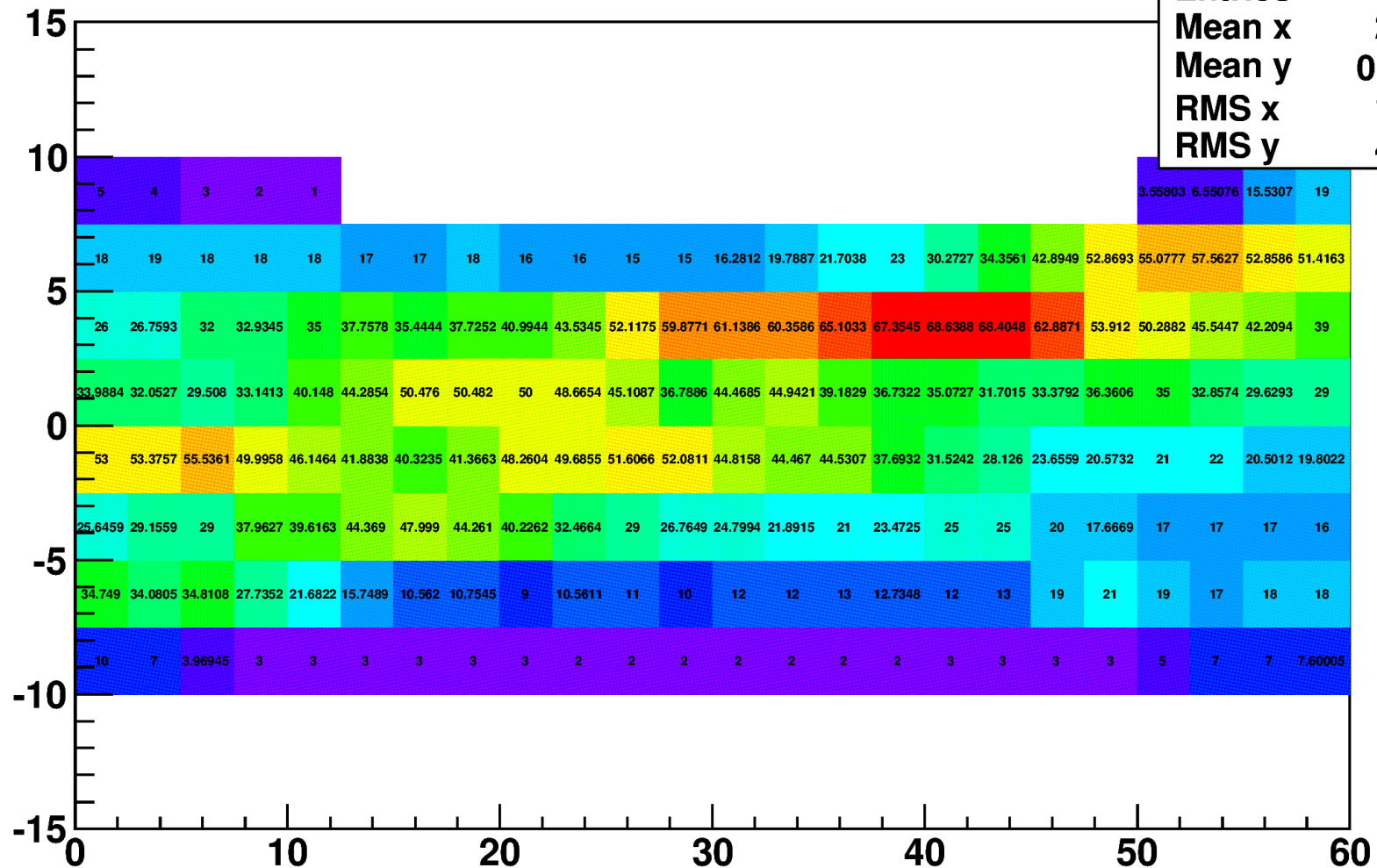
Outlook

- Using the developed software we can investigate the quality of the image reconstruction, changing:
 - dimensions of the scintillators
 - number of detectors
 - shape of the detectors
- We plan to repeat the studies using:
 - More complicated phantoms
 - Simple algorithms with TOF
 - MLEM algorithm (in cooperation with A. Słomski and Z. Rudy)
 - TOF resolution as an additional parameter

Very first „image reconstruction”

hRecoLines

| hRecoLines | |
|------------|--------|
| Entries | 5016 |
| Mean x | 29.95 |
| Mean y | 0.6115 |
| RMS x | 17.29 |
| RMS y | 4.045 |



Chosen phantoms

- Sphere (3cm radius)
- Sphere in a sphere (3 cm, 6 cm)
- Shepp-Logan phantom 2-D
- Shepp-Logan phantom 3-D version
- Two emitting points separated by a distance d