Depth-of-interaction enabled PET Model (doiPET example)

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doiPET example

- This example simulates depth-of-interaction (doi) enabled positron emission tomography (PET) scanner and standard NEMA* NU phantoms.
- The example can be executed in a multithreading mode
- Some realistic approaches of identifying crystal ID are presented.

- The default particle beam is ^{18}F ion at rest defined in the GPS (General particle Source)
- ^{18}F is the recommended isotope by the NEMA NU protocol

Various macro files are provided with the name appended on it for a specific simulation:

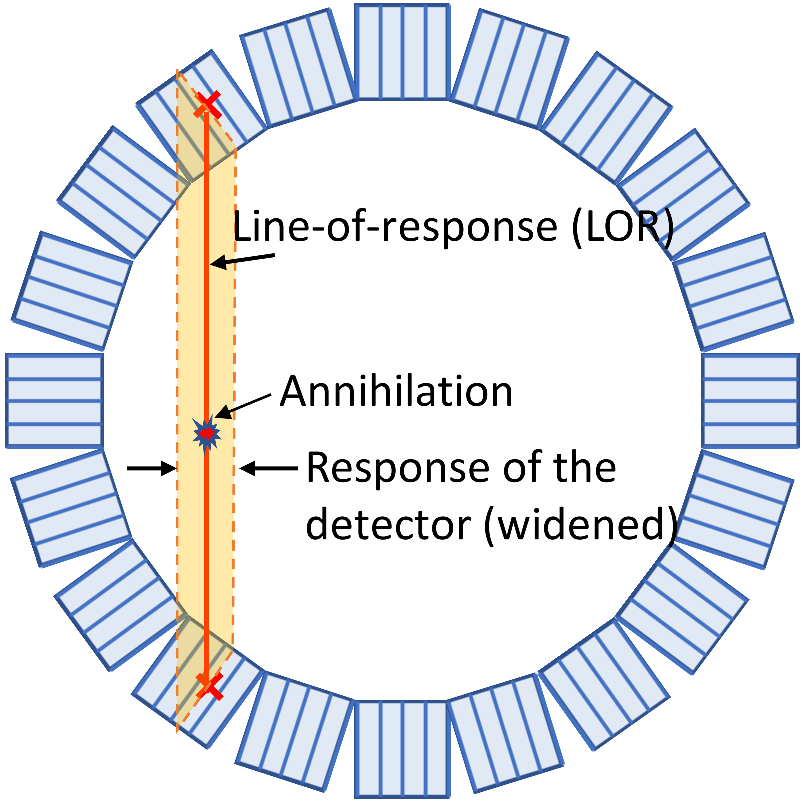
- ✓ run_imageQualityPhantom_wholeBody.mac
- ✓ run_imageQualityPhantom_smallAnimal.mac
- ✓ run_NECR.mac
- ✓ run_sensitivity.mac
- ✓ run_spatialResolution.mac
- ✓ run_normalization.mac (This is not given in the NEMA NU manual, but it is an important part of image reconstruction)

*NEMA - National Electrical Manufacturers Association

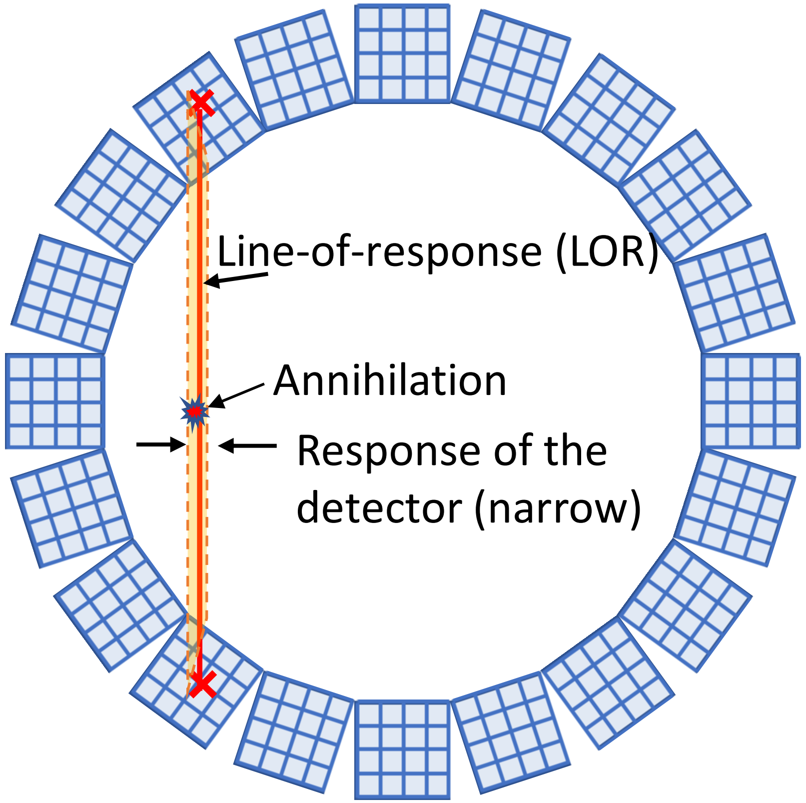
Why DOI PET scanner?

- It improves spatial resolution by reducing parallax error

With DOI PET, the spatial resolution away from the center of the FOV is preserved

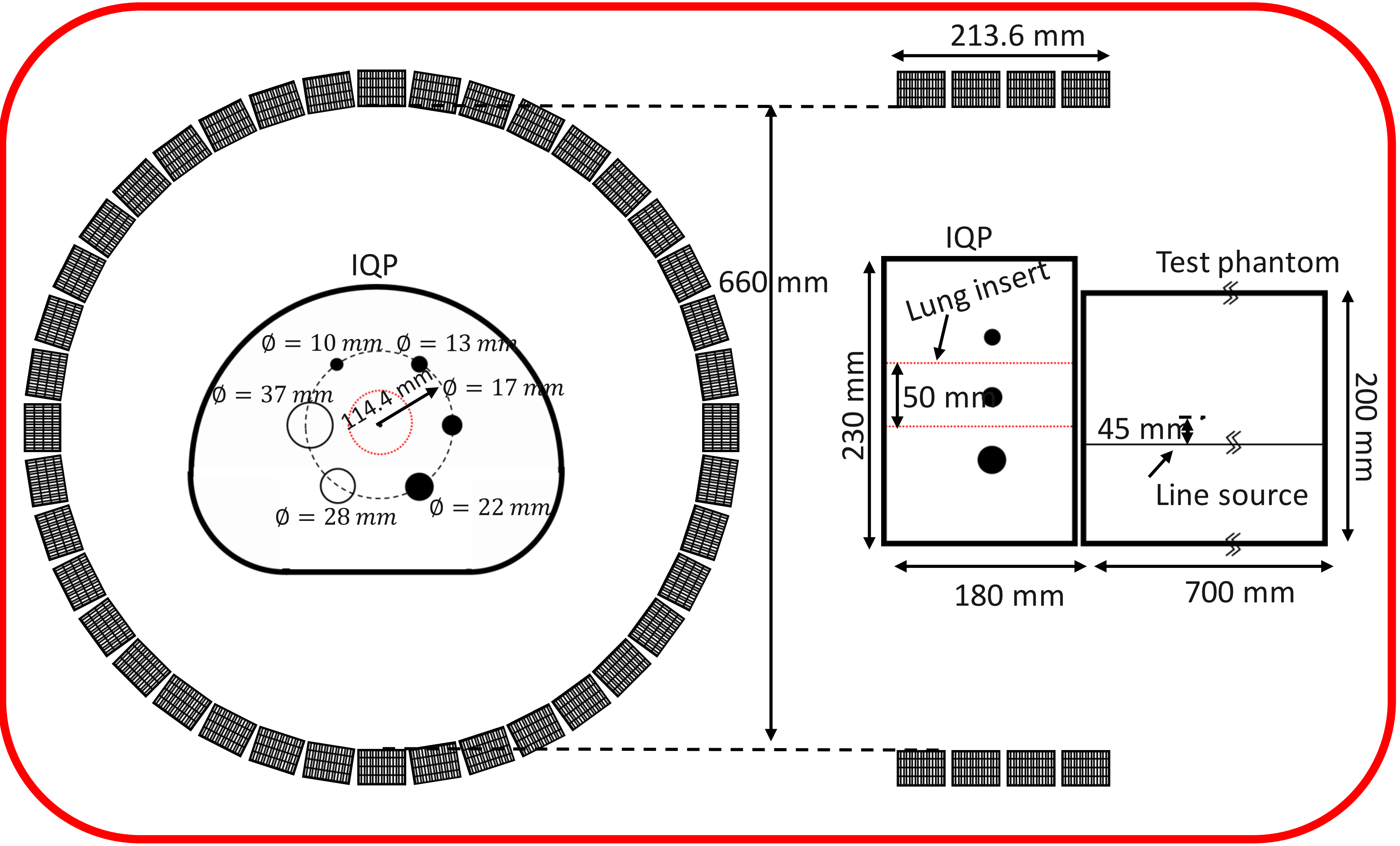


Non-DOI PET

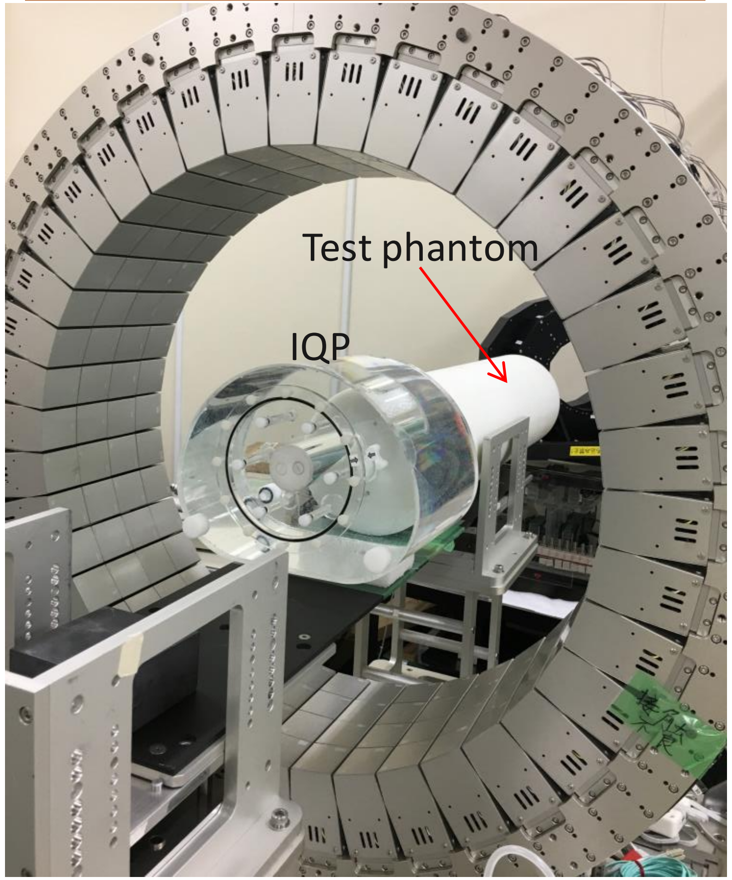


DOI PET

Geometry of the DOI PET Scanner



Physical PET scanner, NIRS Japan

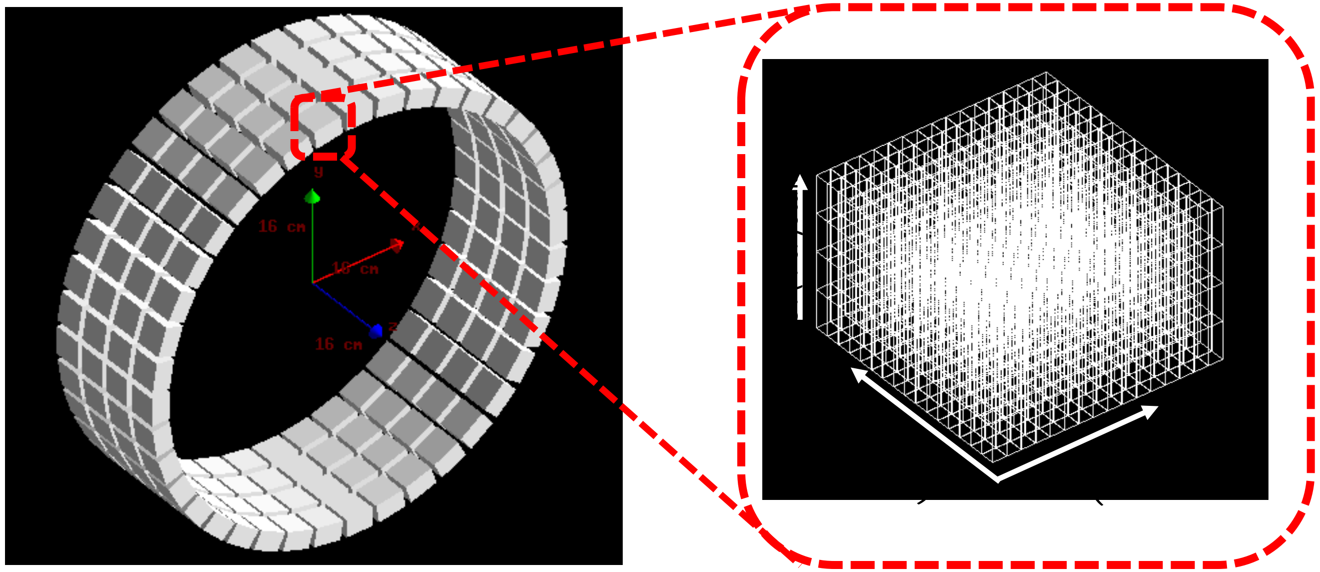


Geometry of the DOI PET Scanner

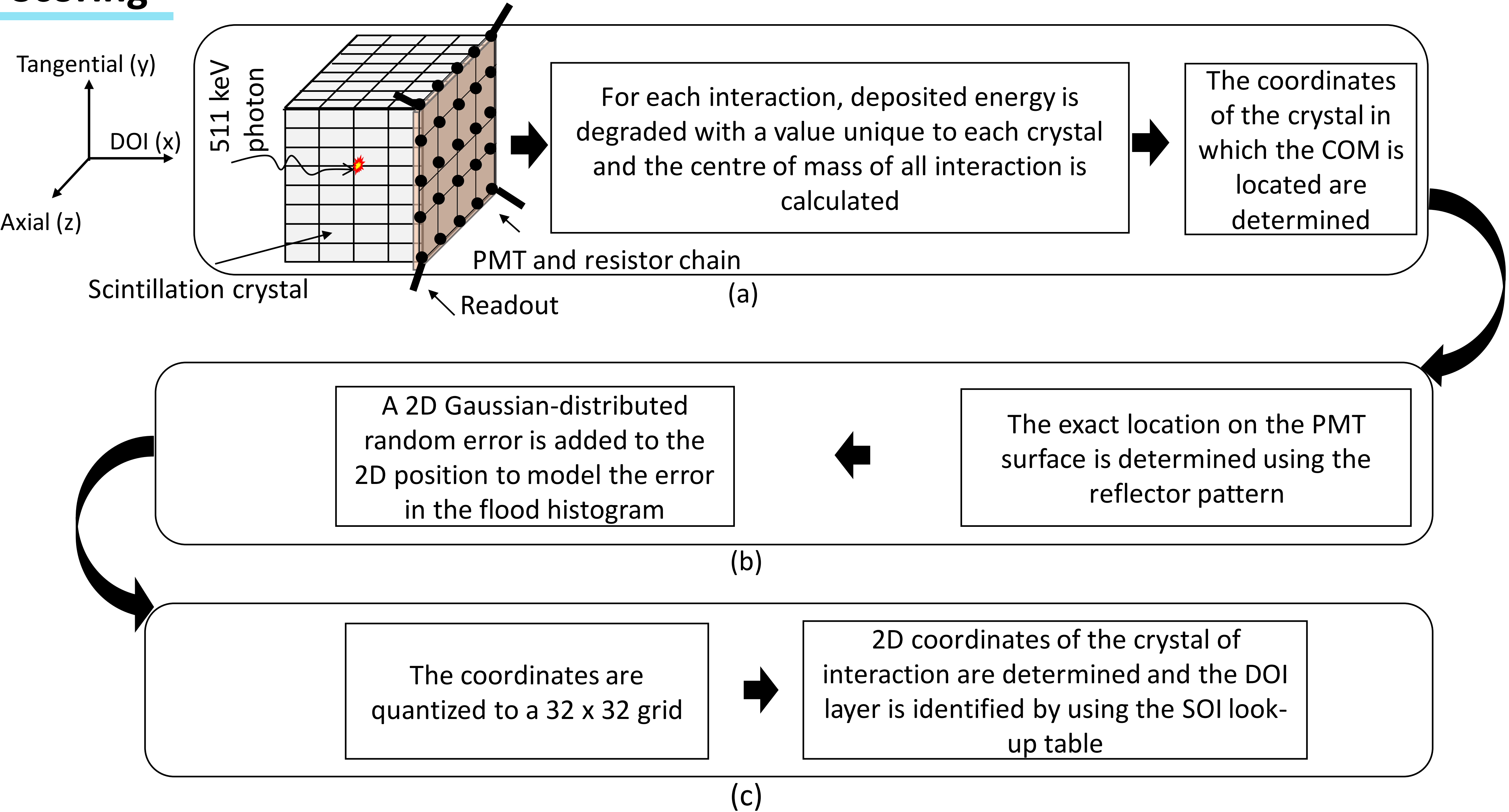
Scanner Specification	
Scintillation material	GSO (sim.), GSOZ(phys.)
Size of crystal	$2.8 \times 2.8 \times 7.5$ mm^3
Crystals per detector	$16 \times 16 \times 4$
Ring diameter	660 mm
Number of rings	4 (40 detectors per ring)
Coincidence time window	10 ns
Timing resolution	4.4 ns
Energy resolution*	Min: 13% and Max: 17%
Energy window	400 keV – 600 keV

*Crystal dependent energy resolution was applied

Each detector has 16x16x4 crystals

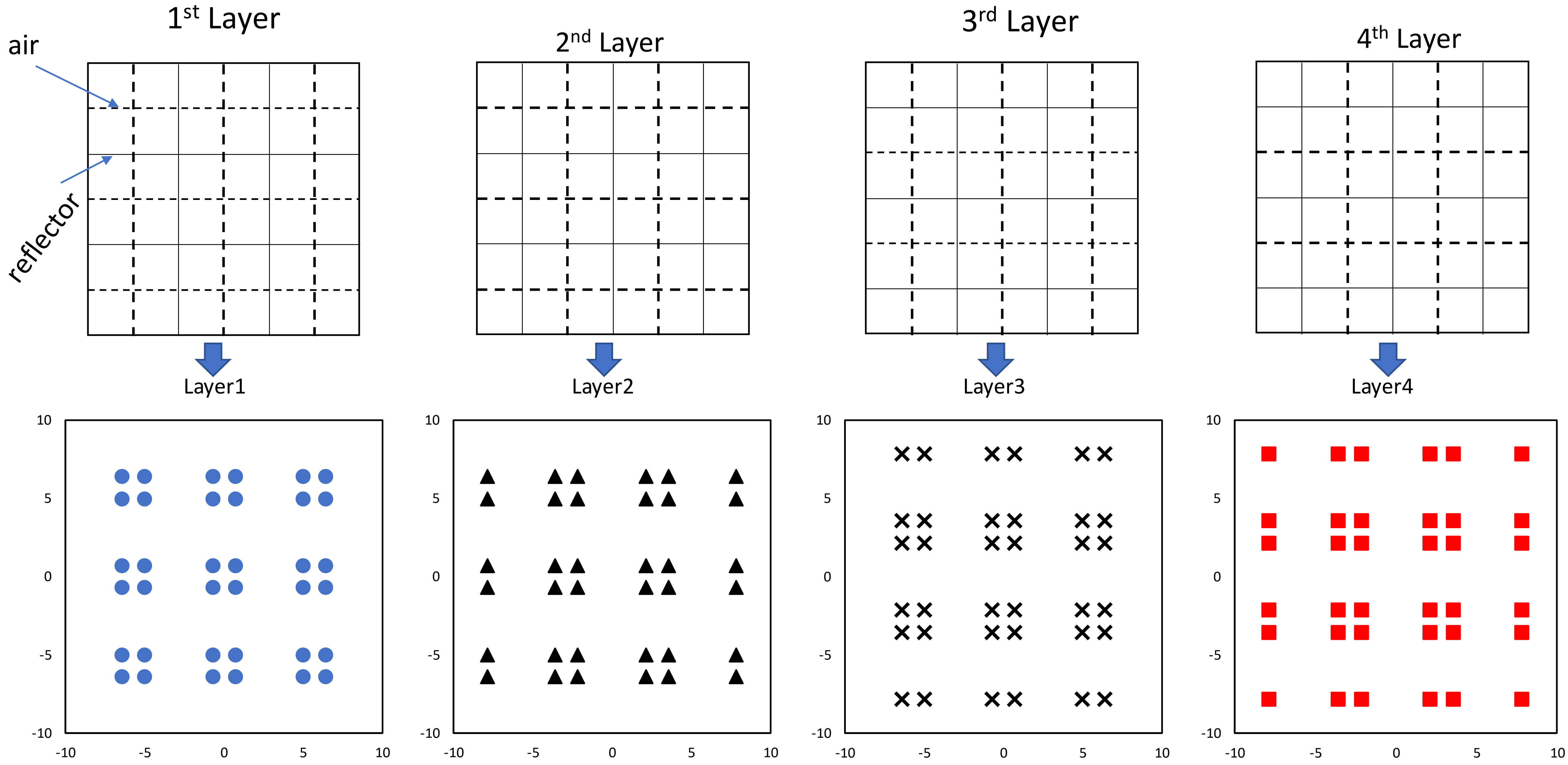


Scoring



Tangential (y)
DOI (x)
Axial (z)
511 keV photon
Scintillation crystal
Readout
PMT and resistor chain
For each interaction, deposited energy is degraded with a value unique to each crystal and the centre of mass of all interaction is calculated
The coordinates of the crystal in which the COM is located are determined
(a)
The exact location on the PMT surface is determined using the reflector pattern
A 2D Gaussian-distributed random error is added to the 2D position to model the error in the flood histogram
(b)
The coordinates are quantized to a 32 x 32 grid
2D coordinates of the crystal of interaction are determined and the DOI layer is identified by using the SOI look-up table
(c)

Reflector Pattern and Position Response

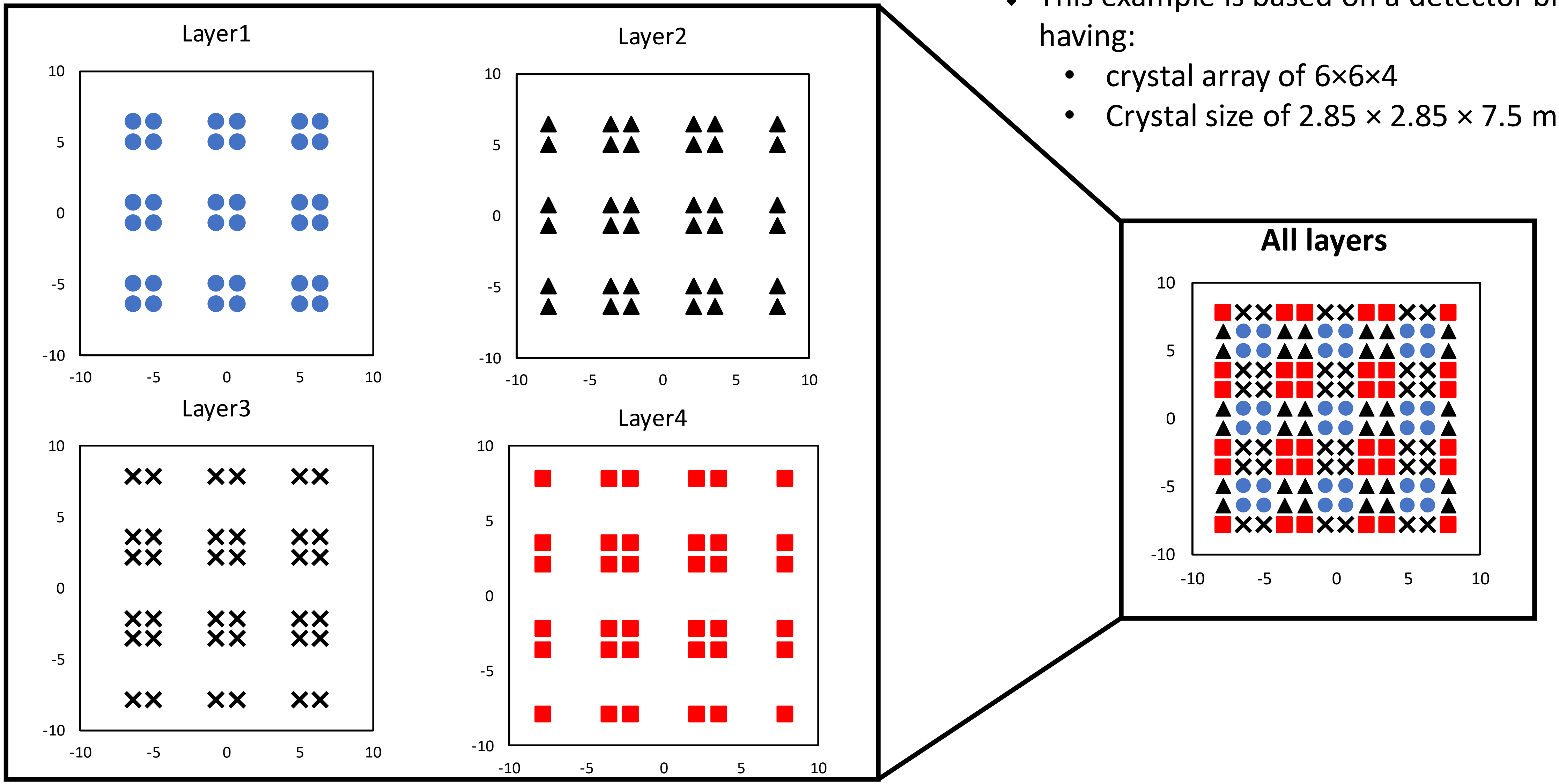


DOI identification

Superimpose all the responses to get the 2D position histogram of all the crystals

❖ This example is based on a detector block having:

- crystal array of 6×6×4
- Crystal size of 2.85 × 2.85 × 7.5 mm^3



Spatial Resolution

- Point like cylindrical sources ($\emptyset = h = 1\ mm$)

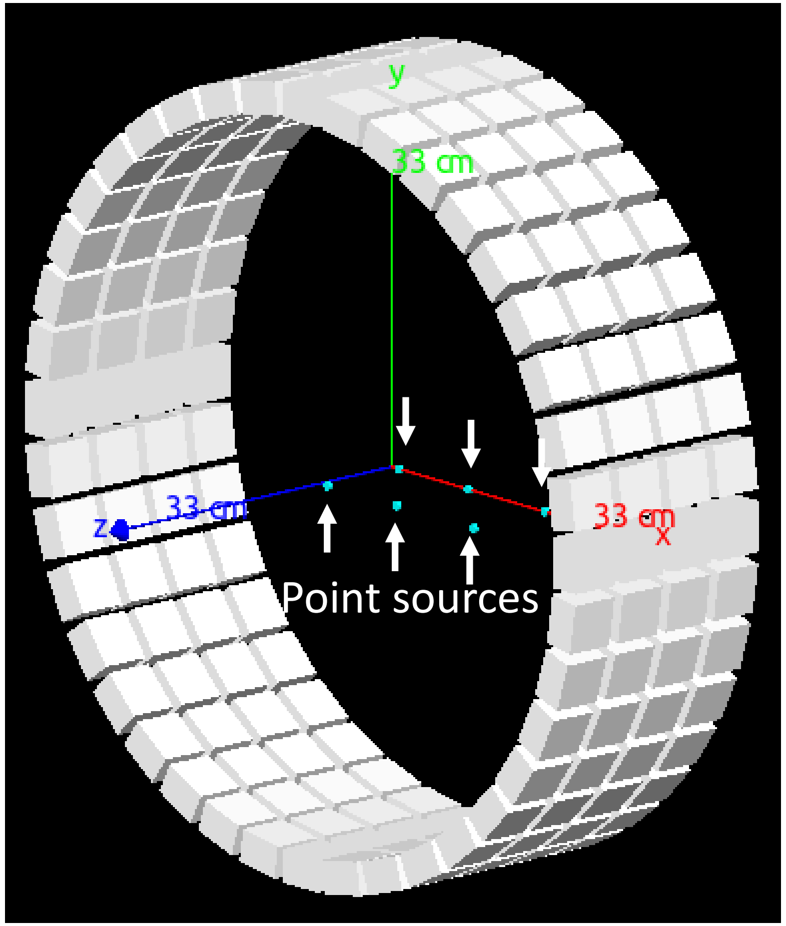


Image reconstruction parameters

- Rebinning: FORE
- FBP
  - ✓ Voxel size: $1 \times 1 \times 1$ mm^3
  - ✓ Number of voxel: $500 \times 500 \times 200$

Dimension	Offset (mm)	Sim	Phys.	Difference (%)
Radial	10	4.0	4.1	2.8
	100	5.1	4.8	-7.2
	200	6.4	5.9	8.8
Tangential	10	4.0	4.8	+16.3
	100	4.1	4.7	+13.7
	200	4.6	4.8	+4.0
Axial	10	5.9	6.5	+9.6
	100	5.1	5.7	+9.7
	200	5.4	5.8	+6.0

Sensitivity

Sensitivity phantom

- Five concentric aluminum tubes with 700 mm in length and different thicknesses were simulated

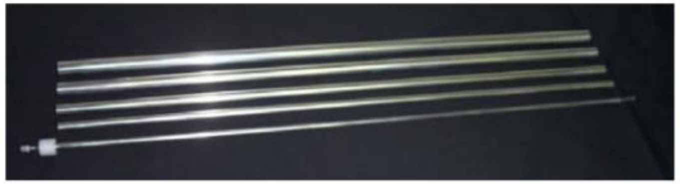
NEMA PET Sensitivity Phantom™
Model PET/NEMA-SEN/P

- 6 Concentric aluminum tubes used to detect camera sensitivity in PET

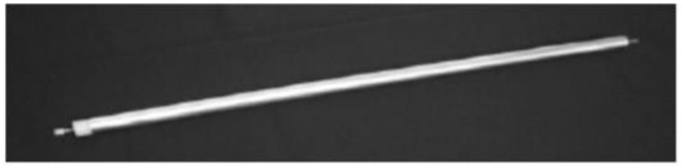
Specifications:
5 internally stacked aluminum tubes all 700 mm in length
1st Tube inside diameter 3.9 mm, outside diameter 6.4 mm
2nd Tube inside diameter 7.0 mm, outside diameter 9.5 mm
3rd Tube inside diameter 10.2 mm, outside diameter 12.7
4th Tube inside diameter 13.4 mm, outside diameter 15.9
5th Tube inside diameter 16.6 mm, outside diameter 19.1
The innermost tube, a fillable polyethylene tubing has an inside diameter of 1 mm, outside diameter 3 mm

* *Performance Measurements of Scintillation Cameras*, NEMA Standards Publication No. NU2, National Electrical Manufacturers Association (NEMA), Washington, D.C., 2001

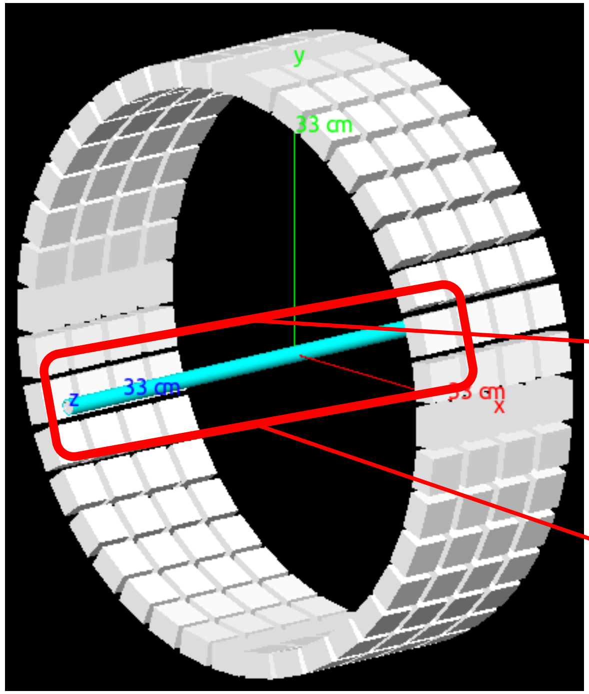
Close up end of NEMA PET Sensitivity Phantom™

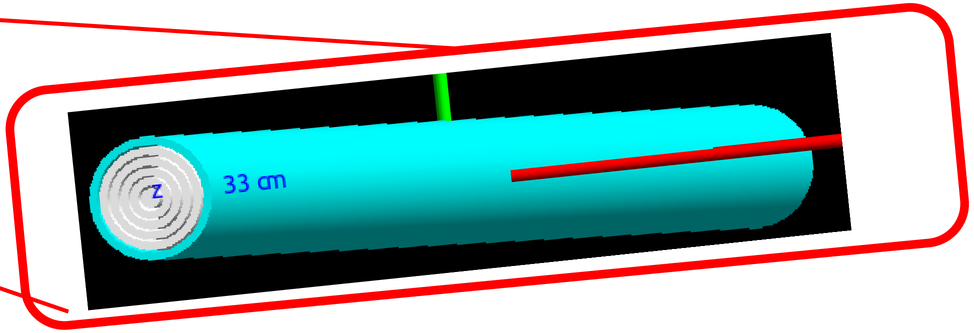


Set of aluminum tubes used in NEMA PET Sensitivity Phantom™

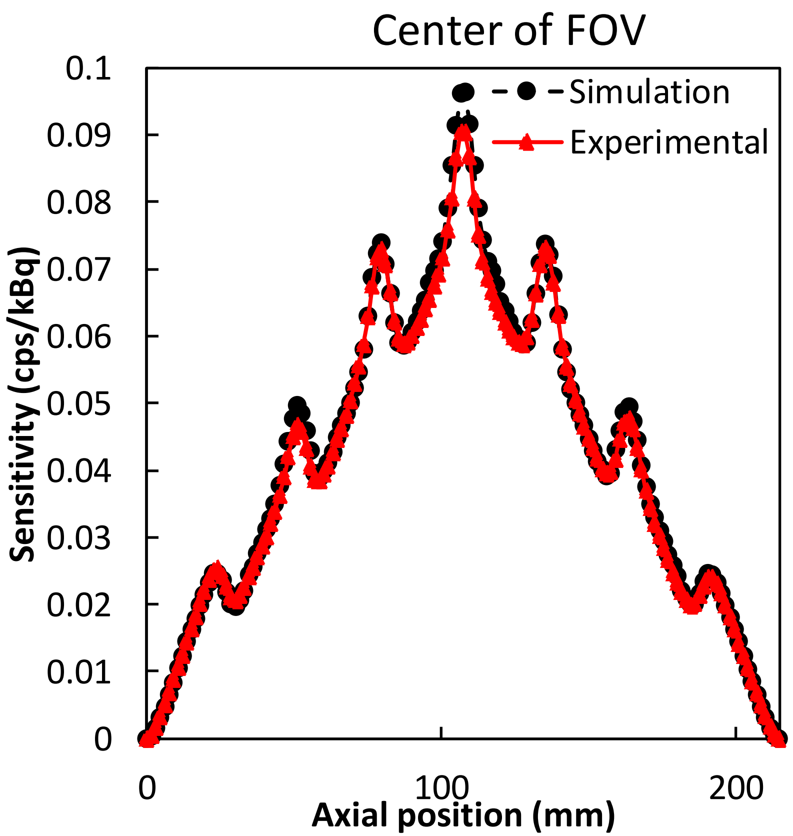


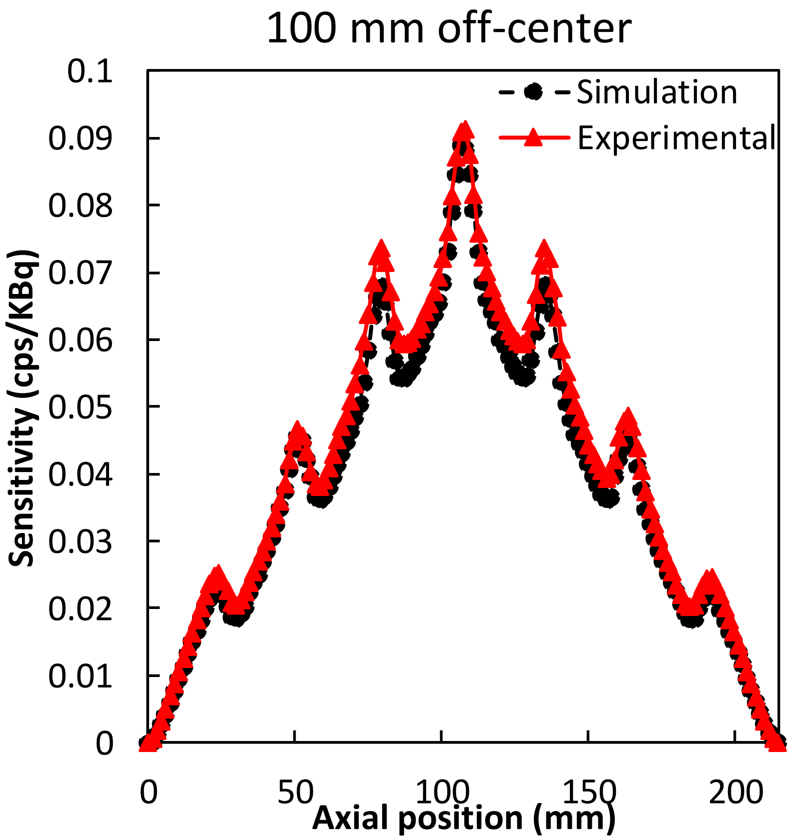
NEMA Sensitivity PET Phantom™





Sensitivity

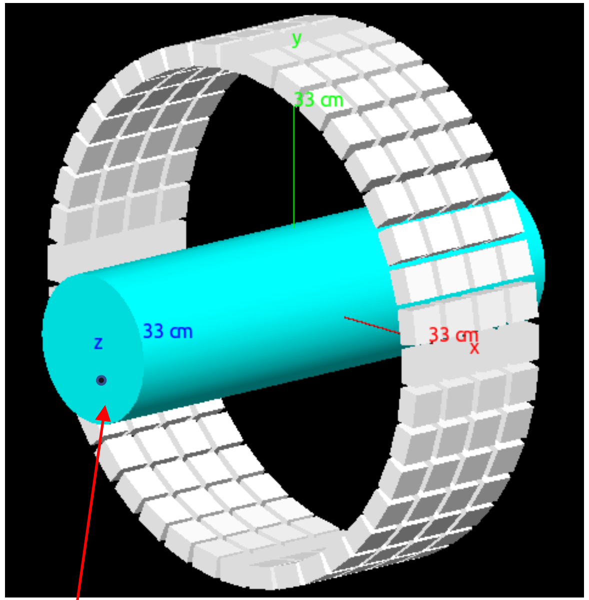




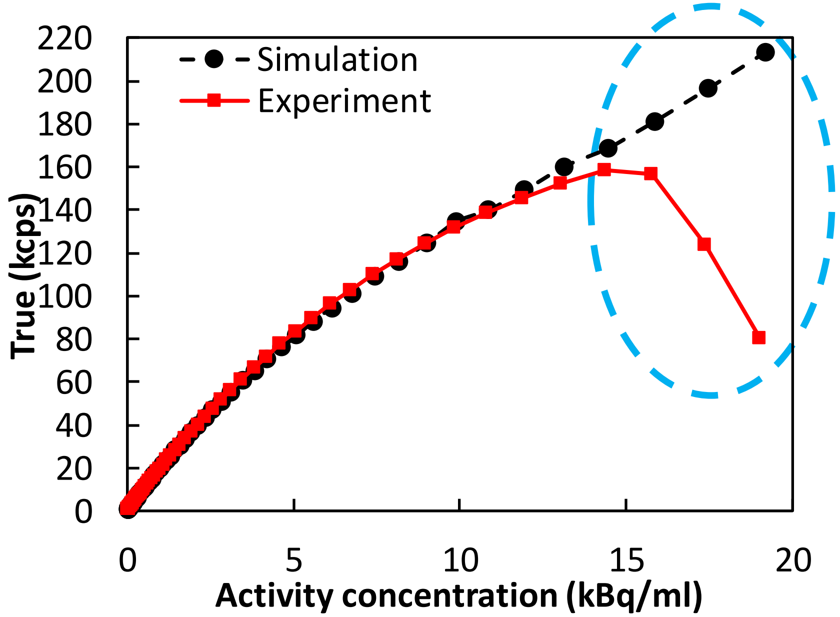
Sensitivity (cps/kBq)			
	Experiment	Simulation	Error (%)
Center of FOV	5.9	6.2	5.1
At 10 cm off-center	5.9	5.7	3.4

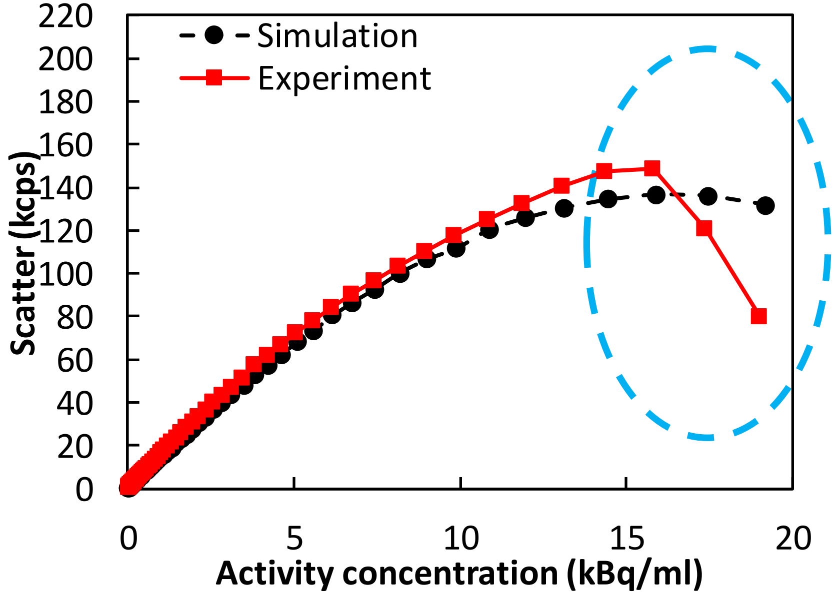
Count Rates

Count rate phantom
Cylindrical phantom (PMMA)
Length: 700 mm
Diameter: 200 mm



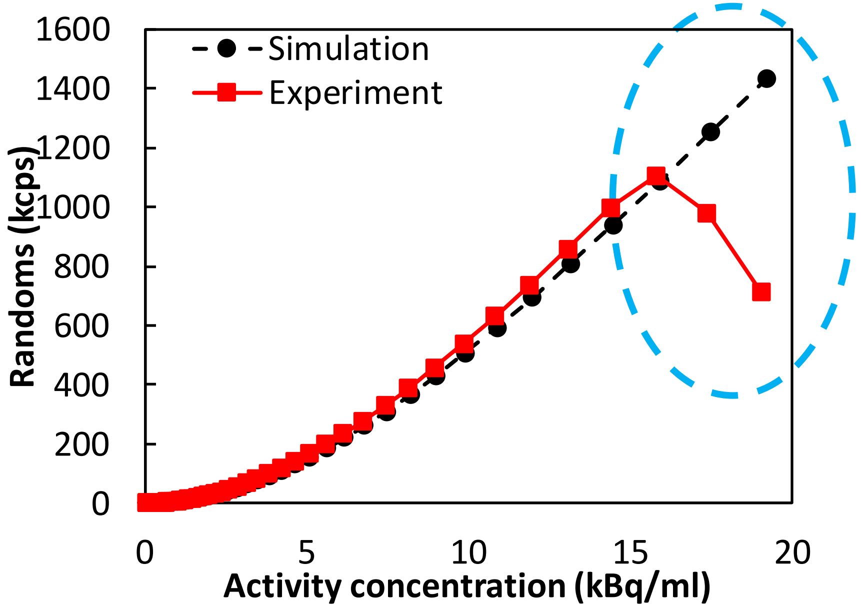
Line source is place at 45 mm off-center

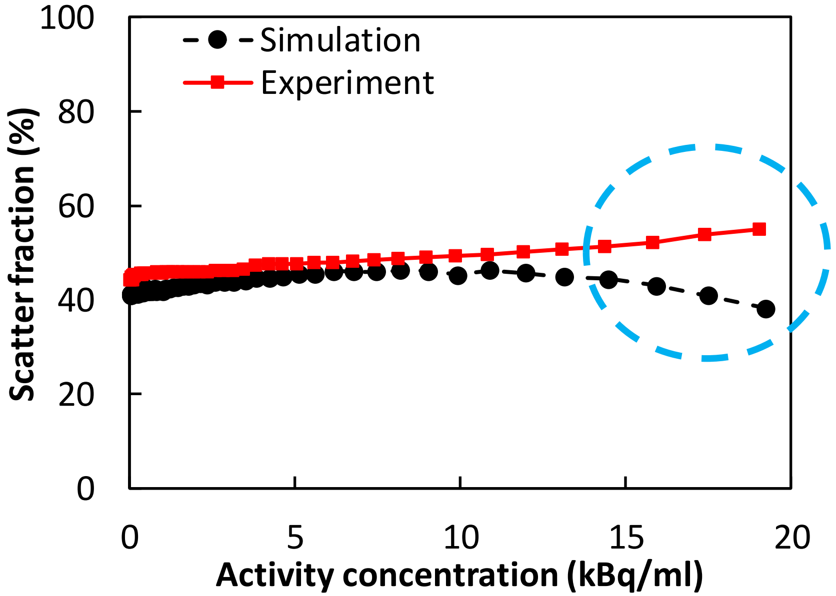




➢ Except at high activities, a very good agreement was obtained

Count Rates





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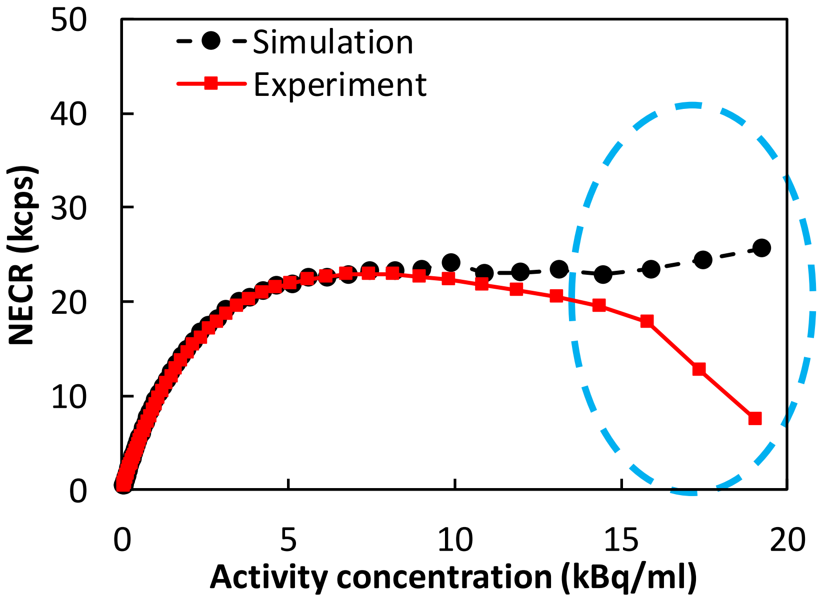


	Expt	Sim
SF at peak	48.4%	47.8 %
SF at low activity (at 0.04 kBq/ml)	44%	42%

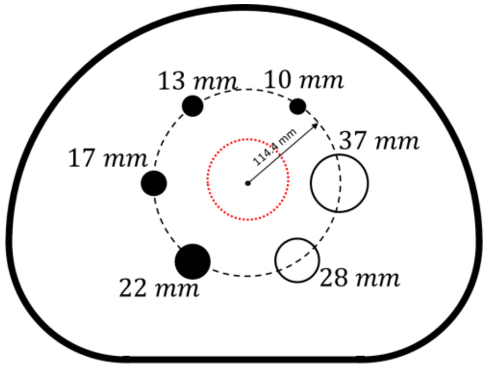
Peak NECR at 7.45 kBq/ml
Exp: 22.9 kcps
Sim: 23.3 kcps (Do not peak at a specific activity)

Image Quality Phantom (IQP): whole body

- To precisely create the image quality phantom, the G4UnionSolid from the Constructive Solid Geometry (CSG) has been used.

Image reconstruction parameters	
Reconstruction algorithm	3D OSEM
Voxel size	3 × 3 × 3 mm^3
Number of voxels	125× 125 × 150
Ray tracing method	Simple Gaussian
Corrections	Attenuation, normalisation, scatter

IQP for Whole body



Reconstructed images of the IQP phantom

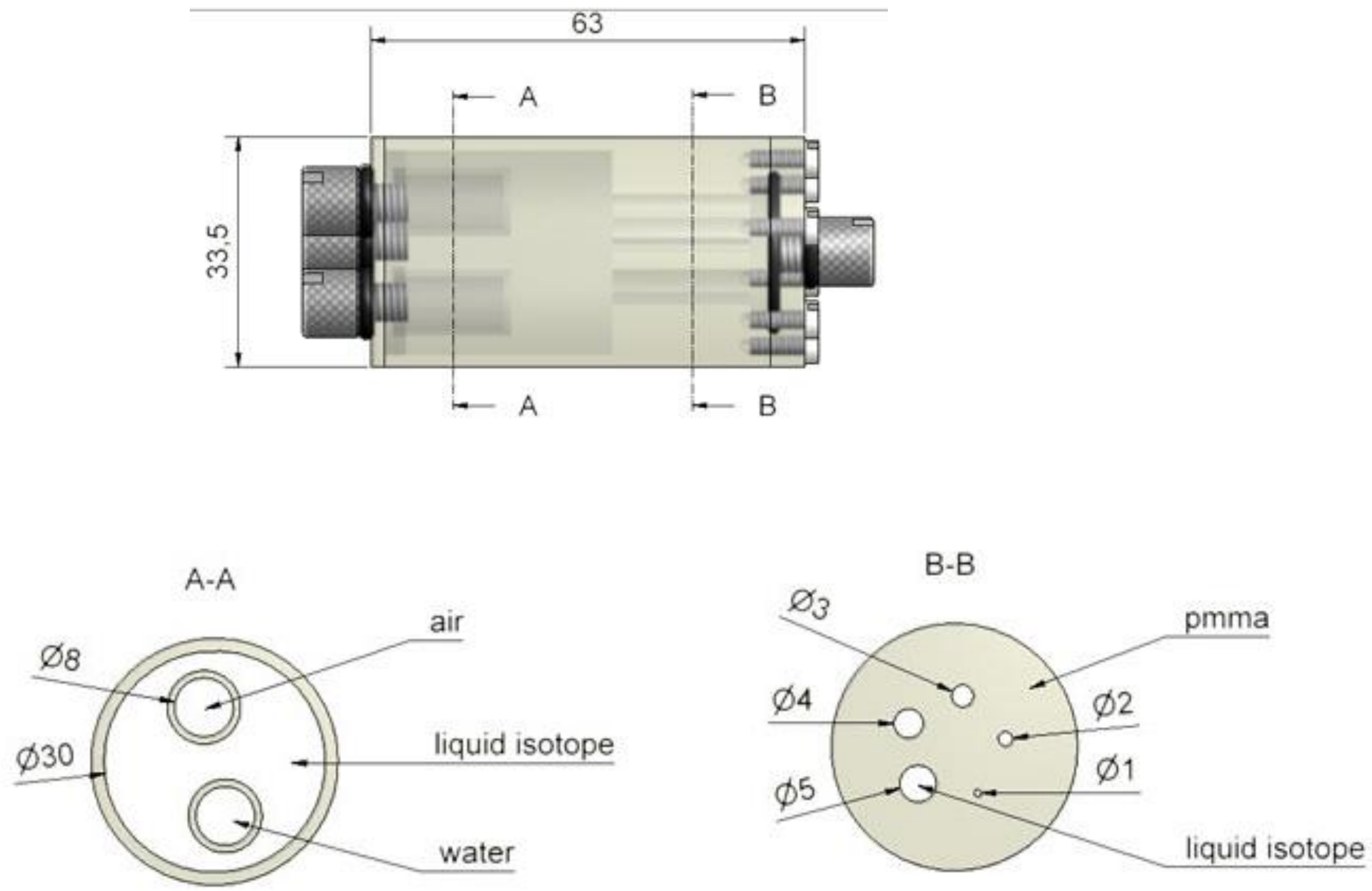
Experiment

Simulation

ROI Φ (mm)	Contrast (%)		Background variability (%)	
	Sim.	Phys.	Sim.	Phys.
10(h)	16.0	20.7	5.4	9.2
13(h)	27.2	31.1	5.1	8.9
17(h)	37.9	40.6	4.7	8.4
22(h)	46.4	43.3	4.2	7.9
28 (c)	34.2	33.2	3.9	7.4
37 (c)	41.4	39.9	3.6	7.0

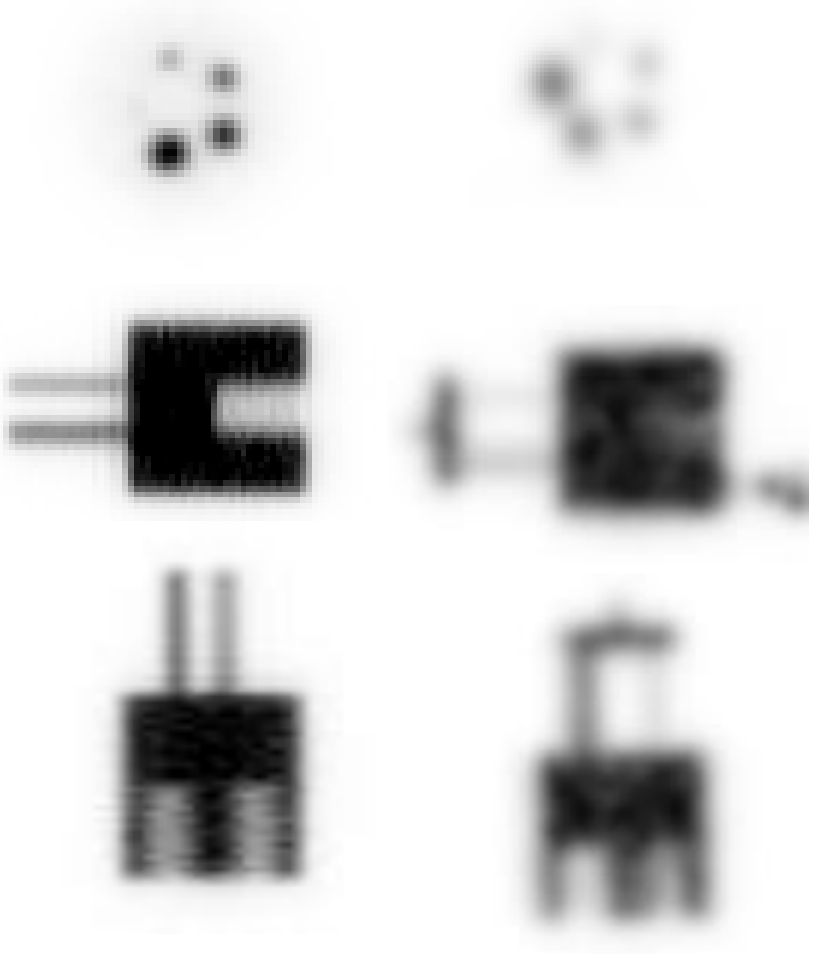
Image Quality Phantom (IQP): Small Animal

Detail of the phantom is found:
Quality assurance in radiology and medicine (http://www.qrm.de/)



Reconstructed images

Simulation | Experimental



Conclusion

- The doiPET Geant4 model was validated against experimental results
- All the NEMA NU 2 standard phantoms were included
- The results show an excellent agreement between the sim. and expt.
- The discrepancies were:
  - 4.3% in sensitivity
  - 5.1% in spatial resolution
  - 1.8% in NECR
  - 8.7% in contrast recover for hot regions, and 3.4% for cold regions

Almost all the key metrics showed a very good agreement between the simulation and the experimental results