Estimating the NEMA characteristics of the J-PET tomograph using the GATE package

Paweł Kowalski
pawel.kowalski@ncbj.gov.pl

National Centre for Nuclear Research
Świerk Computing Centre
3rd Symposium on Positron Emission Tomography

10th September 2018

Contents

1. Introduction
   - NEMA and GATE
   - Simulated geometries
   - 2-level data selection method
2. Sensitivity
3. Spatial Resolution
4. Scatter Fraction and NECR
   - Scatter Fraction
   - NECR
5. Summary
   - Conclusions
   - Comparison to commercial PET scanners

Introduction: NEMA and GATE

NEMA - National Electrical Manufacturers Association

Ther norm NEMA-NU-2 defines following performance characteristics:

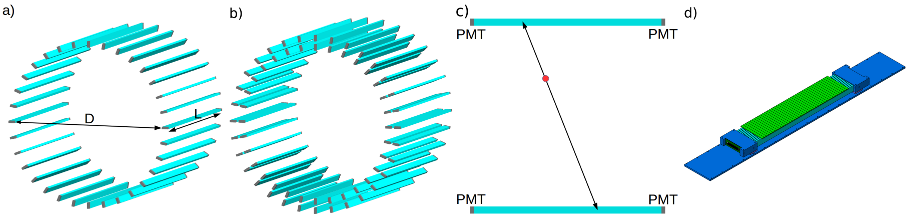
- **Sensitivity**
- **Spatial Resolution**
- **Scatter Fraction** and **NECR**
- Image Quality

GATE – GEANT4 Application for Tomographic Emission

Simulations were performed at CIŚ cluster (National Centre for Nuclear Research, Świerk Computing Centre).

Introduction: Simulated geometries

J-PET - Jagiellonian PET



Layers
1
2

x

Thickness
4 mm
7 mm

x

L [cm]
20
50
100

x

D [cm]
75
85
95

x

Readout
PMT
SiPM
SiPM+WLS

Figure: Configurations of simulated detecting systems which may differ with number of layers of the detector and their diameters (D), thickness and length of the scintilator strips (L) and type of readout

Introduction: 2-level data selection method 1/4

1st level: Coincidence defintion

- time window 3 ns
- exactly 2 scatterings with deposited energy bigger than fixed energy threshold equal to 200 keV
- any number of scatterings with deposited energy bigger than noise threshold equal to 10 keV

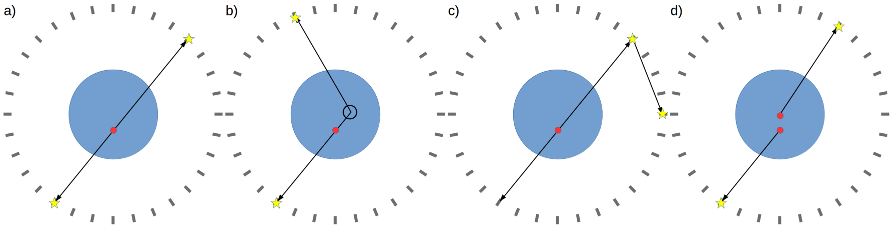


Figure: Different types of coincidences: a) true, b) phantom-scattered, c) detector-scattered, d) accidental

Introduction: 2-level data selection method 2/4

2nd level: Selection based on times and angles differences between subsequent hits in the coincidence

- $\Delta angle$ = central angle between places of scatterings
- $\Delta time = |t1 - t2|$

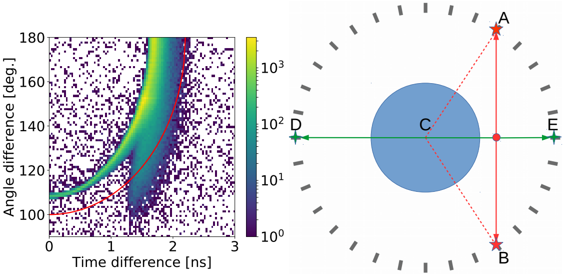


Figure: (left) simulation of the rod source placed in the radial distance of 25 cm from the axial of the scanner; the scatter fraction phantom was placed in the centre of the scanner; true coincidences are placed over the red line; (right) angles differences for extreme cases

Introduction to NEMA characteristics: 2-level data selection method 3/4

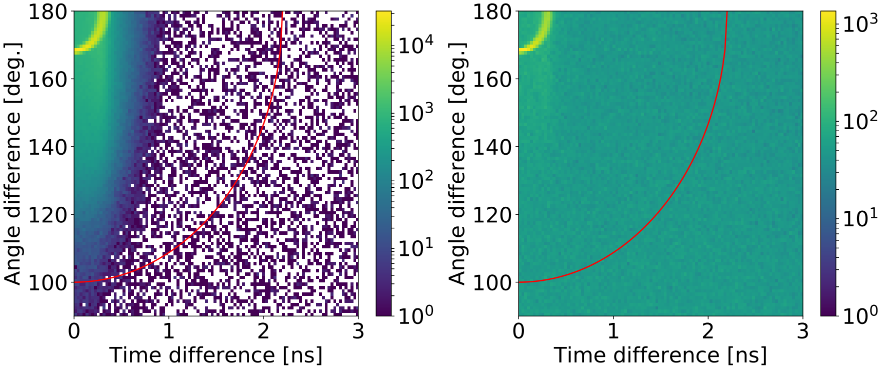


Figure: Results of the 2nd level selection for example simulations for 2 activities 1 MBq and 2000 MBq

Introduction: 2-level data selection method 4/4

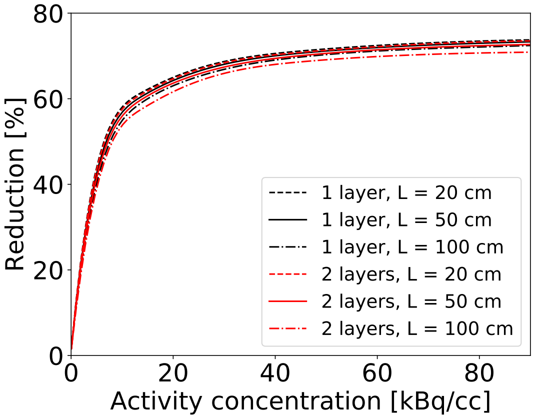


Figure: Reduction of events (2nd level selection) in function of activity concentration for NECR simulations

Sensitivity: Definitions

Sensitivity of a positron emission tomograph is expressed as the rate in counts per second that true coincidence events are detected for a given source strength.

Then Sensitivity may be calculated as:
Sensitivity = T/time/activity

In measurements, the material surrounding the source, attenuates created gamma rays, prohibiting a measurement without interfering attenuation. To arrive at an attenuation free measurement, successive measurements are made with a uniform line source surrounded by known absorbers. From these measurements, the sensitivity with no absorber can be extrapolated.

In simulations, we can obtain sensitivity with no absorber directly, without simulating tube phantoms.

We can use simple linear source with length 70 cm in the centre of the AFOV.

Sensitivity: Results

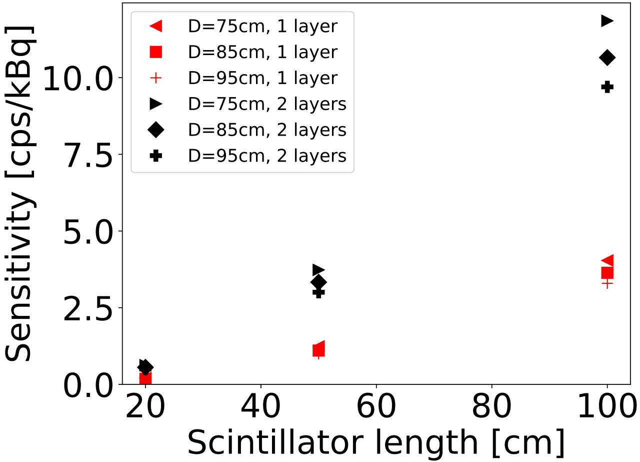


Figure: Sensitivities for 18 simulated geometries (thickness = 7 mm)

Sensitivity: Results

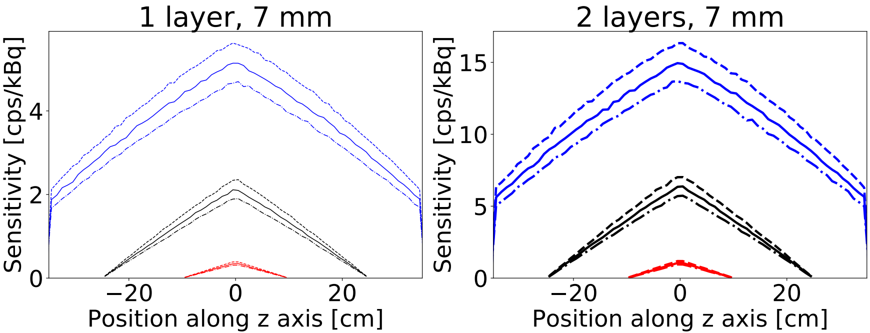


Figure: Sensitivity profiles grouped by the number of layers; legend: D = 75 cm (- -), D = 85 cm (-), D = 95 cm (-.-), 1 layer (thin lines), 2 layers (thick lines), L = 20 cm (red), L = 50 cm (black), L = 100 cm (blue)

Spatial Resolution: Definitions

Spatial resolution is an ability of the system to distinguish between two points after image reconstruction

Algoritm of obtaining the Spatial Resolution:

1. point source of gamma photons is located at 6 points inside the Axial Field of View of the system
2. at least 100.000 prompt counts is acquired in each position
3. image reconstruction is performed for each of locations (algorithm of reconstruction should be Filtered Back Projection (FBP))
4. FWHM is calculated for 1D profiles crossing voxel of the reconstructed image in all three dimensions for each position of the source

Spatial Resolution: Definitions

STIR - Software for Tomographic Image Reconstruction

STIR is Open Source software for use in tomographic imaging. Its aim is to provide a Multi-Platform Object-Oriented framework for all data manipulations in tomographic imaging. Currently, the emphasis is on (iterative) image reconstruction in PET and SPECT, but other application areas and imaging modalities can and might be added.

http://stir.sourceforge.net/

Spatial Resolution: Results

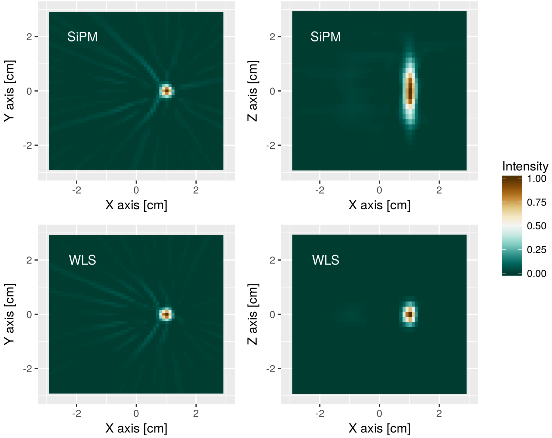


Figure: Reconstruction of the point source placed in position of (1,0,0) cm for 2 types of readout: SiPM and WLS (L = 50 cm, thickness = 4 mm) [reconstruction performed by R. Shopa using the STIR software]

Spatial Resolution: Results

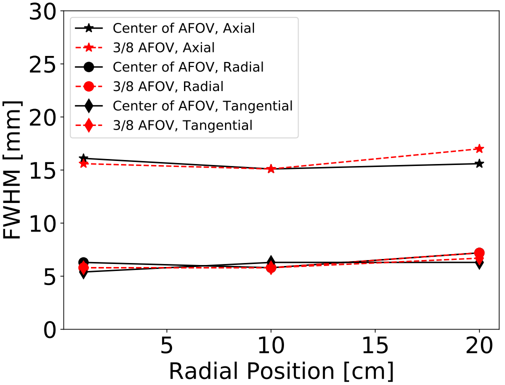


Figure: Spatial resolution in three directions - the radial, tangential and axial. The geometry was fixed to the single layer chamber with the diameter of 85 cm and strips with length of 50 cm and thickness 7 mm. Silicon photomultipliers (SiPM) were used as photodetectors.

Spatial Resolution: Results

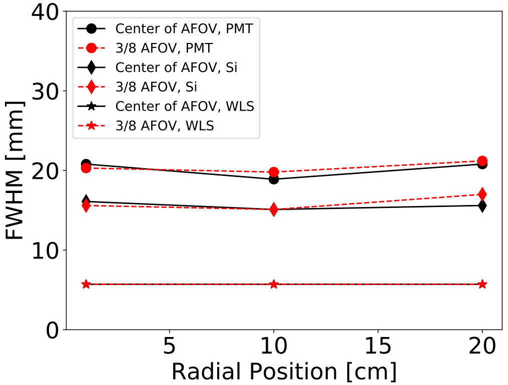


Figure: Axial resolution for different types of detectors attached to scintillator strips and two axial positions as a function of radial position of the source. Presented results were obtained for the single-layer geometry with the diameter of 85 cm and strips with length of 50 cm and thickness 7 mm.

Spatial Resolution: Results

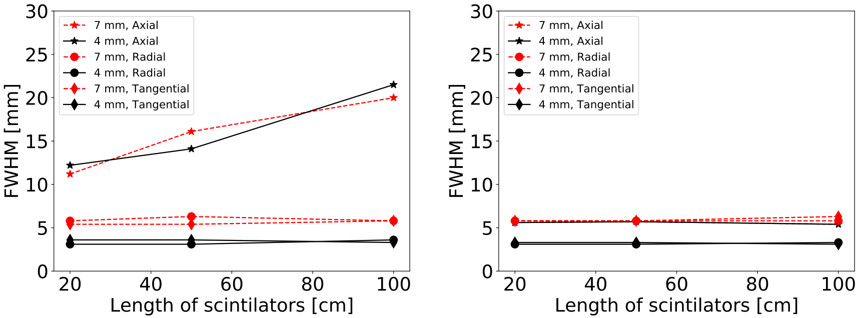


Figure: Spatial resolution for 3 lengths and 2 thicknesses of scintillator strips for silicon photomultipliers (left) and silicon photomultipliers with the WLS strips (right).

Scatter Fraction: Definitons

Scatter Fraction is a dimensionless ratio of scattered coincidence events to the sum of scattered and true coincidence events in a defined region of interest in the scanner's field of view (definition from the NEMA norm)

$$\mathbf{SF = S/(S+T)}$$

S – number of scattered coincidences
T – number of true coincidences

Scatter Fraction: Definitons

In the J-PET scanner there are not only coincidences scattered in the phantom but also scattered in the scintillating strips.

Types of coincidences:

1. true – true coincidence
2. psca – phantom-scattered coincidence
3. dsca – detector-scattered coincidence
4. acci – accidental coincidence

$SF_1 = \mathbf{psca/(true{+}psca)}$
$SF_2 = \mathbf{(psca{+}dsca)/(true{+}psca{+}dsca)}$

Previous studies show that if we use presented definition of the coincidence (2 hits with energies over the energy threshold equal to 200 keV), then the difference between SF_1 and SF_2 is negligible.

Scatter Fraction: Definitons

Details of measurements from the NEMA norm:

1. Phantom – solid cylinder composed of polyethylene with a gravity 0.96+-0.01, outside diameter 203+-3 mm, length 700+-5 mm; hole with diameter 6.4 mm is drilled parallel to the central axis of the cylinder at a radial distance of 45 mm
2. Source – line source; polyethylene tube with diameter 4.8 mm filled with a known activity
3. Data collection – 500.000 counts
4. Data processing using analysis of sinograms

Figure: Scatter Fraction phantom

Scatter Fraction: Definitons

Algoritm of obtaining the Scatter Fraction:

1. Space inside the J-PET detector is divided into N virtual slices (conventional scanners have natural physical slices that come from sizes of the scintillating crystals)
2. Oblique sinograms (N^2) are obained for all combinations between each pair of virtual slices
3. Single Slice Rebinning (SSRB) algorithm is used to obtain 2N-1 rebinned sinograms
4. All rebinned sinogram are summed
5. For the summed sinogram all projections are aligned to put maximum values at zero and they are summed
6. After summing, values of obtained profile at distances $\pm$ 2 mm from zero are calculated
7. The area of the profile over tle line crossing two points at $\pm$ 2 mm is treated as true coincidences, below this line as scattered coincidences

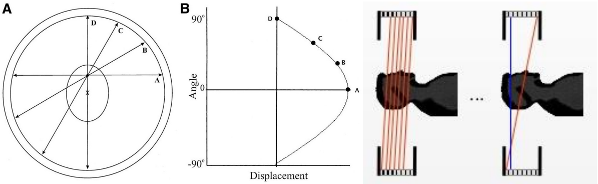


Figure: (left) pictorial definition of sinogram; (right) oblique [red] and normal [blue] sinograms

Scatter Fraction: Results

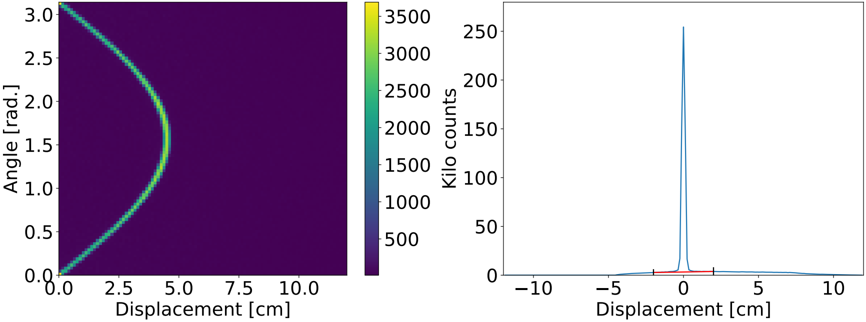


Figure: (left) sinogram for geometry with 50 cm strips and activity equal to 1 MBq; (right) alligned to zero (for each projection = sinogram row) and summed sinogram; true coincidences are over the red line while scattered below

Scatter Fraction: Results

Nr of layers	L = 20 cm	L = 50 cm	L = 100 cm
1	36.0%	35.8%	34.8%
2	35.1%	35.6%	34.7%

Figure: Scatter fraction for six geometries calculated using sinograms analysis

Nr of layers	L = 20 cm	L = 50 cm	L = 100 cm
1	49.1%	49.1%	47.6%
2	51.1%	51.2%	50.1%

Figure: Scatter fraction for six geometries calculated using true Monte Carlo

NECR: Definitions

Noise Equivalent Count Rate (NECR) - the purpose is to measure the effects of the generation of random events at several levels of source activity

$\mathrm{NECR} = T^2/(T + S + R)$

T – true coincidences
S – scattered coincidences
R – random (accidental) coincidences

Method:

- similar to method of obtaining SF
- the difference: coincidences treated in SF algorithm as scattered here contain also random coincidences

NECR: Results

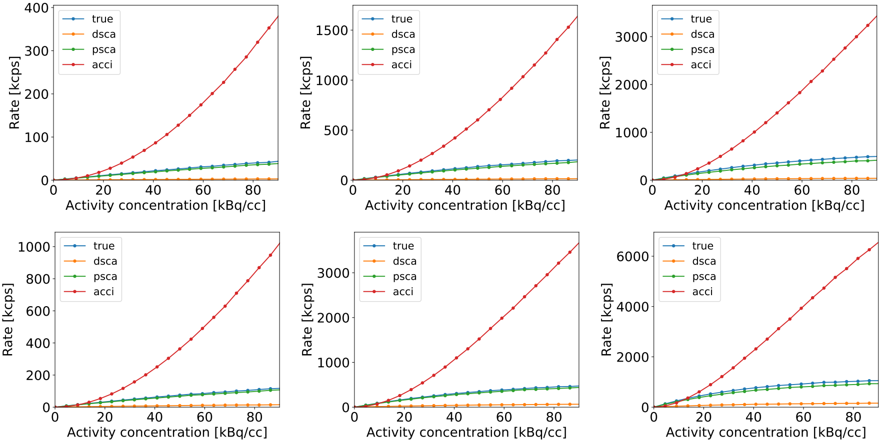


Figure: In first row there are rates for single layer geometries while in second row for 2-layer geometries; in first column there are rates for L=20cm, next for L=50cm and L=100cm (true Monte Carlo)

NECR: Results

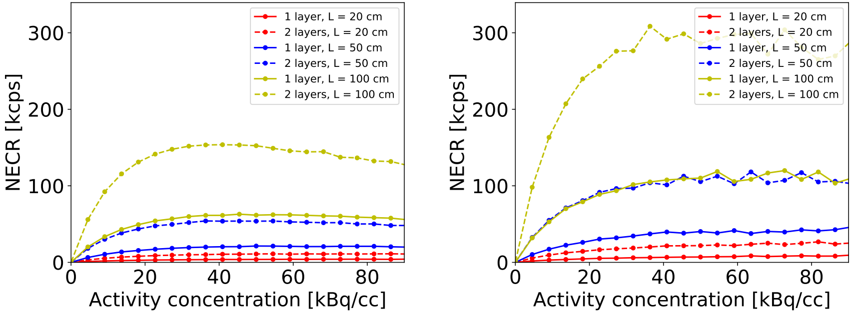


Figure: NECR calculated using two methods: (left) using true MC method and (right) using the method specified in the NEMA norm (sinograms analysis). Difference between the method based on sinograms analysis and true MC method is caused by the usage of the NEMA defined radial cut at 12 cm from the axis of the scanner [Yang, 2015].

The NECR peak shows the optimal activity concentration, for which, there is the best ratio between the true and false coincidences.

Summary: Conclusions

- The best spatial resolutions were obtained for the 4 mm thick strips and the SiPM readout with additional layer of the WLS strips.
- Adding second cylindrical layer of strips seems to have slight influence on the spatial resolution and the scatter fraction, but it strongly improves the sensitivity and the NECR characteristics. Increasing the diameter of the detecting chamber worsens the sensitivity of the scanner.
- The longer the strips, the higher the sensitivity, the higher the NECR peak (which is obtained for smaller value of the activity concentration) and the smaller the scatter fraction. On the other hand, without WLS strips, the axial resolution worsens with the growth of strips length.
- In order to take into account all above figures of merit in process of projecting the J-PET prototype, the compromise must be found between the geometrical acceptance, the background, the image quality and the production cost.
- It seems that from all tested geometries, the best results were obtained for the double-layer geometry built from strips with length of 100 cm and thickness of 4 mm, the diameter equal to 75 cm and the SiPM photomultipliers with the additional layer of the WLS strips used as readout.

Article summarizing presented results was published in the PMB journal and is available online: `http://iopscience.iop.org/article/10.1088/1361-6560/aad29b/meta`.

Summary: Comparison to commercial PET scanners

	GE Discovery IQ (PET/CT)m, 5 rings (AFOV = 260 mm)	Siemens Biograph mCT (PET/CT) (AFOV = 218 mm)	Philips Vereos PET/CT (AFOV = 164 mm)	J-PET (L = 100 cm, Thickness = 4 mm, D = 75 cm, 2 layers, SiPM+WLS readout)
Spatial resolution	in range of 4.2 mm at 1 cm to 8.5 mm at 20 cm	from 4.4 mm to 5.9 mm	from 3.99 mm to 4.64 mm	at the centre: 3mm (radial, tangential), 6 mm (axial)
Sensitivity	measured at the centre and at 10 cm is 22.8 and 20.4 cps/kBq	9.7 cps/kBq in the centre of the AFOV	at the centre is 22.1 cps/kBq and at 10 cm is 22.2 cps/kBq	at the centre is 14.9 cps/kBq
Scatter fraction	36.2 %	33.2%	31.6 %	34.7 %
NECR	peak of 124 kcps at 9.1 kBq/cc	peak of 180.3 kcps at 29 kBq/cc	peak of 157.6 kcps at 52.8 kBq/cc	peak of 300 kcps at about 40 kBq/cc

Thank you for attention