Monte Carlo simulation of Digital Photon Counting PET

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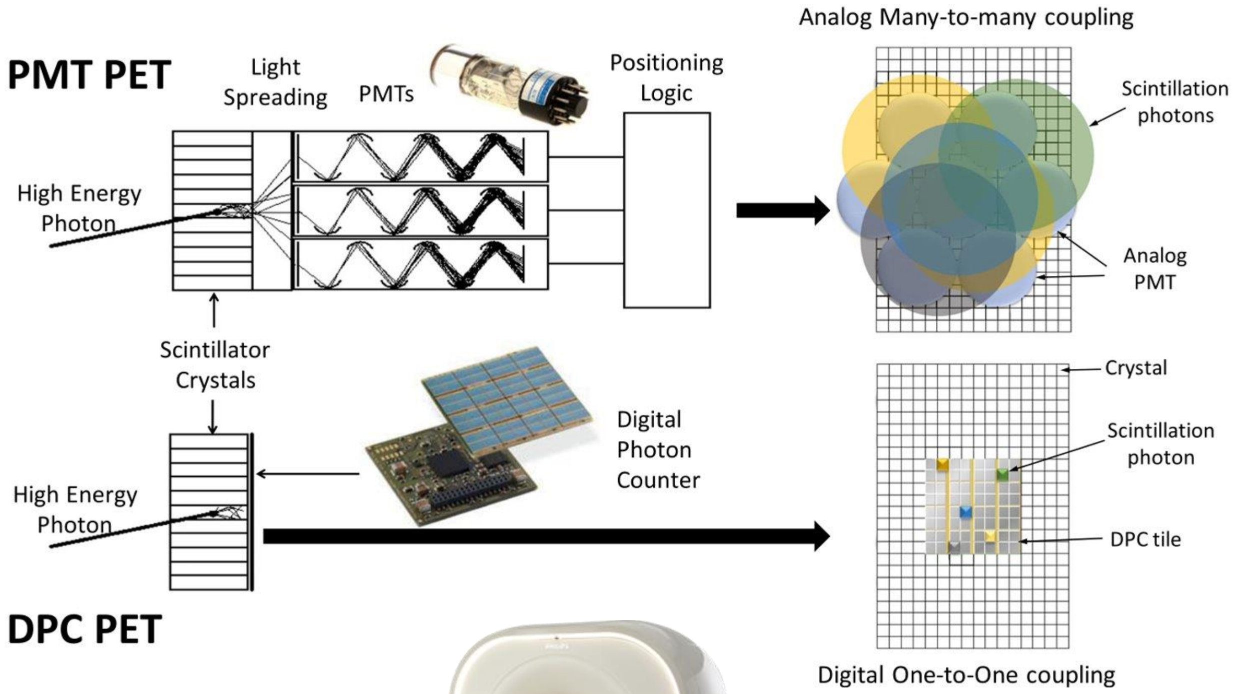
Introduction

Digital Photon Counting PET (Vereos, Philips)

- 764 mm detector ring
- 164 mm axial FOV
- 1:1 coupling between LYSO crystals and SiPM DPC detectors
- Fully digital chain + low deadtime
- Improved **spatial resolution**
- Improved **timing resolution**
- Improved **accuracy**



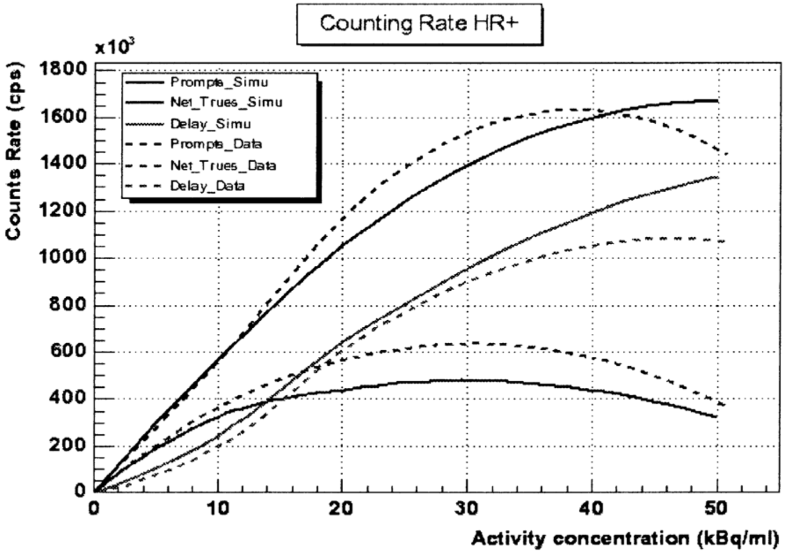
Vereos DPC SiPM PET

Aim

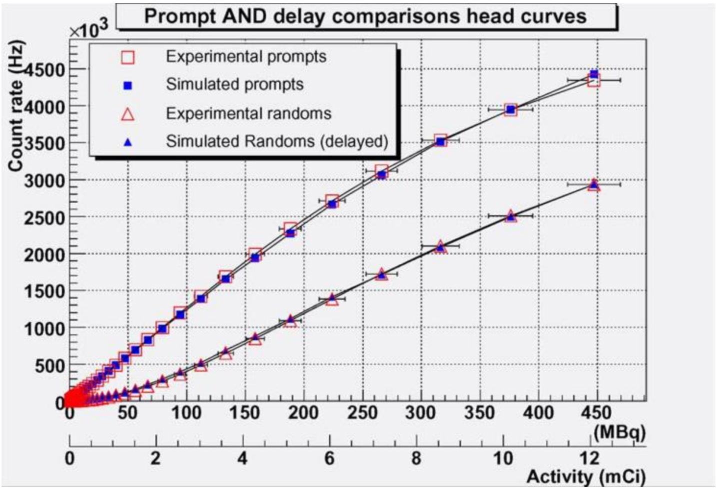
Validate a Monte Carlo model of the DPC-PET

Validated Monte Carlo PET models using GATE

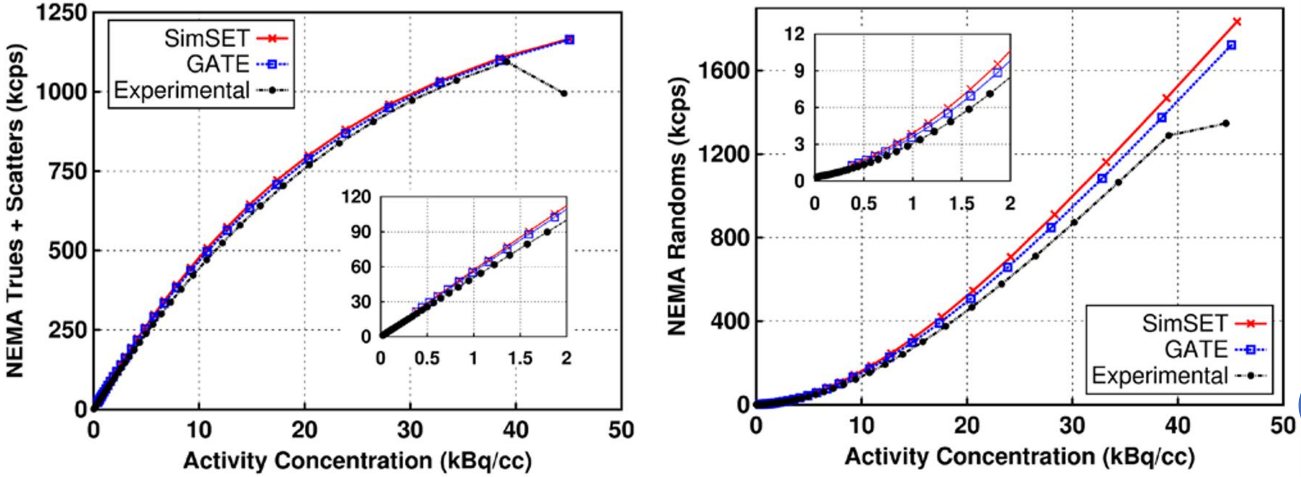
- ECAT: HRRT & EXACT HR+
- Philips: Allegro & GEMINI
- GE: Advance & Discovery
- Siemens: Biograph 6, Inveon, Biograpgh mcT



(2005)



(2008)



(2015)

2. Jan, S., Comtat, C., Strul, D., Santin, G., Trebossen, R.: Monte Carlo simulation for the ECAT EXACT HR+ system using GATE. IEEE Transactions on Nuclear Science 52 (3), 627–633 (2005)
3. Guez, D., Bataille, F., Comtat, C., Honoŕ e, P.-F., Jan, S., Kerhoas, S.: Counting rates modeling for PET scanners with GATE. IEEE Transactions on Nuclear Science 55 (1), 516–523 (2008)
4. Poon, J.K., Dahlbom, M.L., Casey, M.E., Qi, J., Cherry, S.R., Badawi, R.D.: Validation of the Simset simulation package for modeling the Siemens Biograph mCT PET scanner. Physics in Medicine & Biology 60 (3), 35 (2015)

Aim

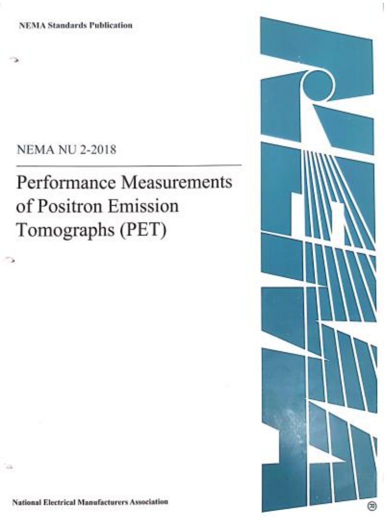
Validate a Monte Carlo model of the DPC-PET

Vereos DPC-PET

- SiPM PET
- Validation based on the NEMA NU2-2018 guidelines
- Comparison between **experimental** and **simulated** data

Studied PET performance independent of reconstruction

1) **Count rates, NECR and scatter fraction**
2) **Time of Flight (TOF) and energy resolutions**
3) **Sensitivity**
4) **Spatial resolution (before reconstruction)**



NEMA Standards Publication

NEMA NU 2-2018

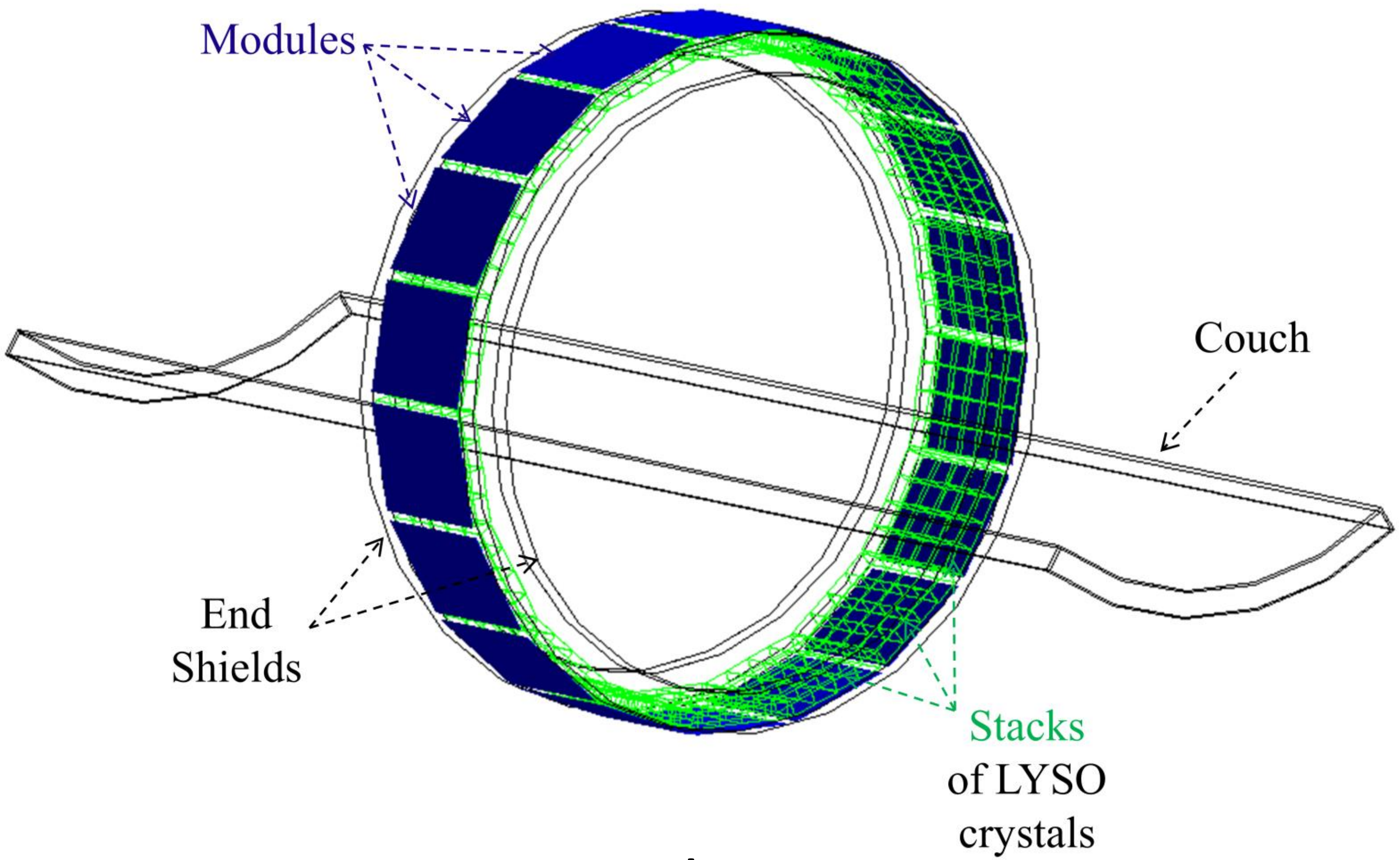
Performance Measurements of Positron Emission Tomographs (PET)

National Electrical Manufacturers Association

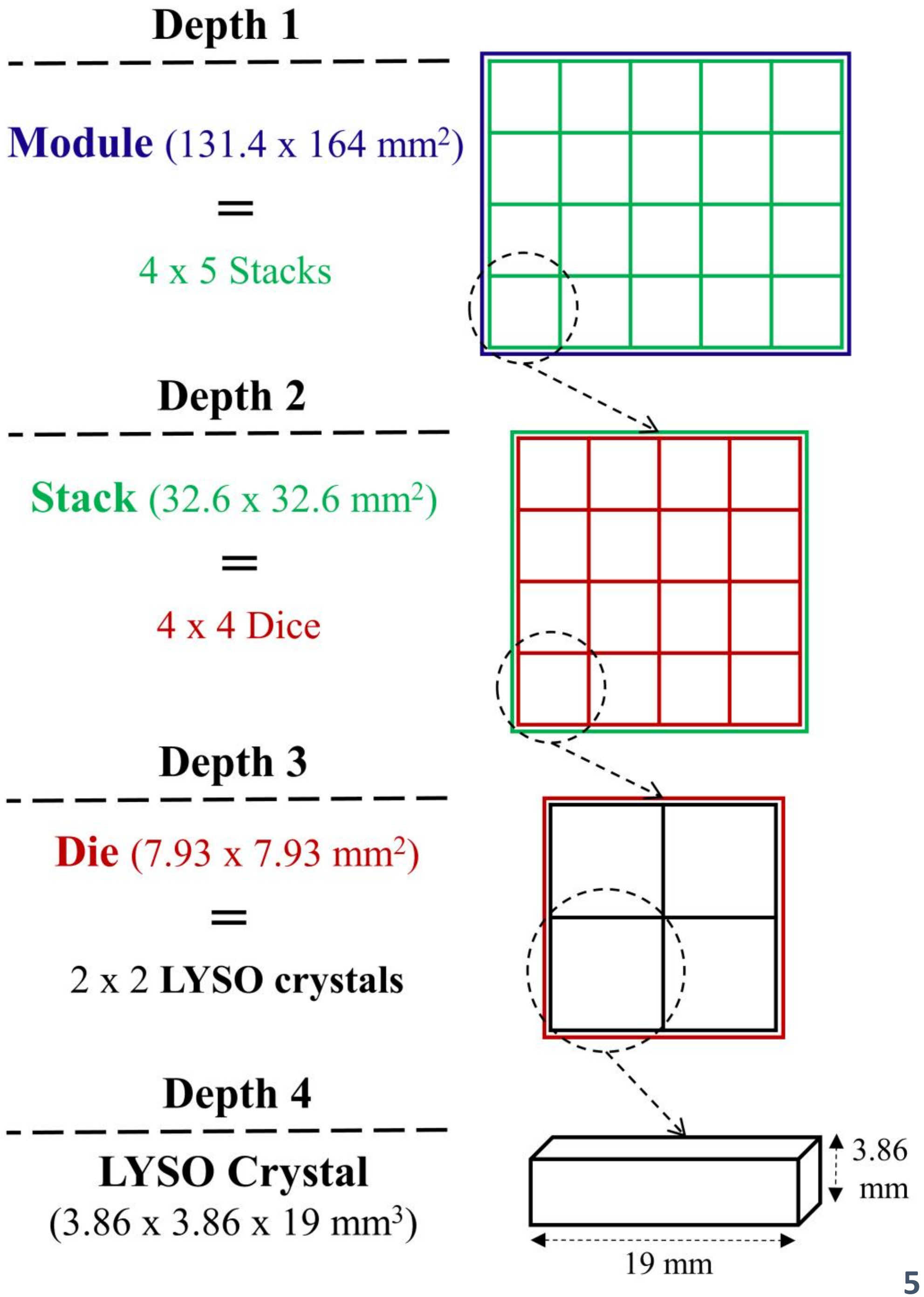
NDA with Philips for PET geometry and digitizer chain in GATE

5. NEMA Standards Publication NU 2-2018. Performance Measurements of Positron Emission Tomographs. Rosslyn, USA (2018).

Scanner geometry : Philips Vereos DPC-PET



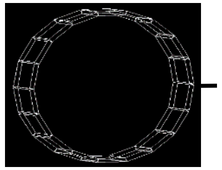
23 040 LYSO crystals
1:1 couping: 23 040 SiPMs

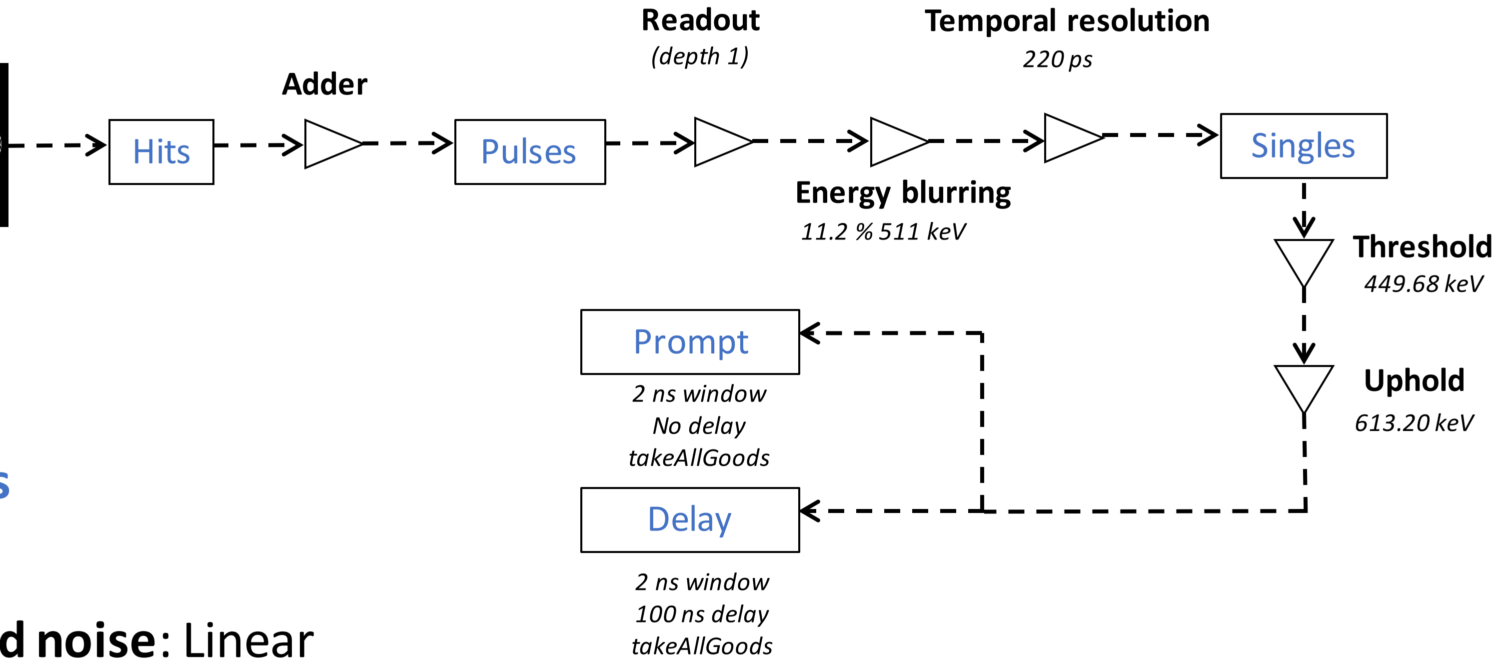


Digitizer

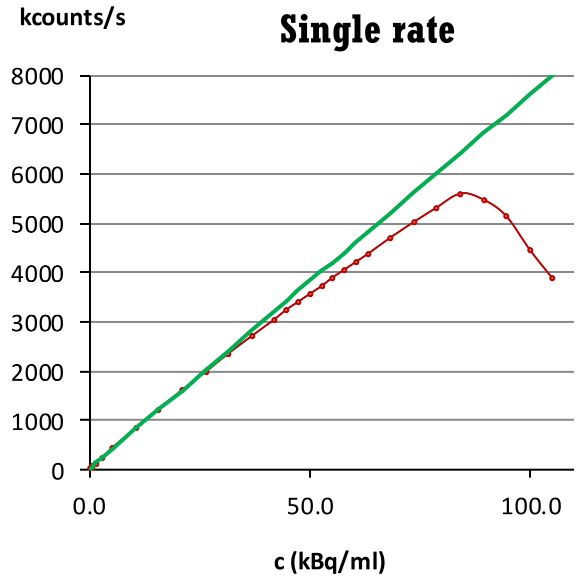
Optimizing the proposed digitizer

- **Background noise : 456 kcps**
- **Deadtime : 5.3 ns**
- **Pile-up : 5.3 ns**
- **Detection efficiency : 0.864**





Experimental determination of parameters



- **Background noise**: Linear regression from singles rate at low activity (no deadtime effect)

- Paralysable **deadtime**

$$\tau = -\frac{1}{S_{in}} \ln\left(\frac{S_{out}}{S_{in}}\right)$$

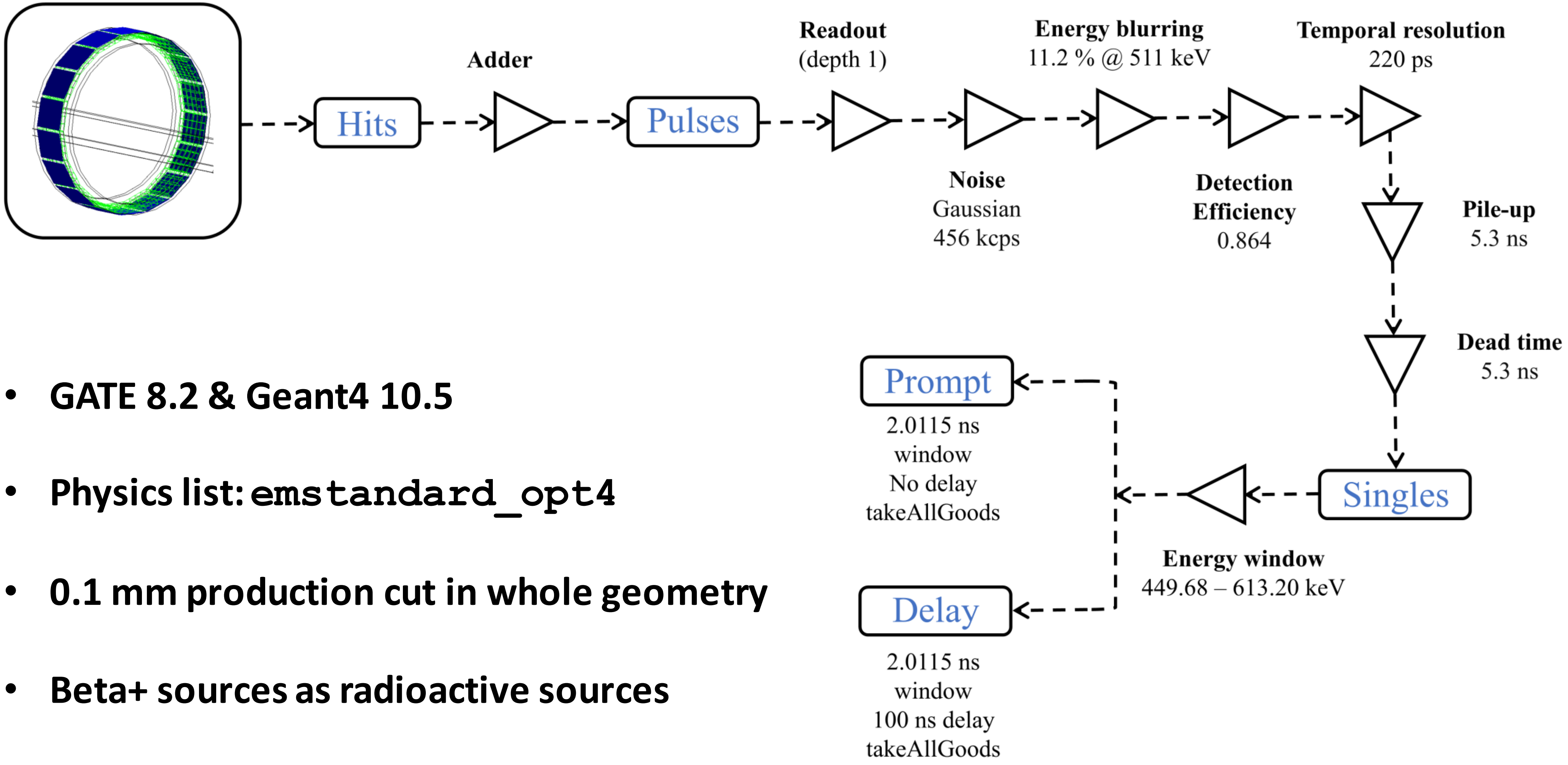
- **Detection efficiency (DE)**

$$DE = \frac{S_{out,exp}}{S_{out,simu}}$$

3. Guez, D., Bataille, F., Comtat, C., Honoŕe, P.-F., Jan, S., Kerhoas, S.: Counting rates modeling for PET scanners with GATE. IEEE Transactions on Nuclear Science 55 (1), 516–523 (2008)

Digitizer

Final digitizer chain



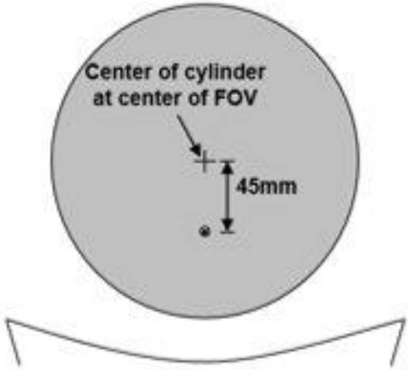
- **GATE 8.2 & Geant4 10.5**
- **Physics list: `emstandard_opt4`**
- **0.1 mm production cut in whole geometry**
- **Beta+ sources as radioactive sources**

Method: Count rates, NECR and scattered fraction

Validation by the NEMA NU2-2018 guidelines

Cylindrical scatter phantom

- High concentration ^{18}F source centered in the FOV
- 30 acquisitions over 16h



Analysis

For each acquisition:

- Single event rate **S**

From the <Prompt> window

- Total event rate **Tot**
- Random+Scatter event rate **R+Sc**

From the <Delay> window

- Random event rate **R**

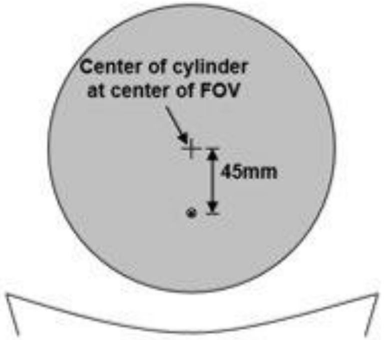
Analysis

- **True event rate: T = Tot - (R + Sc)**
- **Scatter event rate: Sc = (R+Sc) - R**

- **Scatter fraction:** $SF = \frac{Sc}{Sc+T}$
- **Noise equivalent count rate:** $NECR = \frac{T^2}{Tot}$

Method: TOF and energy resolution

Validation by the NEMA NU2-2018 guidelines

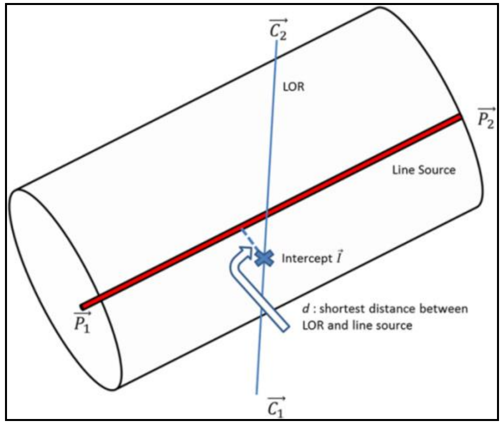


Wang *et al.* Method

- Cylindrical phantom: same acquisitions as for count rates

Analysis

- For each of the 30 acquisitions

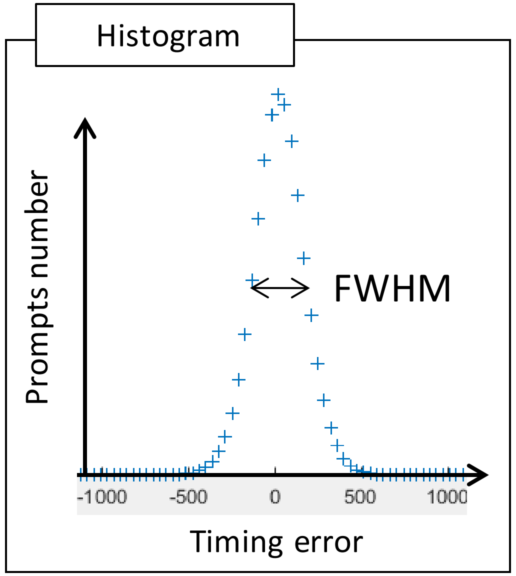


Extract measured TOF: ΔT_M

Determine theoretical TOF: ΔT_{th}

Timing error calculation: ΔT_M - ΔT_{Th}

Scatter correction



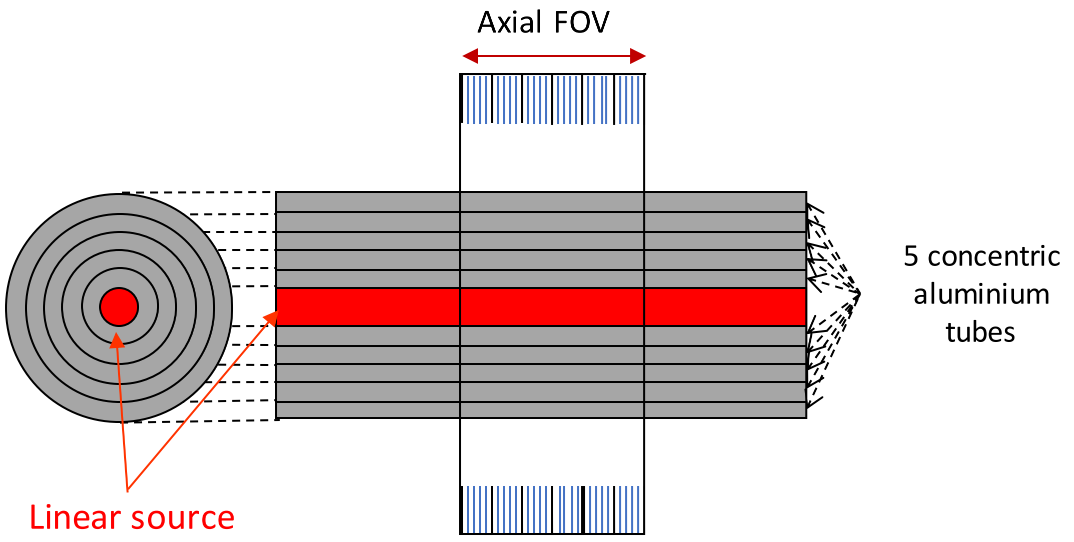
6. Wang, G.-C., Li, X., Niu, X., Du, H., Balakrishnan, K., Ye, H., Burr, K.: PET timing performance measurement method using nNEMA NEC phantom. IEEE transactions on Nuclear Science 63 (3), 1335–1342 (2016)

Method: Sensitivity

Validation by the NEMA NU2-2018 guidelines

Sensitivity phantom

- ^{18}F source – 7 MBq centered in FOV
- 5 different acquisitions for different aluminium thicknesses



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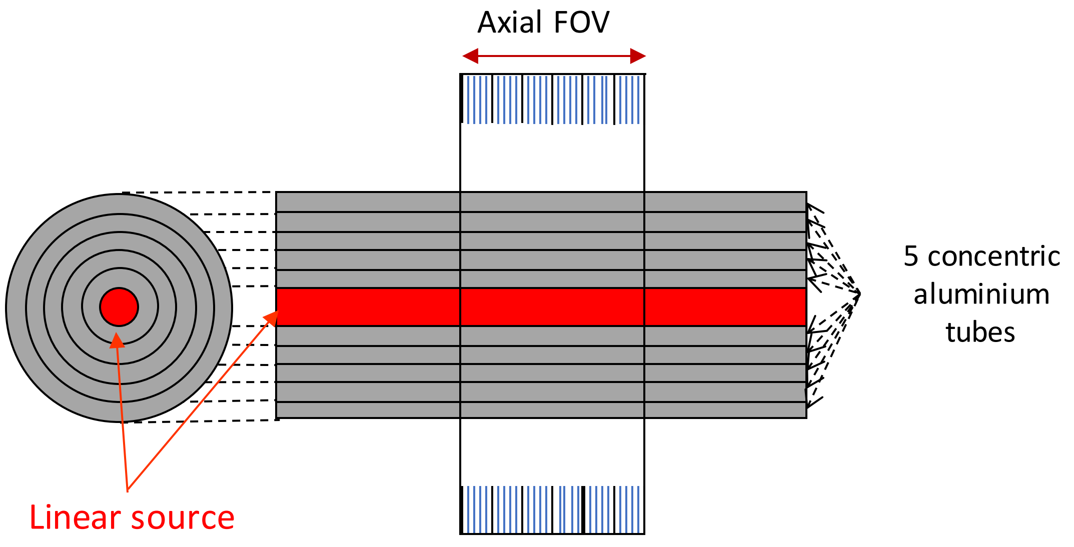
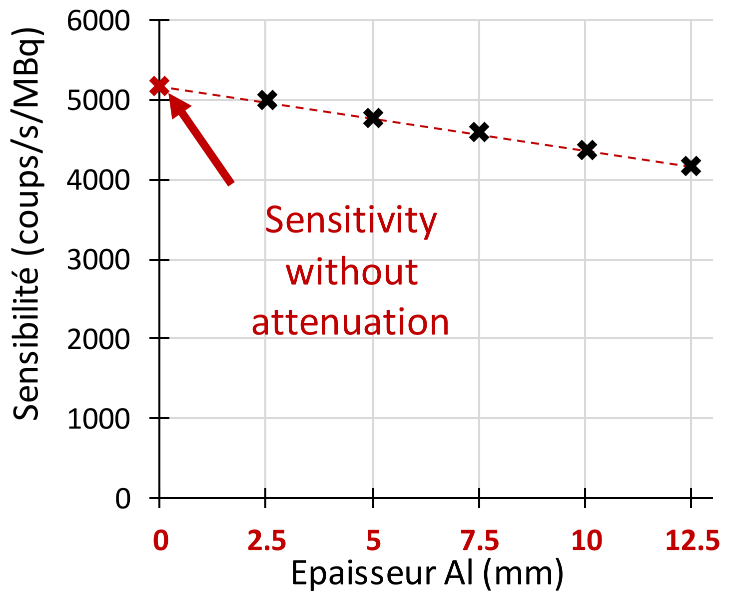


Analysis

- Sensitivity for each thickness (cps/MBq)
- Extrapolation to zero thickness: sensitivity without photon attenuation



Method: Spatial resolution

Validation by the NEMA NU2-2018 guidelines

- Usually determined from the point spread function of a point source: dependent on reconstruction algorithm

- New method proposed from listmode data
  - Point source: 2 GBq/mL

  •The smallest vector between the LOR and the source, was projected along each axis X, Y and Z

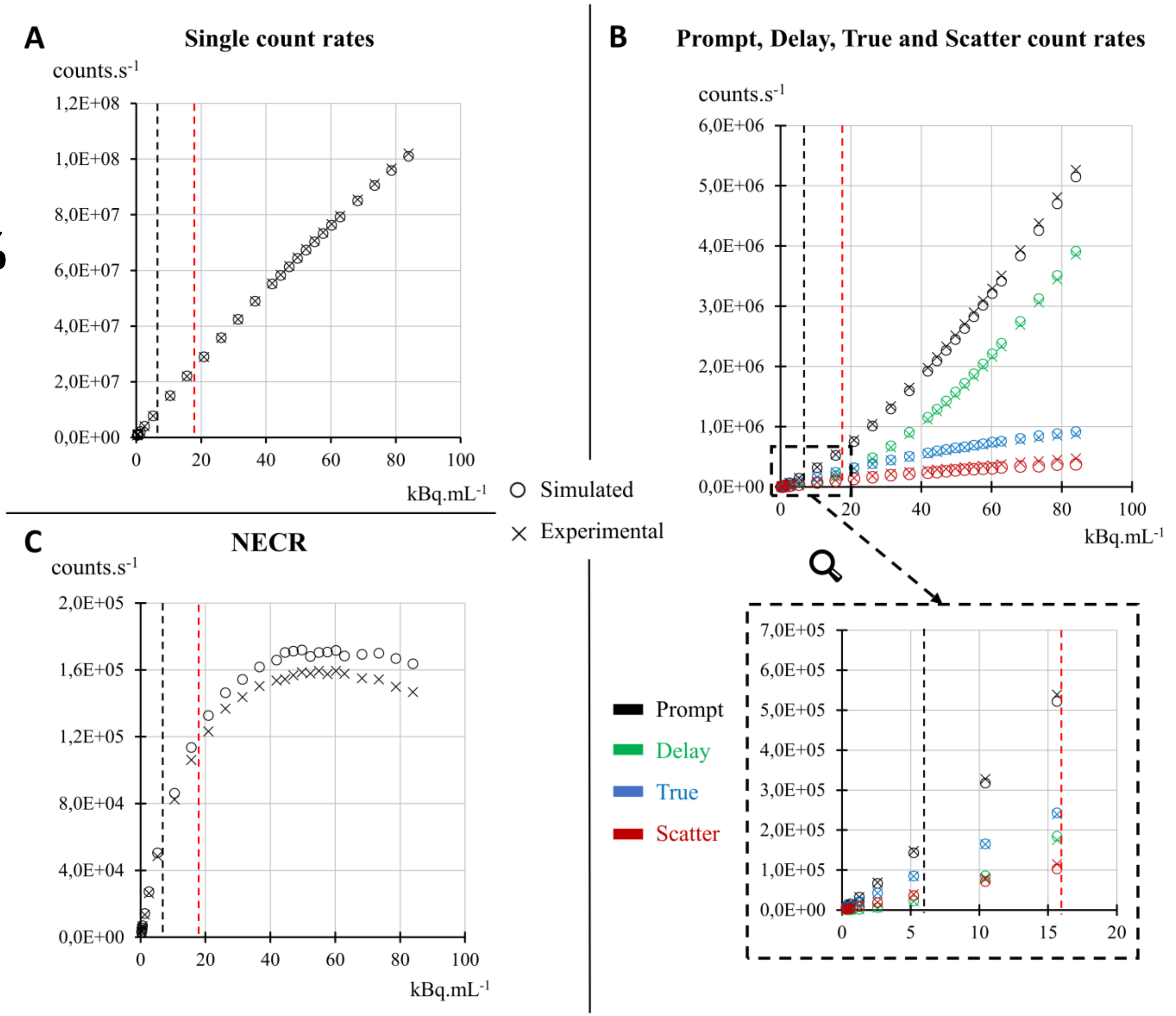
  •Each distribution was then binned into histograms and the spatial resolution for a given direction was determined with FWHM

  - 5 positions in (x,y,z): (0,1,0), (0,10,0), (0,20,0), (10,0,0) and (20,0,0) cm

Results: Count rates, NECR and scattered fraction

Maximum relative differences: experimental v/s GATE

- **Singles: 1%**
- **NECR: 12%**



- **Total coincidences: 4%**
- **Randoms: 6%**
- **Trues: 5%**
- **Scattered: 20%**

Results: Count rates, NECR and scattered fraction

Maximum relative differences: experimental v/s GATE

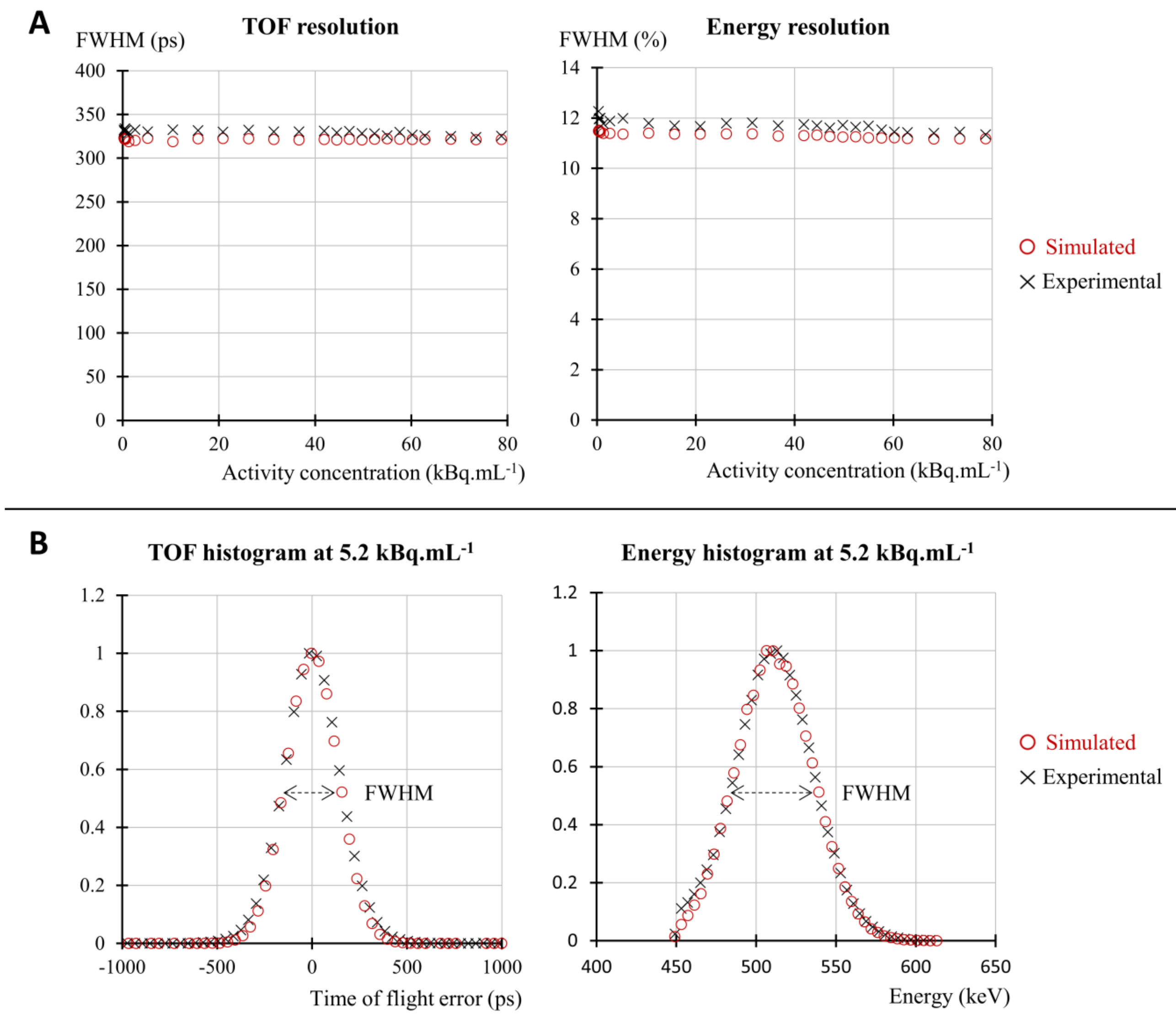
Parameter	Experimental	MC simulation	Raush *et al.* [1]	Zhang *et al.* [2]
NECR @ peak value	159.4 kcps @ 54.9 $kBq.mL^{-1}$	172 kcps @ 49.7 $kBq.mL^{-1}$	153.4 kcps @ 54.9 $kBq.mL^{-1}$	171 kcps @ 50.5 $kBq.mL^{-1}$
NECR @ 5.3 $kBq.mL^{-1}$	48.5 kcps	50.6 kcps	47.2 kcps	n/a
Scatter fraction @ peak NECR	33.2% @ 54.9 $kBq.mL^{-1}$	29.6% @ 49.7 $kBq.mL^{-1}$	33.9% @ 54.9 $kBq.mL^{-1}$	30.8% @ 50.5 $kBq.mL^{-1}$
Scatter fraction @ low count rates	31.8% @ 0.4 $kBq.mL^{-1}$	29.6% @ 0.4 $kBq.mL^{-1}$	31.7% @ 0.4 $kBq.mL^{-1}$	n/a

Table 2 Comparison of the VEREOS characteristics for NECR and scatter fractions between the experimental and Monte Carlo simulated data in this study. Additional comparison is added from experimental data published from Raush et al. [1] and Zhang et al. [2]

- **Peak NECR: <10%**
- **NECR at low count rate: <5%**
- **SF at peak NECR: <12%**
- **SF at low cout rate: <3%**

Results: TOF and energy resolution

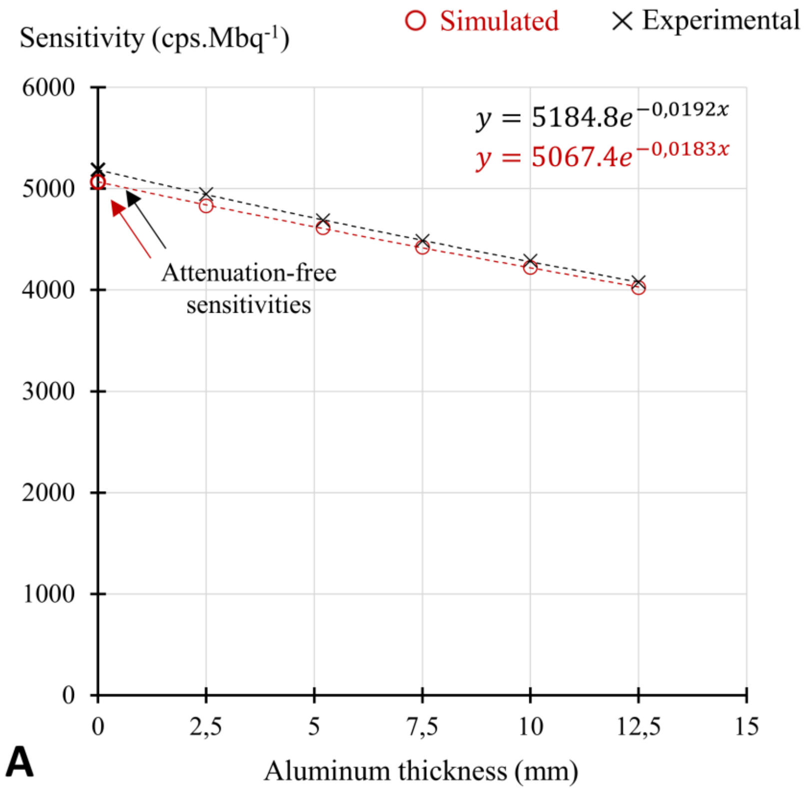
Maximum relative differences: experimental v/s GATE

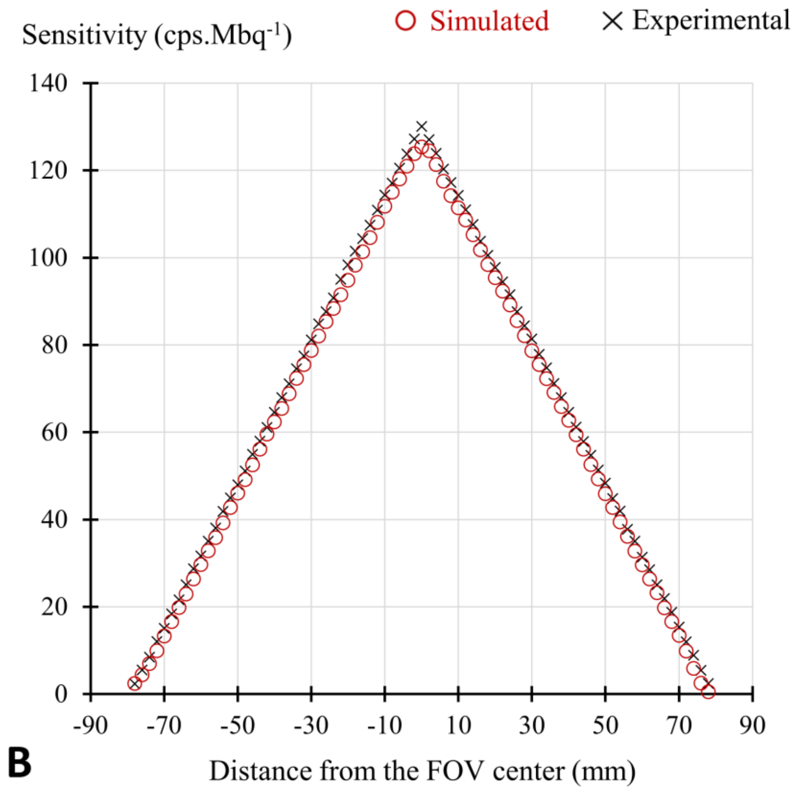


- **5% for both TOF and energy resolutions**

Results: Sensitivity

Maximum relative differences: experimental v/s GATE





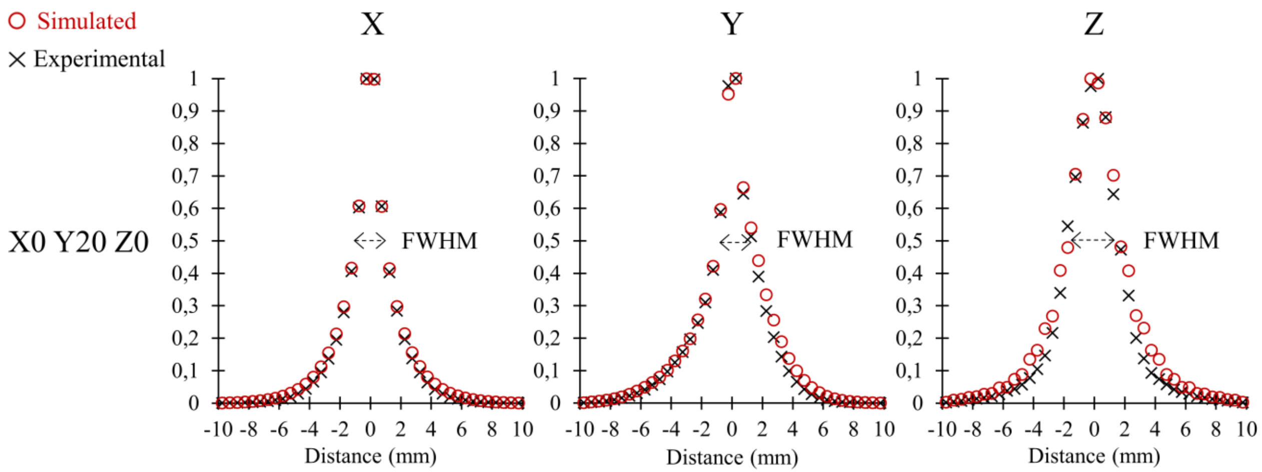
A: 2.3% at zero thickness

B: 13% on the sides of the FOV

Results: Intrinsic spatial resolution

Maximum relative differences: experimental v/s GATE

Position (cm)	Sim. FWHM (mm) X	Sim. FWHM (mm) Y	Sim. FWHM (mm) Z	Exp. FWHM (mm) X	Exp. FWHM (mm) Y	Exp. FWHM (mm) Z	Rel. diff. (%) X	Rel. diff. (%) Y	Rel. diff. (%) Z
(0,1,0)	1.96	1.75	2.40	1.93	1.71	2.37	1.8	2.3	1.1
(0,10,0)	2.01	2.15	3.40	1.97	2.09	3.51	1.8	3.1	-3.1
(0,20,0)	1.93	2.37	3.39	1.90	2.18	3.37	1.6	8.7	0.5
(10,0,0)	2.04	1.87	3.35	1.95	1.87	3.50	4.5	-0.2	-4.4
(20,0,0)	2.08	1.87	3.40	1.89	1.90	3.40	9.9	-1.3	-0.1



- **<5% overall**
- **<10% at (0,20,0) and (20,0,0) positions**

Bugs reported during simulations

Corrected bugs

- Correction on **noise module**
- Correction on **deadtime module**
  - Memory allocation bugs

- Job splitting: possible by split on simulation time

- Parallel computing using these modules now possible: 24 hour simulation reduced to 30 minutes on 48 different jobs.

- Accuracy <1%

Conclusion

- Overall good agreement between experimental and simulated values
- Validated Monte Carlo Model of the DPC PET
- Paper submitted to EJNMMI Physics – under revision
- NDA – negotiation under course for open access of the mac files
- Future work
  - Image quality validation
  - Validation of the model for Yttrium-90