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GATE simulation of Discovery MI PET/CT scanner and its extended axial field-of-view to 2 m

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DMI scanner specifications

Axial Field of View	20 cm
# of r-sectors	34
# of major rings	4
# of detector rings	36
Patient bore diameter	70 cm
Each ring has	544 crystals
Total crystals	19584
Crystal material	LYSO
Crystal size	3.95 x 5.3 x 25 mm^3
Coincidence window	4.9 ns
Energy window	425 - 650 keV
Timing resolution	385 ps
# of CT slice	128

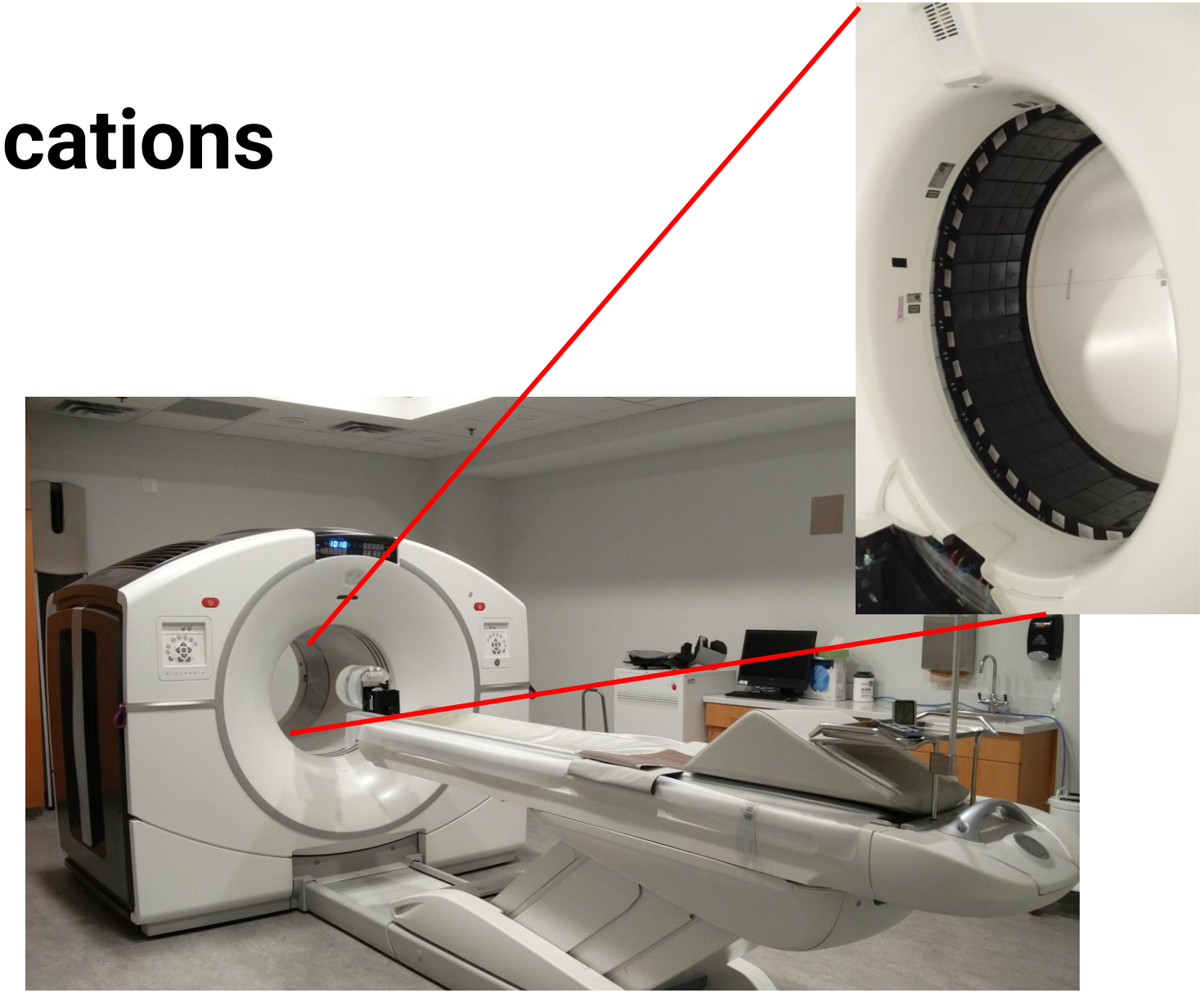

Fig: Discovery MI PET/CT scanner at UIowa

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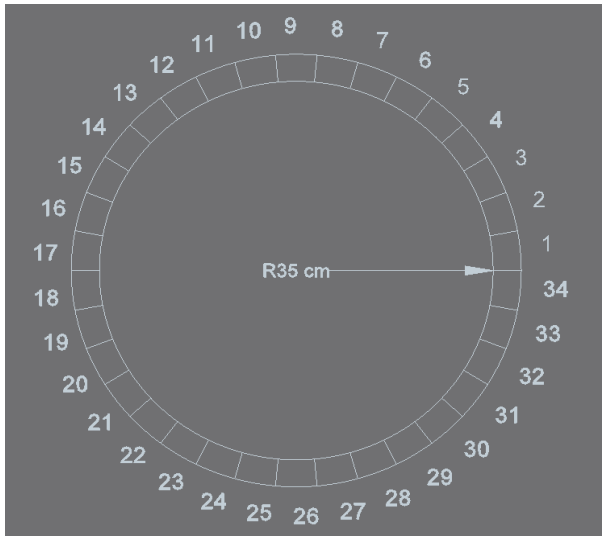
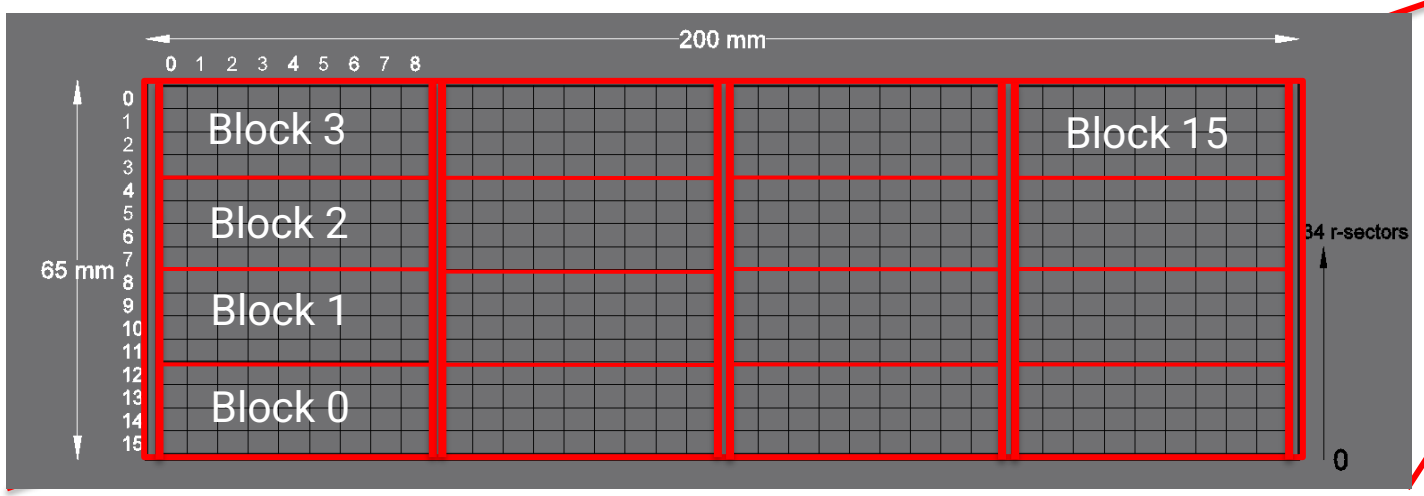
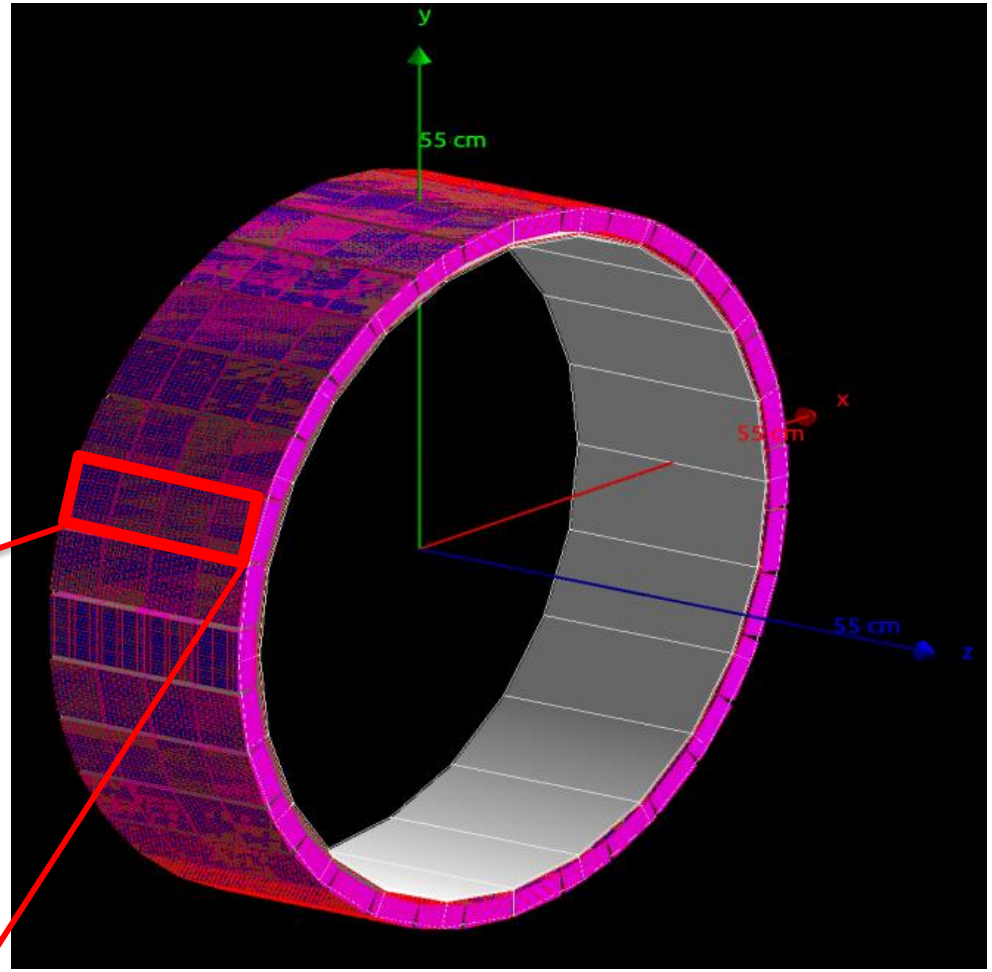
DMI 4-ring scanner modeling in GATE

Discovery MI PET Scanner
# of crystals: 19584
Crystal size: 3.95 x 5.3 x 25 mm^3
Crystals per ring: 544
Crystals: LYSO
Bore diameter: 70 cm
Rings: 4 - major rings
36 detector rings







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GATE digitizer module

 # 1. Sum all pulses

```
/gate/digitizer/Singles/insert                adder
/gate/digitizer/Singles/insert                readout
/gate/digitizer/Singles/readout/setDepth      2
```

 # 2. Gaussian blurring of energy spectrum

```
/gate/digitizer/Singles/insert                          blurring
/gate/digitizer/Singles/blurring/setResolution          0.12
/gate/digitizer/Singles/blurring/setEnergyOfReference   511 keV
```

 # 3. Coincidence resolving time - temporal resolution

```
/gate/digitizer/Singles/insert                          timeResolution
/gate/digitizer/Singles/timeResolution/setTimeResolution 385 ps
```

 # 4. Deadtime

```
/gate/digitizer/Singles/insert                deadtime
/gate/digitizer/Singles/deadtime/setDeadTime  200. ns
/gate/digitizer/Singles/deadtime/setMode      nonparalysable
/gate/digitizer/Singles/deadtime/chooseDTVolume my_module
```

 # 5. Energy window

```
/gate/digitizer/Singles/insert                          thresholder
/gate/digitizer/Singles/thresholder/setThreshold        425 keV
/gate/digitizer/Singles/insert                          upholder
/gate/digitizer/Singles/upholder/setUphold              650 keV
/gate/digitizer/Singles/describe
```

 # 6. Coincidence Sorter

```
/gate/digitizer/Coincidences/setWindow                  2.45 ns
/gate/digitizer/Coincidences/minSectorDifference        3
/gate/digitizer/Coincidences/MultiplesPolicy
takeAllGoods
/gate/digitizer/Coincidences/describe
```

 # 7. Delayed window

```
/gate/digitizer/name                  delay
/gate/digitizer/insert                coincidenceSorter
/gate/digitizer/delay/setWindow       2.45 ns
/gate/digitizer/delay/setOffset       500. ns
/gate/digitizer/delay/MultiplesPolicy takeAllGoods
/gate/digitizer/delay/describe
```


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NEMA NU-2 Tests 2018

1. Sensitivity
2. Noise equivalent count rates, scatter fraction
3. Spatial resolution (FBP, no scatter, no attenuation)
4. Image quality (Requires vendor specific reconstructions)

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Large Axial Field of View Scanners

Scanner	Architecture	Crystal size (mm^3)	Crystal	AFOV
uEXPLORER	United Imaging Healthcare's uMI 550 and 780 PET/CT	2.76 x 2.76 x 18.1	LYSO	194 cm
PennPET Explorer	Philips Vereos PET	3.86 x 3.86 x 19	LYSO	64 cm
Siemens Vision Quadra	Siemens Biograph Vision PET	3.2 x 3.2 x 20	LSO	106 cm

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1. Sensitivity: 4 ring and extended AFOV up to 2 m

- Ability of scanner to detect annihilation photons
- Model scanner geometry (4, 8, 20, and 40-ring) in GATE keeping all crystals geometry same
- Phantom material: plastic tube with 5 aluminum sleeves
- Aluminum sleeves were added subsequently one at a time
- Source: back-to-back gamma

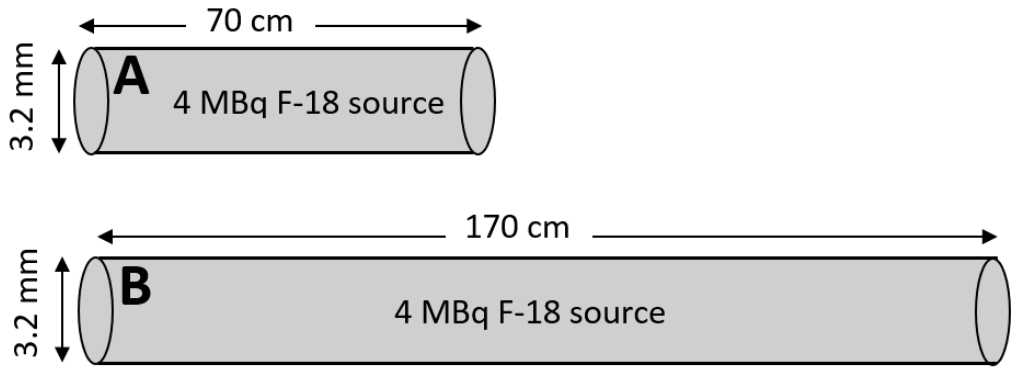

Fig1 **A**: NEMA sensitivity phantom for 4 (AFOV 20 cm) & 8-ring (AFOV 40 cm) scanner (**B**) 170 cm long phantom for 20 (AFOV 1m) & 40-ring (AFOV 2 m) scanner. Only the inner polyethylene tube is shown in figure.

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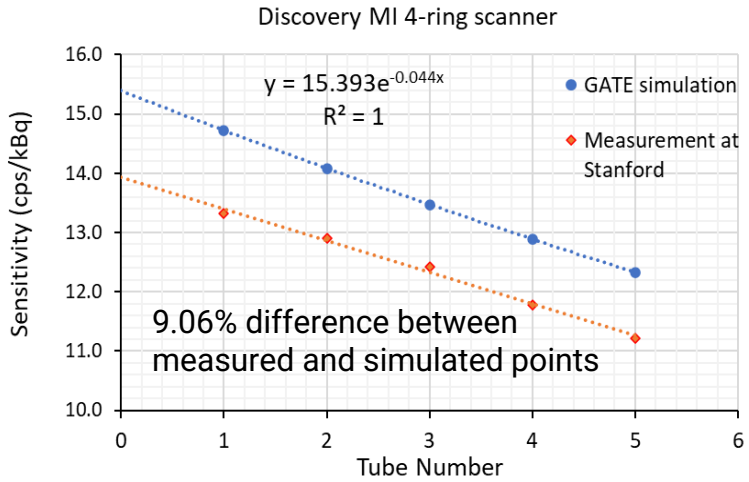
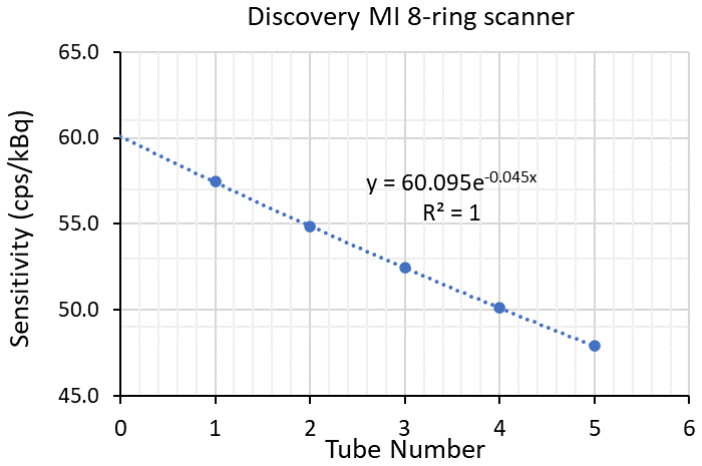
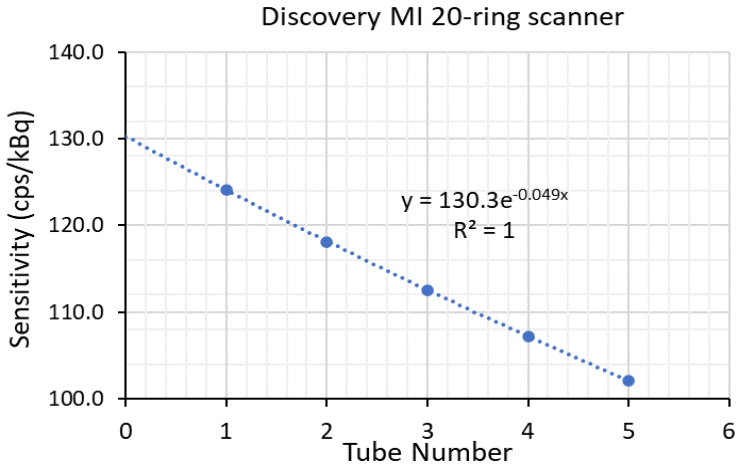
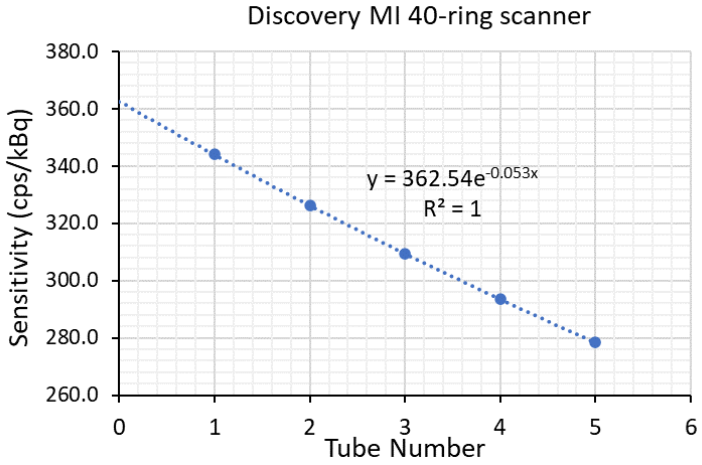
Sensitivity results

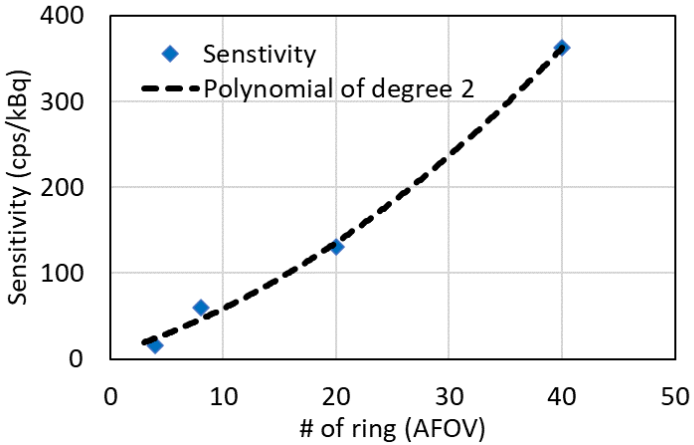




# ring	AFOV (cm)	Sensitivity cps/kBq	Sensitivity gain
4	20	15.39	1
8	40	60.09	3.90
20	100	130.30	8.47
40	200	362.98	23.55







Note: Simulation results were compared to measurement results presented in: "Hsu, D.F.C., et al., *Studies of a Next-Generation Silicon-Photomultiplier-Based Time-of-Flight PET/CT System.* J Nucl Med, 2017. **58**(9): p. 1511-1518".

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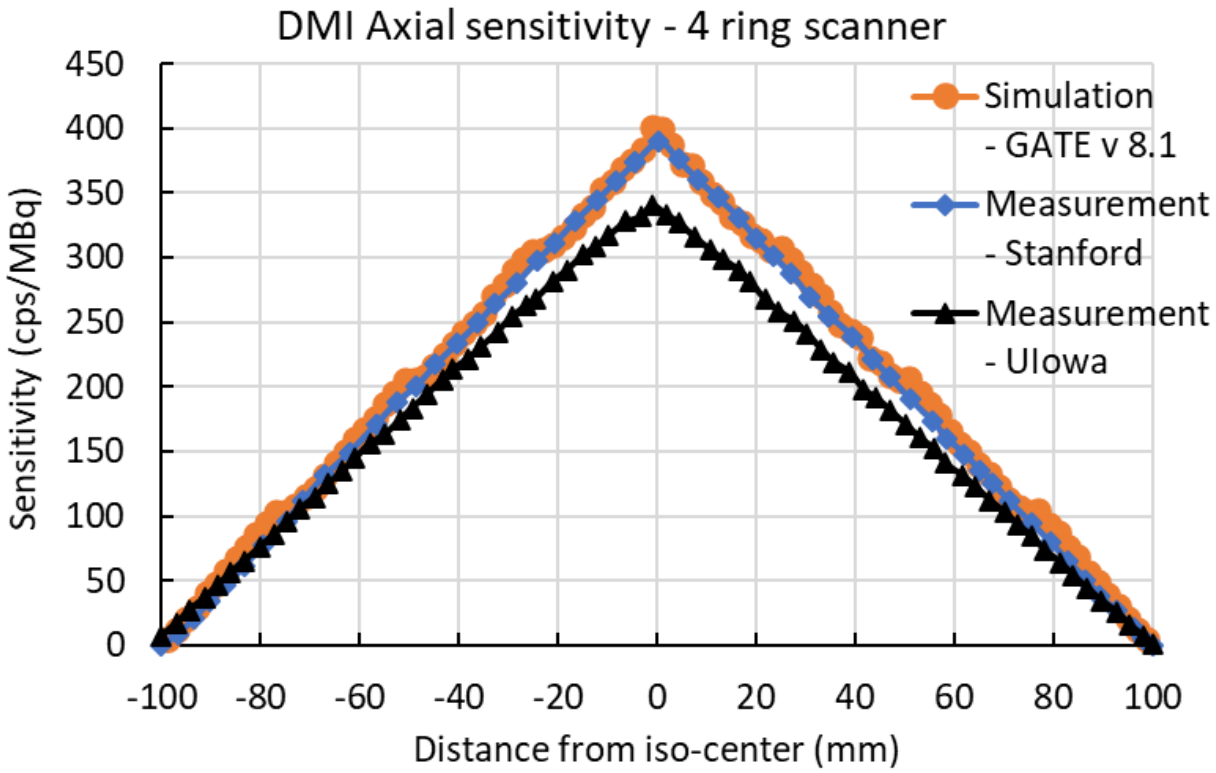
Axial sensitivity



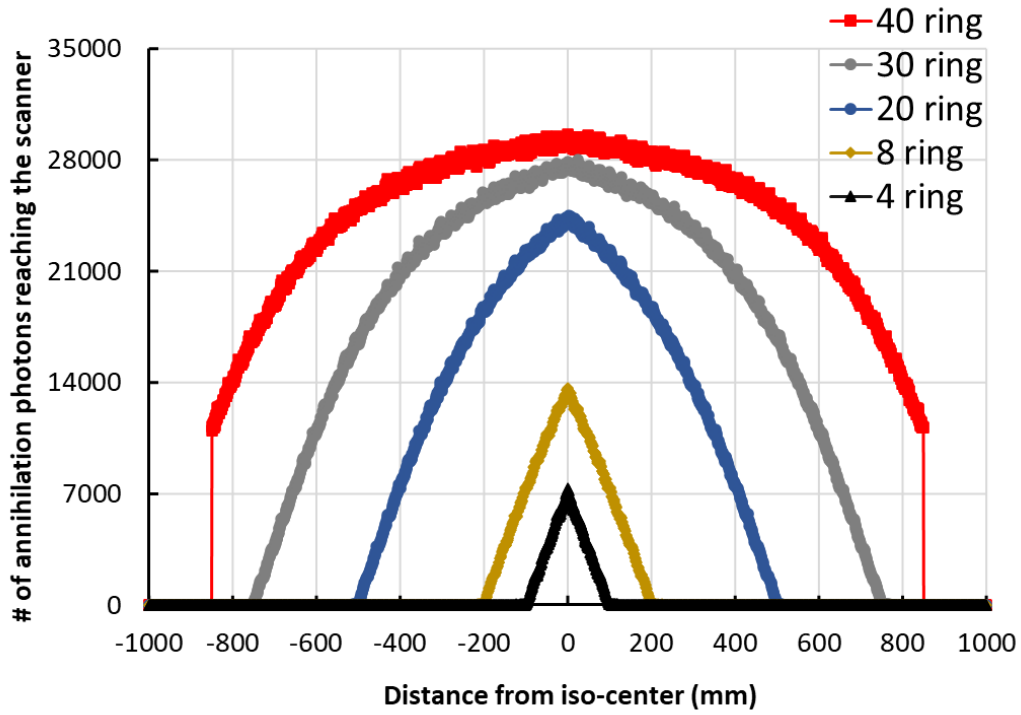


Fig: Axial sensitivity profile for a 3.2 mm diameter 170 cm long line source shown for a scanner with 4, 8, 20, 30, and 40-ring. 30 sec GATE simulation and 4 MBq ^{18}F activity was used.

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2. Spatial resolution

- 3-point sources
- Sources are glass capillary tubes of height = 1 mm, ID = 1 mm & OD = 1.8 mm
- Source volume = 0.00079 cc
- Activity used: 0.15 kBq (~ 190 kBq/cc), same activity in all tubes
- Simulation time: ~6 hrs (in GATE) to ensure at least 100,000 coincidences per NEMA suggestions
- Image Reconstruction using FBP, no attenuation, no scatter

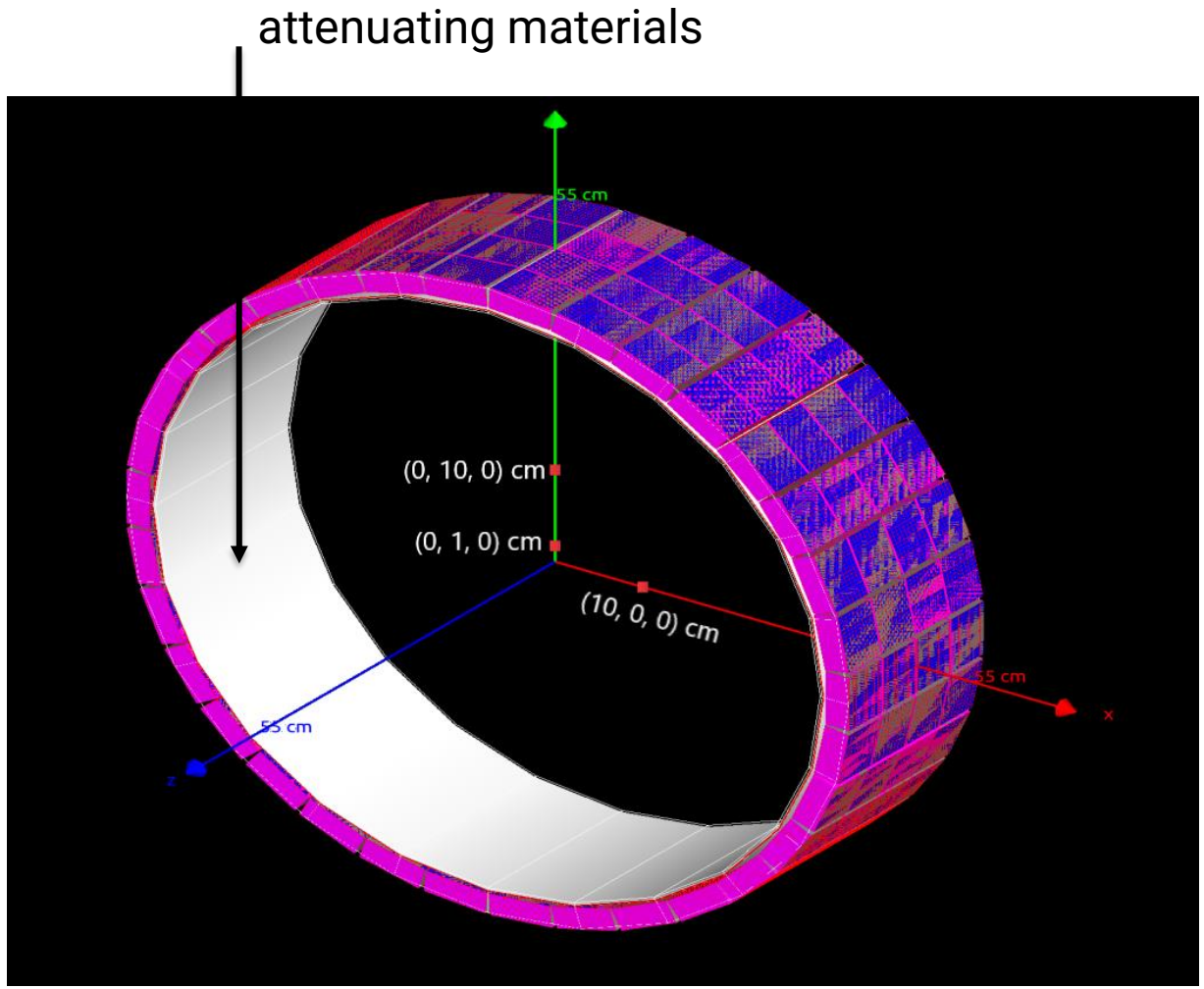

Fig: Sources positioning for spatial resolution test

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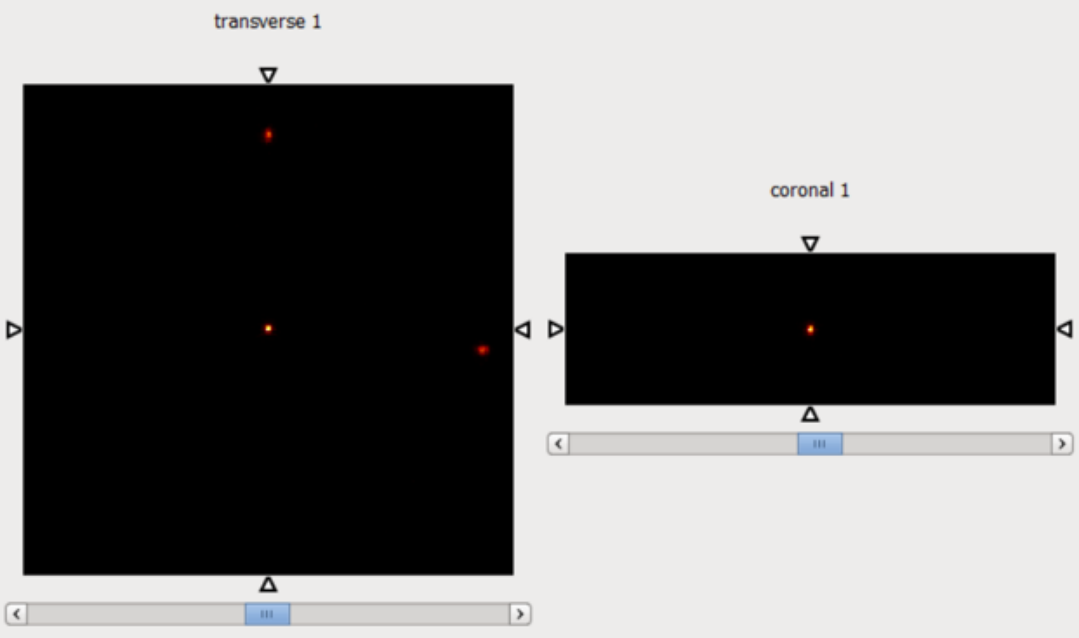
FWHM calculations



- Image reconstruction with FBP
- Voxel size = 2 x 2 x 3.5 mm^3
- Matrix size = 259 x 259 x 71
- Generate line profile and calculate FWHM

	GATE		Measurement (Stanford)	
	FWHM	FWTM	FWHM	FWTM
(0, 1, 0) cm				
Radial	3.84	8.82	4.17	9.14
Tangential	4.00	8.64	4.40	9.17
Axial	4.41	9.76	4.57	10.38
(0, 10, 0) cm				
Radial	5.17	9.43	5.65	10.36
Tangential	4.96	9.03	4.74	9.68
Axial	5.90	11.41	6.39	12.34

Percent differences up to 9.5%

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3. Count rates and scatter fraction

- At least 500,000 coincidences per NEMA standards
- Activity concentration was calculated based on the activity in the scatter phantom
- Simulations were performed using activity in the range of (1 – 800) MBq

$$NECR = \frac{C_T^2}{C_S + C_T + kC_R}$$

Where k = 1 is set, based on based on the assumption that a low variance estimate of randoms is used

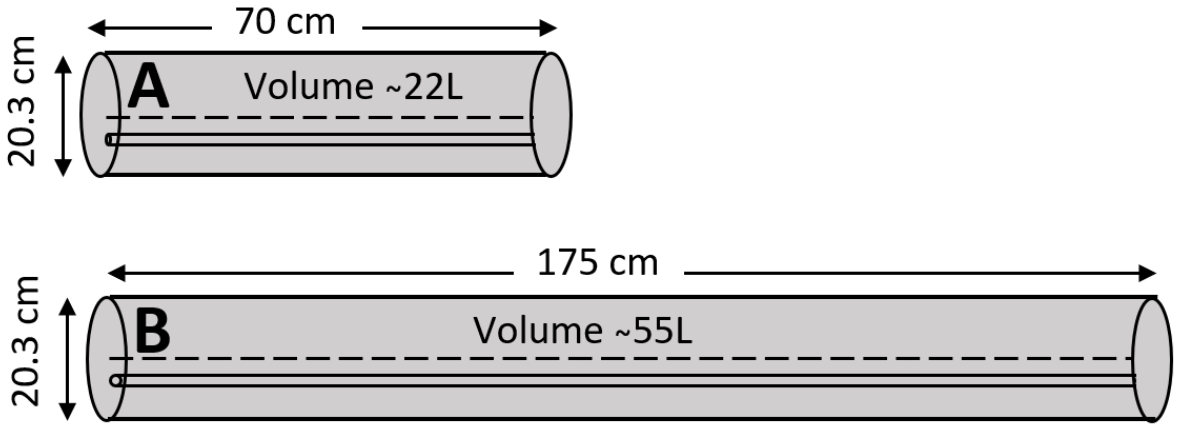

Fig (A): Scatter phantom for 4-ring (B) modified scatter phantom for 20 and 40-ring scanner. In both figures, the line source of inner diameter 3.2 mm radially offset 45 mm from central horizontal axis.

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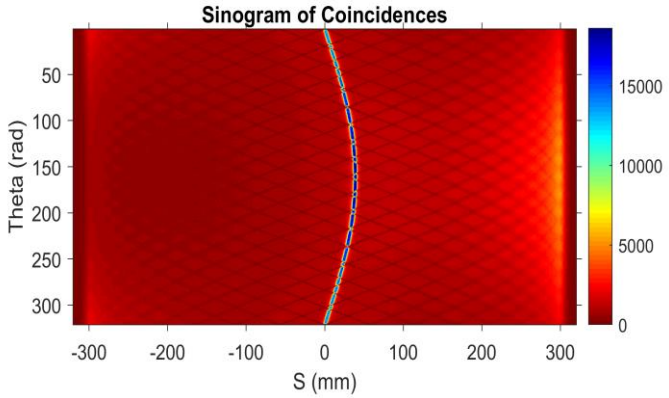
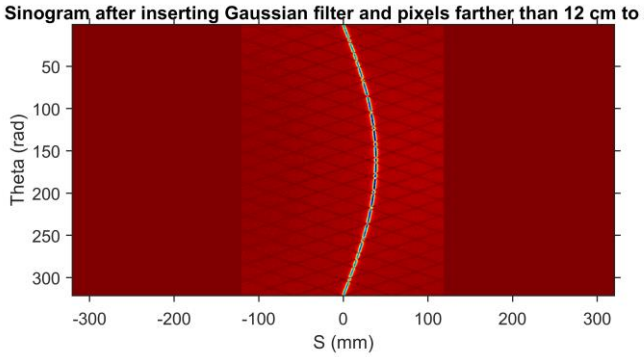
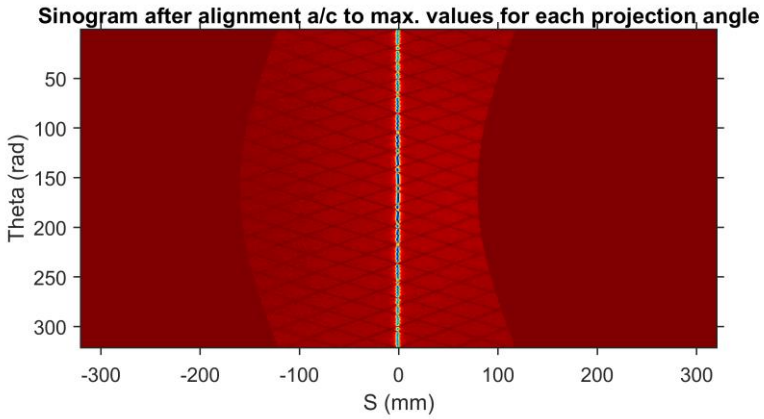
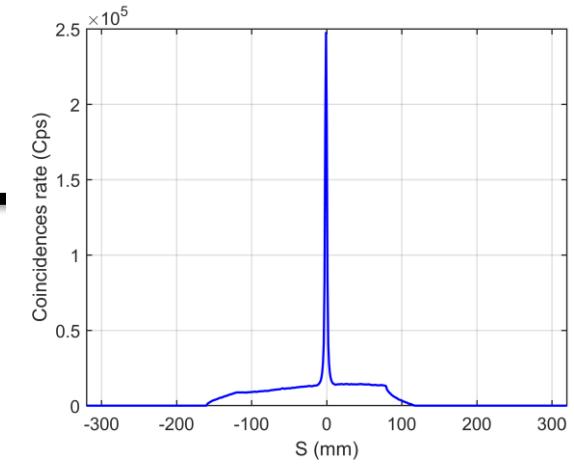
NEMA protocols to estimate count rates:

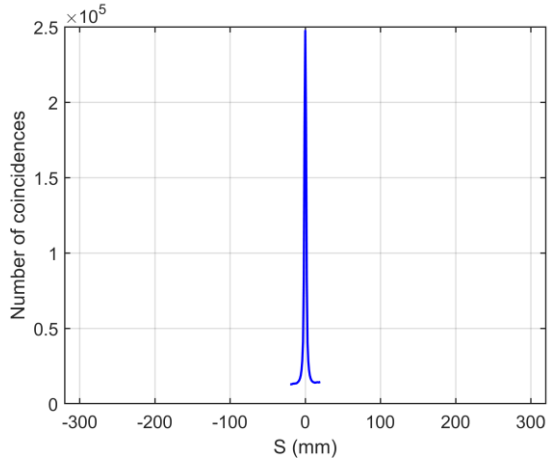
e.g., activity using 800 MBq











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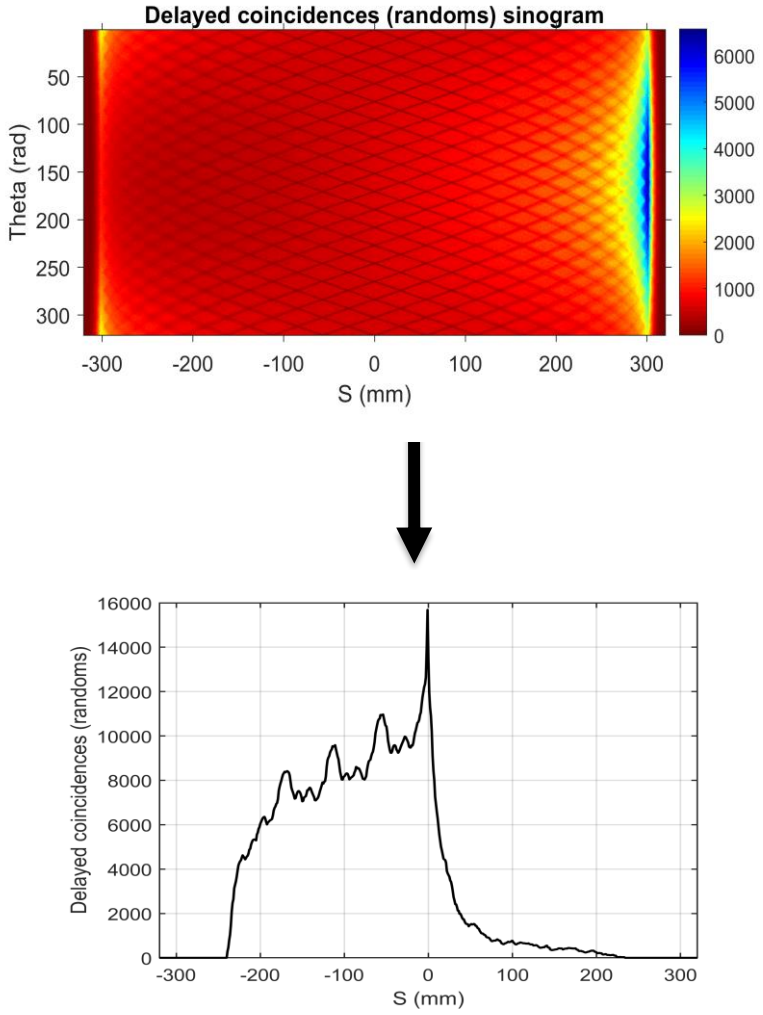
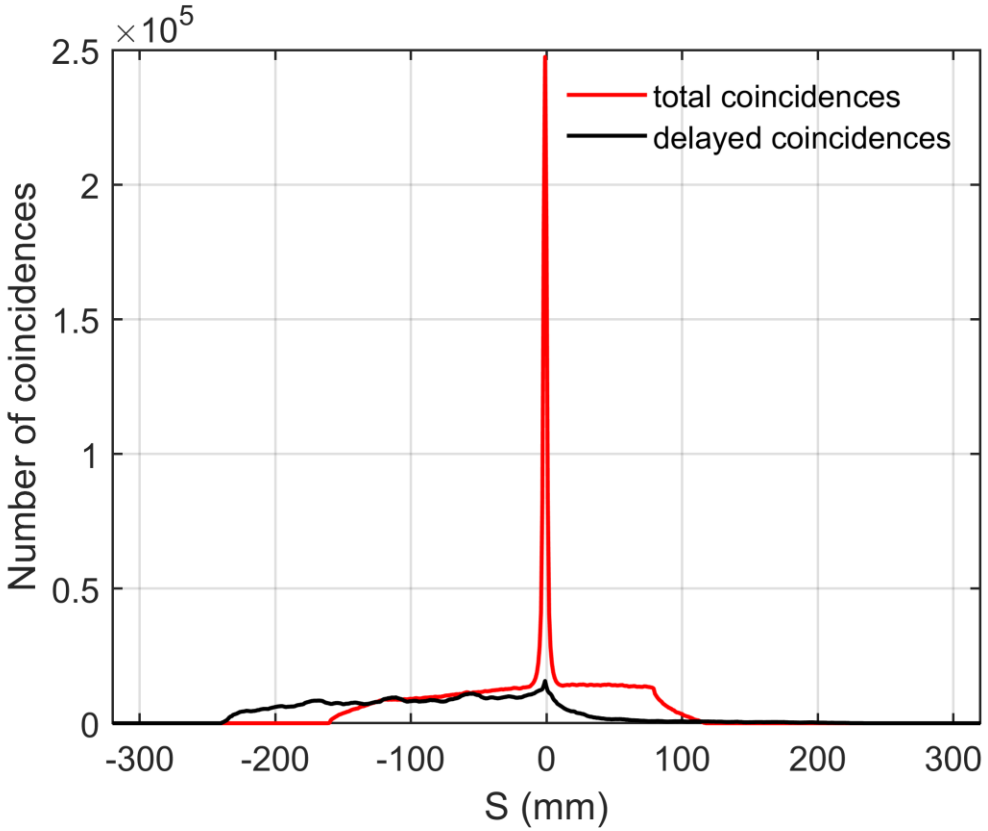
Delayed sinogram and prompts vs delayed coincidences





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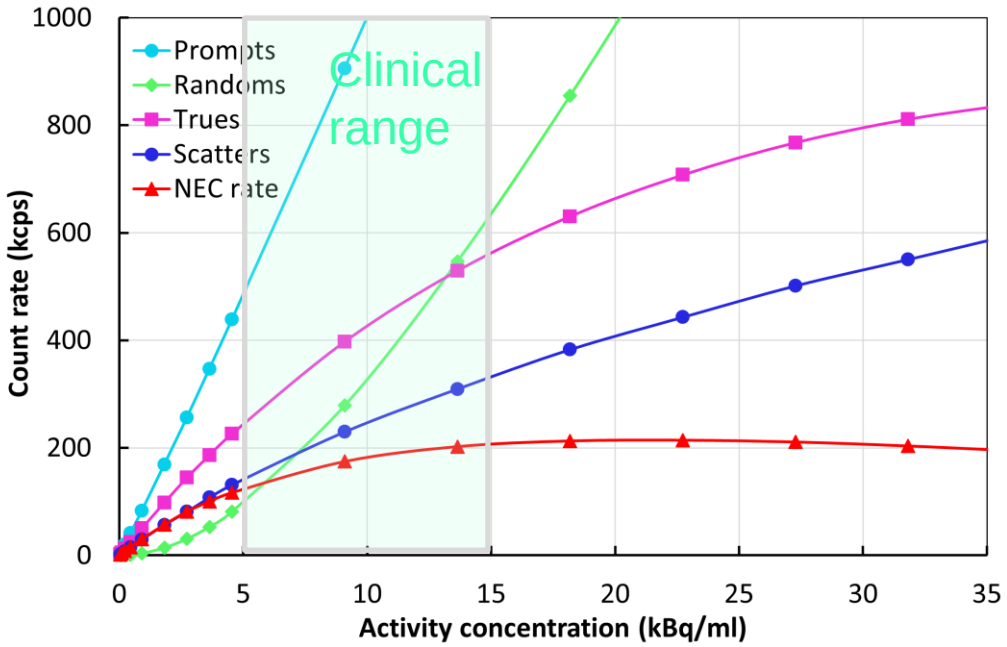
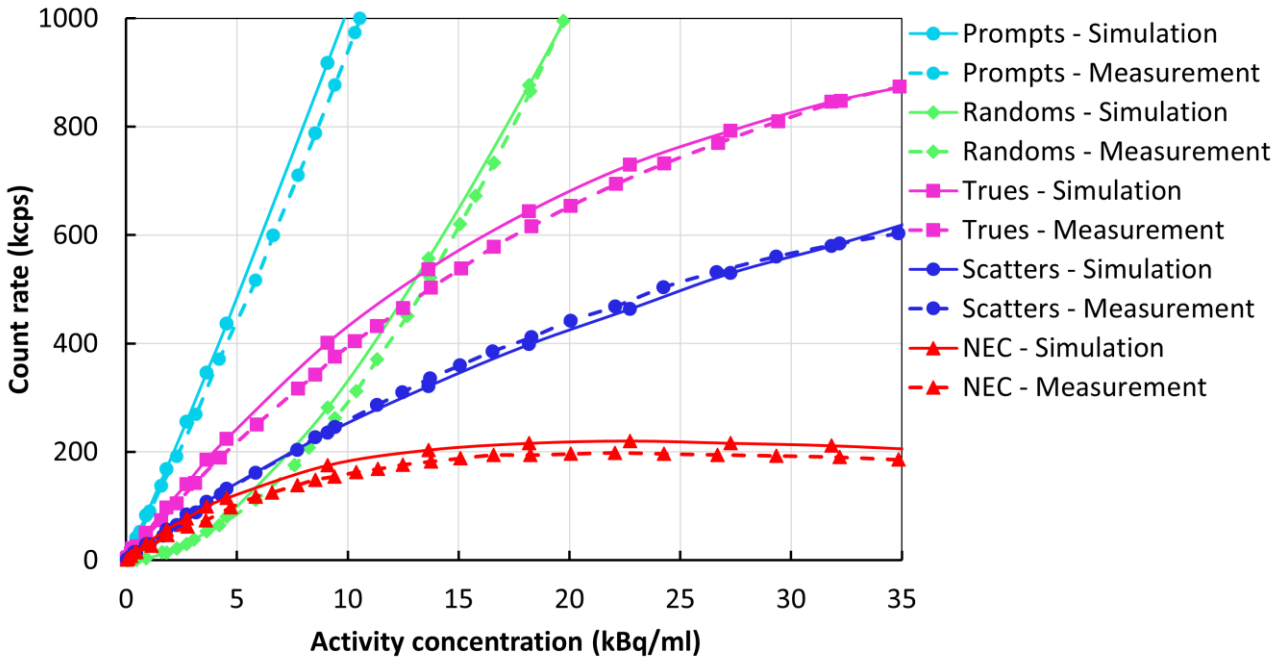
Results: Simulation vs measurement

4-ring scanner with 70 cm scatter phantom

Simulation



Simulation vs Measurement



Plot on right: Comparison with measurement performed at Stanford university by *Hsu et al., "Studies of a Next-Generation Silicon-Photomultiplier-Based Time-of-Flight PET/CT System", JNM, 2017*

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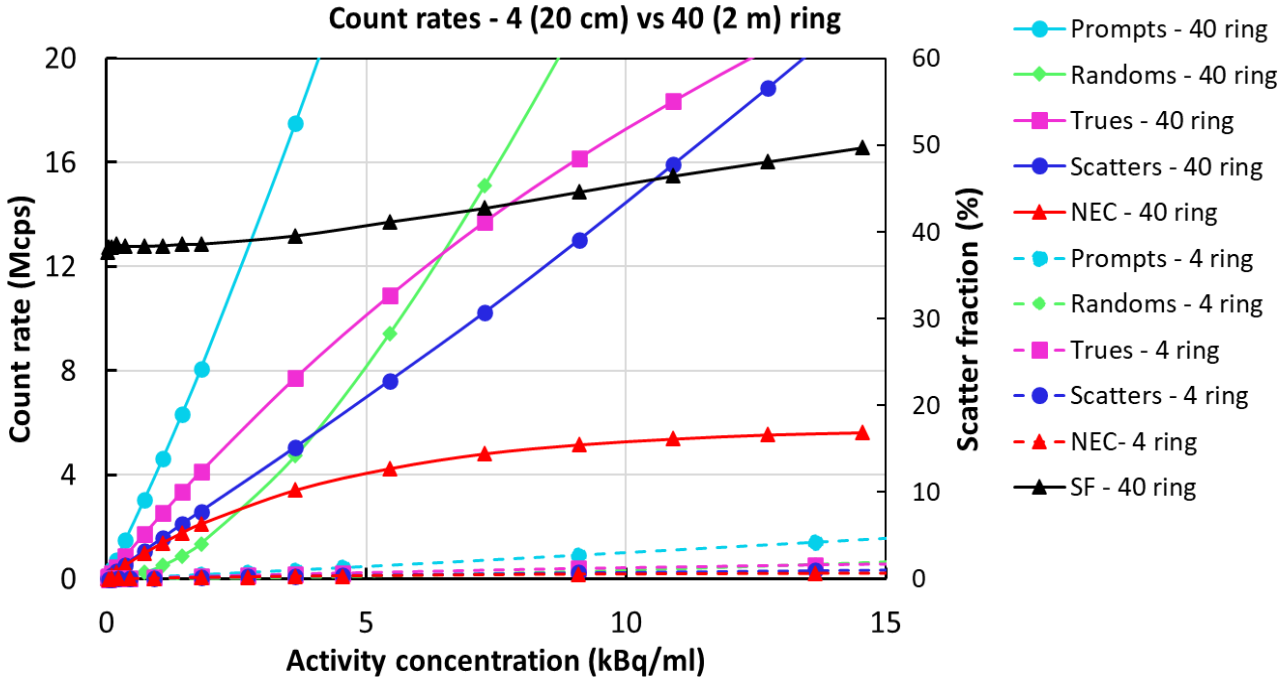
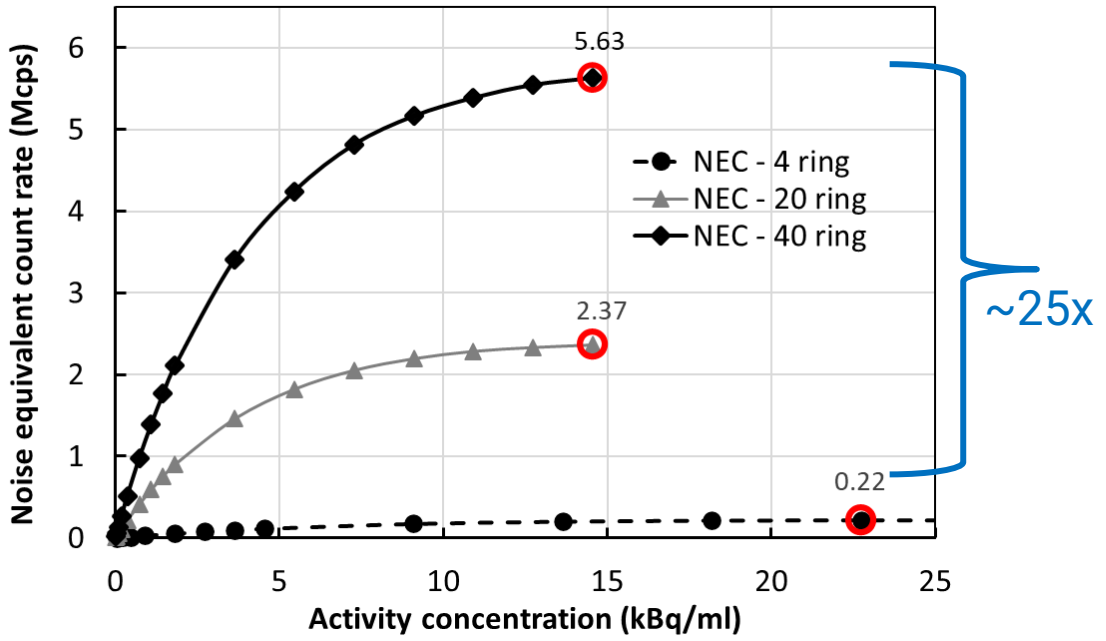
Count rates comparison

- 4-ring scanner with 70 cm scatter phantom
- 20 & 40-ring scanner with 175 cm long scatter phantom





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Conclusion

- Comparison of simulation with measurements resulted satisfactory (~9%), being the values within the measurement uncertainties, in the range of activities practically used in research scans
- Sensitivity gain of ~24-fold if we increase the AFOV to 2 meter
- NECR comparison of 4-ring vs 40-ring scanner gives a performance gain of ~25-fold
- Overall, this preliminary study suggests that gain of ~25x can be achieved if we increase the scanner AFOV to 2 m using the DMI scanner architecture

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Thank you for your kind attention!

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