Detailed simulations of a full-body RPC-PET scanner

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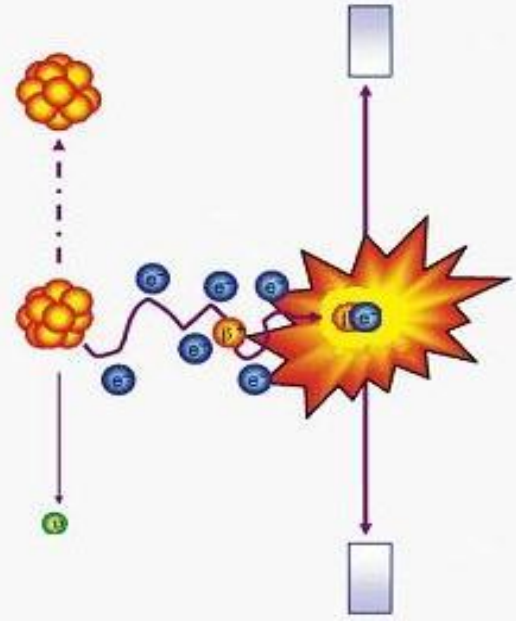
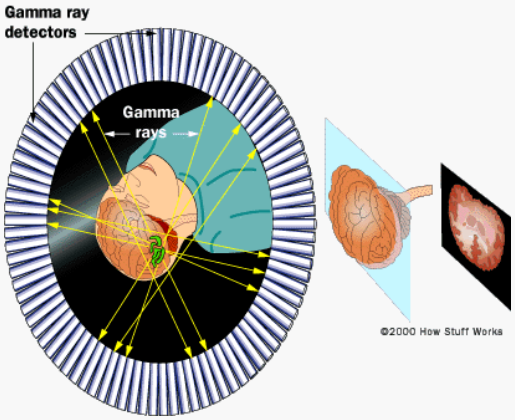
1. Introduction to PET

Brief PET overview

- PET is a medical imaging technique, aimed to study functional processes
- An appropriate molecule, labelled with a positron emitter radioisotope, is injected in the patient
- When a decay occurs, a positron is emitted, which loses energy in several collisions, combining then with an electron from the medium
- Since the positron is the electron antimatter, an annihilation occurs, resulting in two 511 keV photons emitted in opposite directions
- Annihilation photons, detected in an appropriate time window (4 to 12 ns), are recorded, defining a Line Of Response (LOR)
- Image is reconstructed from the acquired LOR

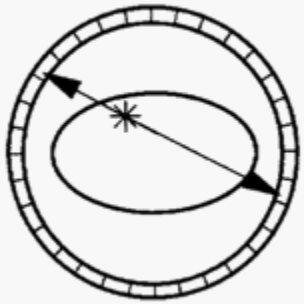




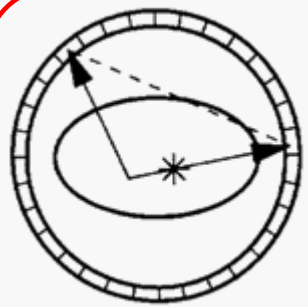
1. Introduction to PET

Brief PET overview

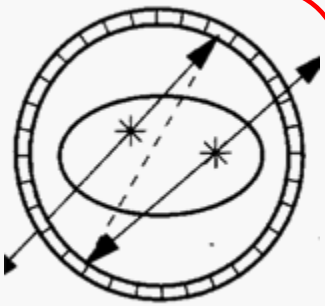
- Three types of coincidence events can occur
  - True coincidences: photons from a single decay leave the patient without suffering interactions
  - Scattered coincidences: one or both photons from a single decay interact in the patient, losing energy, and changing their initial direction
  - Random coincidences: photons from different decays detected in coincidence



True



Scattered



Random

False lines of response ⇒ must be rejected

1. Introduction to PET

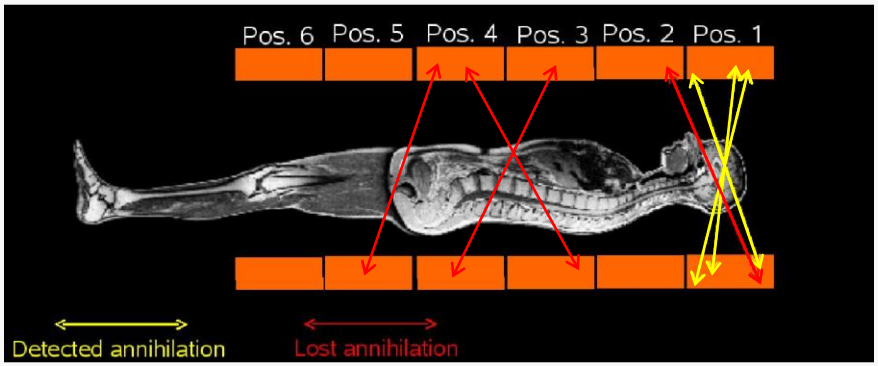
Brief PET overview

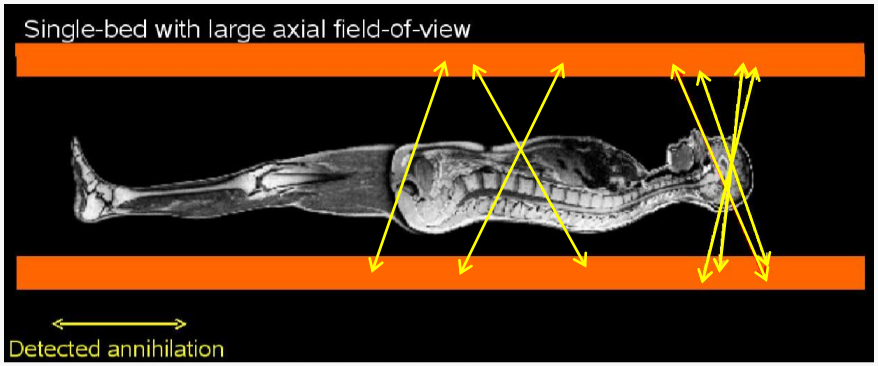
- **State of the art PET scanners**
  - Scintillation crystal detectors with high efficiency for 511 keV photons and good energy resolution for scatter rejection
  - Reduced Axial Field Of View
  - Several bed positions to obtain a full body image
  - Increased injected activity
  - Discontinuous uptake signal

- **Full body PET scanner**

[D.B.Crosetto, 2000]

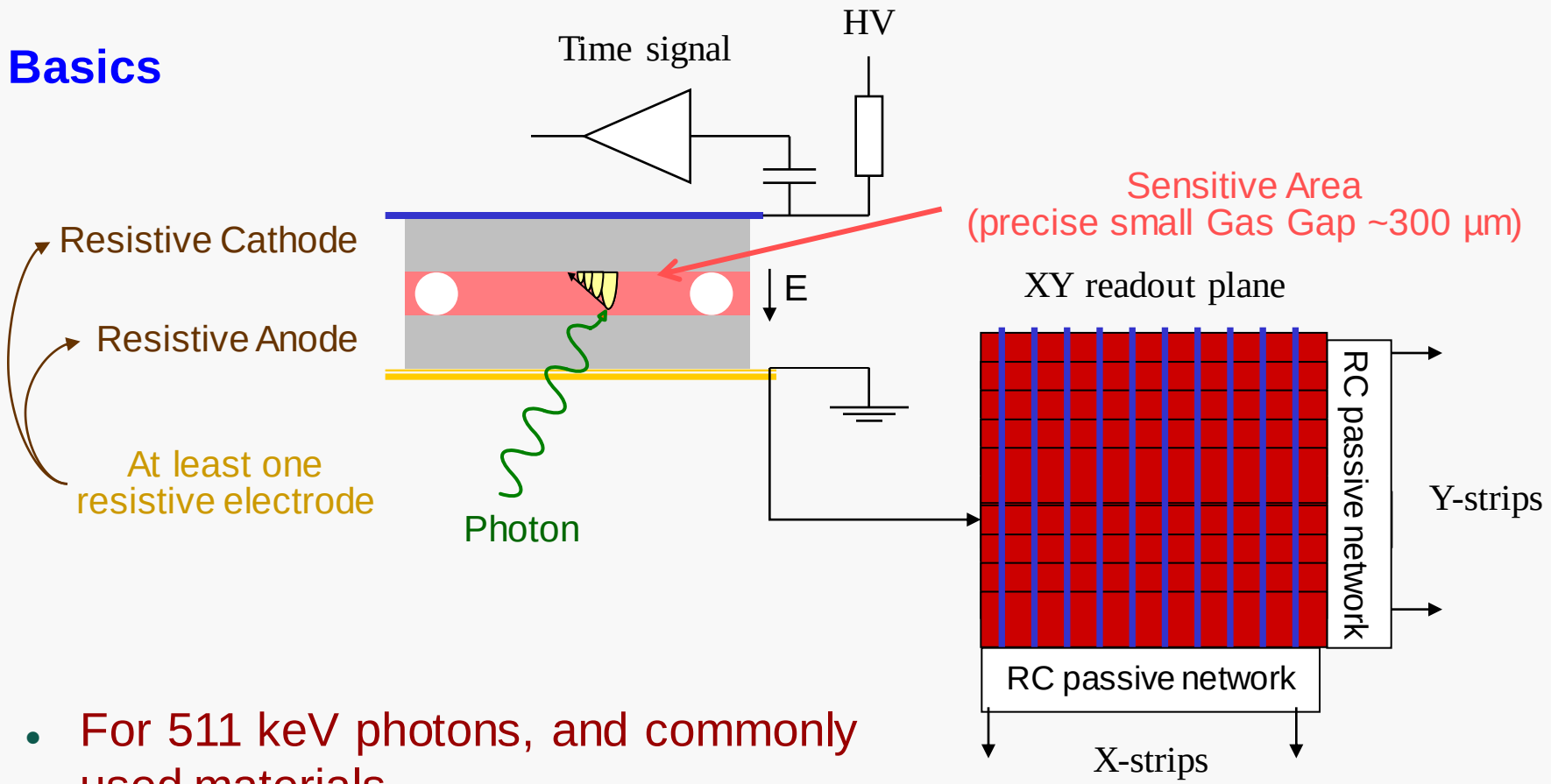
  - Full Axial Field Of View
  - Single bed position to obtain a full body image
  - Reduced injected activity
  - Continuous uptake signal
  - Too expensive with crystal detectors
  - RPC may be a suitable detector for full body PET scanners





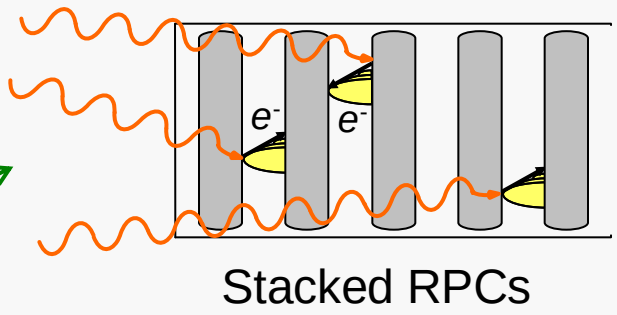
2. Resistive Plate Chamber

Basics



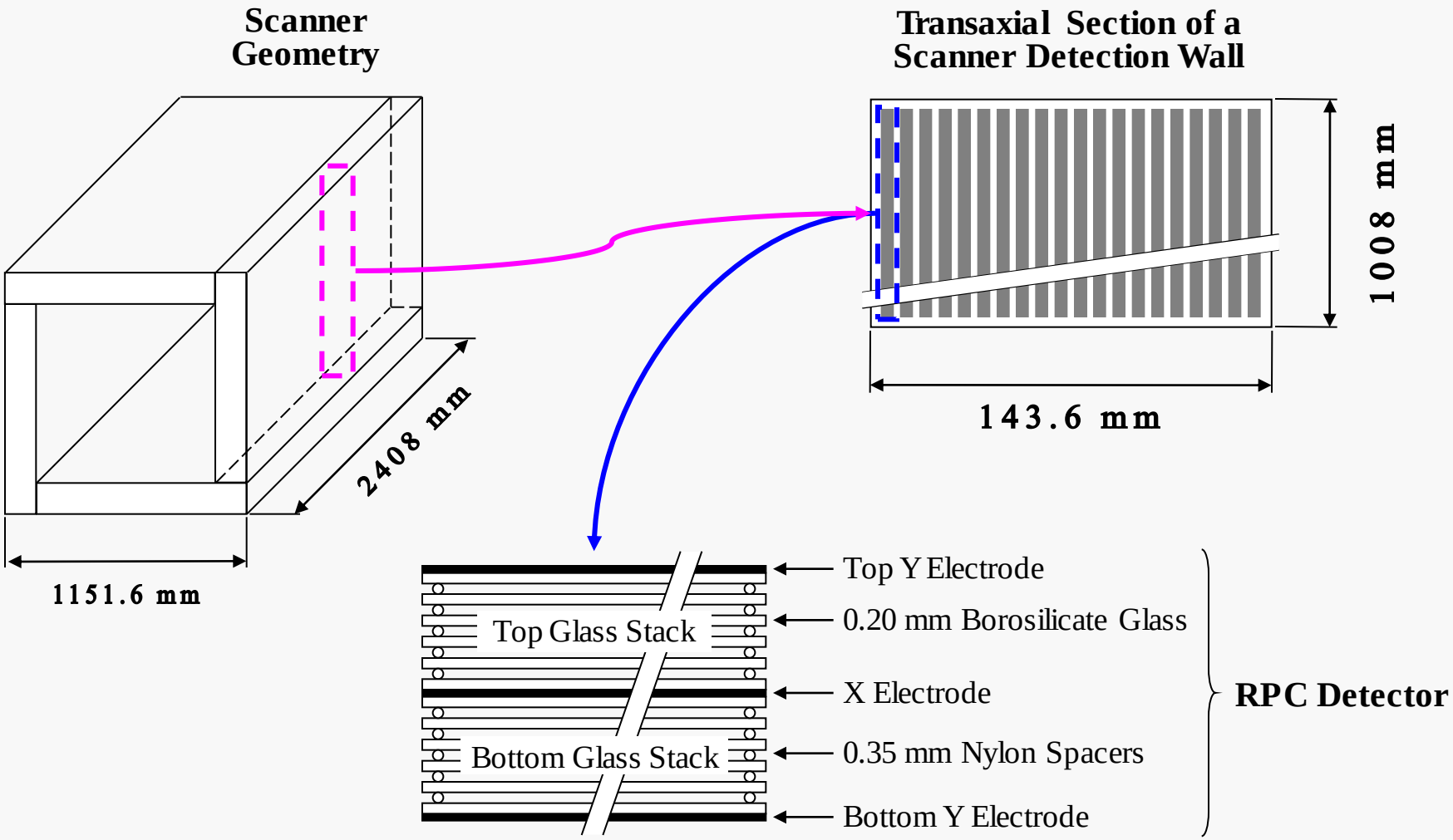
[A. Blanco et al., 2003]

- For 511 keV photons, and commonly used materials
  - Good timing resolution of 300 ps FWHM for photon pairs
  - No energy resolution
  - < 0.4% efficiency per gap for singles



3. RPC-PET

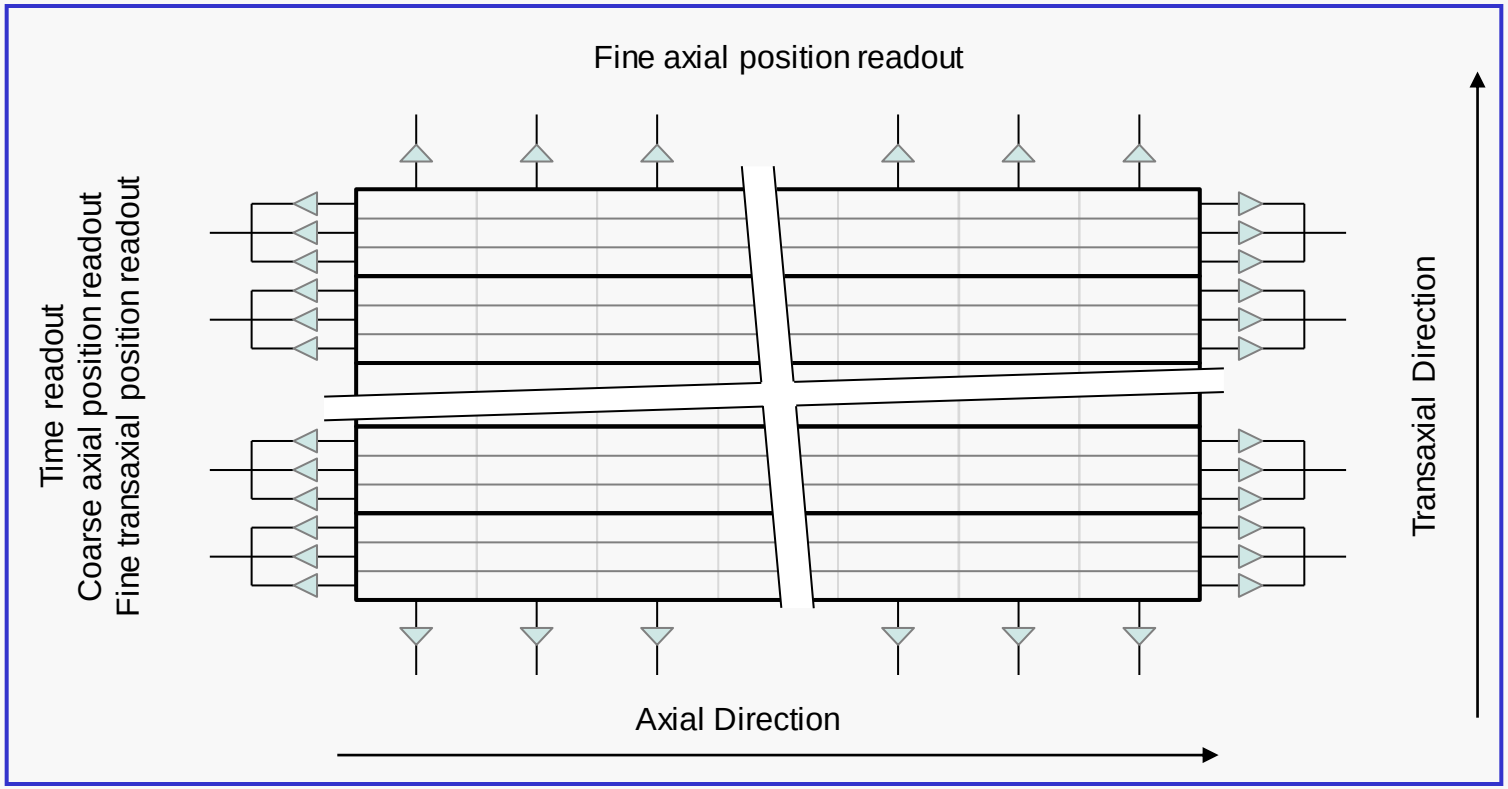
Simulations – Scanner geometry



3. RPC-PET

Data processing – Dead time processing

- Each detector, has 10 independent transaxial readout sections (total of 800 for the scanner)
  - Non-paralyzable dead time for time signals
  - Paralyzable dead time for position signals

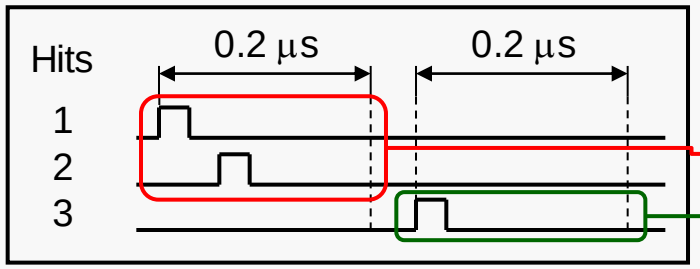


[Patent pending]

3. RPC-PET

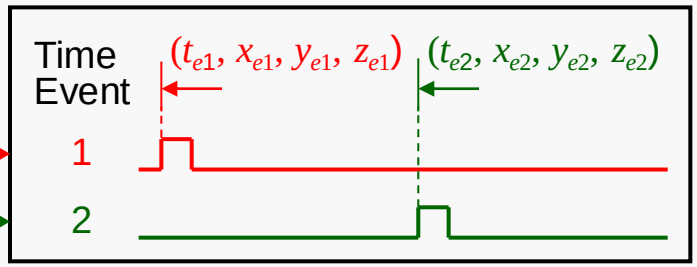
Data processing – Dead time processing (readout section)

Non-paralyzable dead time model applied to all simulation hits



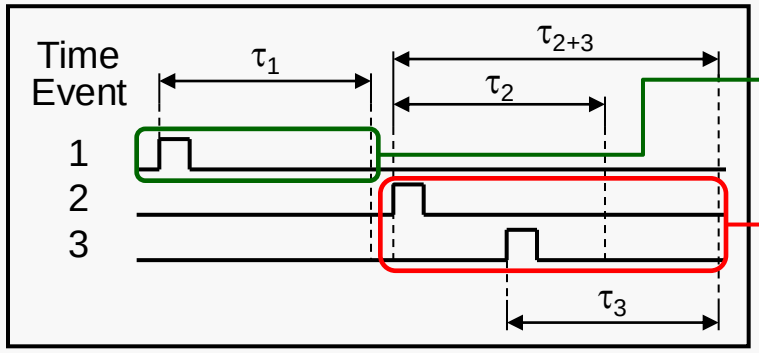
$$\text{Hit 1} \rightarrow \begin{cases} t_{h1} \\ x_{h1} \\ y_{h1} \\ z_{h1} \end{cases} \quad \text{Hit 2} \rightarrow \begin{cases} t_{h2} \\ x_{h2} \\ y_{h2} \\ z_{h2} \end{cases} \quad \text{Hit 3} \rightarrow \begin{cases} t_{h3} \\ x_{h3} \\ y_{h3} \\ z_{h3} \end{cases}$$

Readout generated time events



$$\text{Event 1} \rightarrow \begin{cases} t_{e1} = t_{h1} \\ x_{e1} = (x_{h1} + x_{h2})/2 \\ y_{e1} = (y_{h1} + y_{h2})/2 \\ z_{e1} = (z_{h1} + z_{h2})/2 \end{cases} \quad \text{Event 2} \rightarrow \begin{cases} t_{e2} = t_{h3} \\ x_{e2} = x_{h3} \\ y_{e2} = y_{h3} \\ z_{e2} = z_{h3} \end{cases}$$

Paralyzable dead time model applied to all valid time events



Final Event

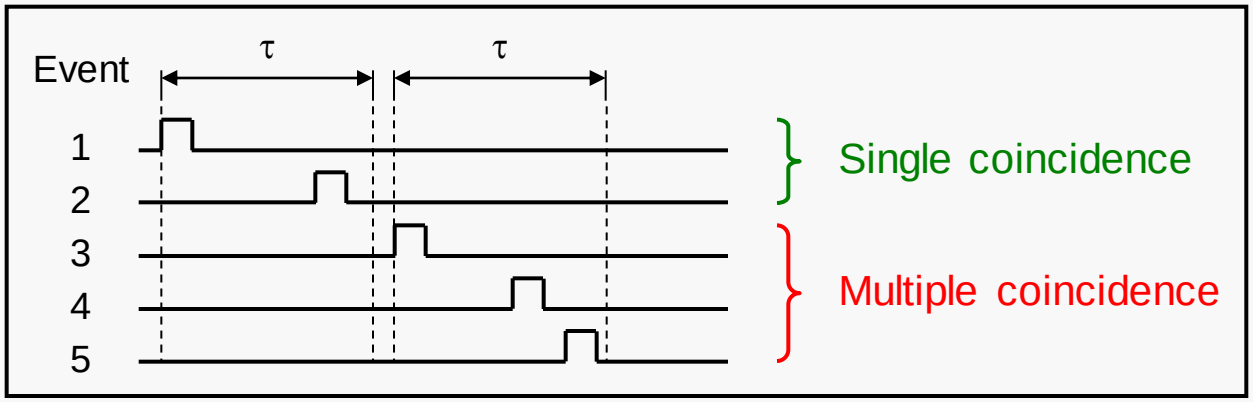
Fine position (3.44 mm binning in the radial direction, and 2 mm binning in the transaxial and axial directions)

Both events can be rejected or accepted with a coarse position (3.44 mm binning in the radial direction, 3 cm binning in the transaxial direction and 1 cm σ Gaussian blur in the axial direction)

3. RPC-PET

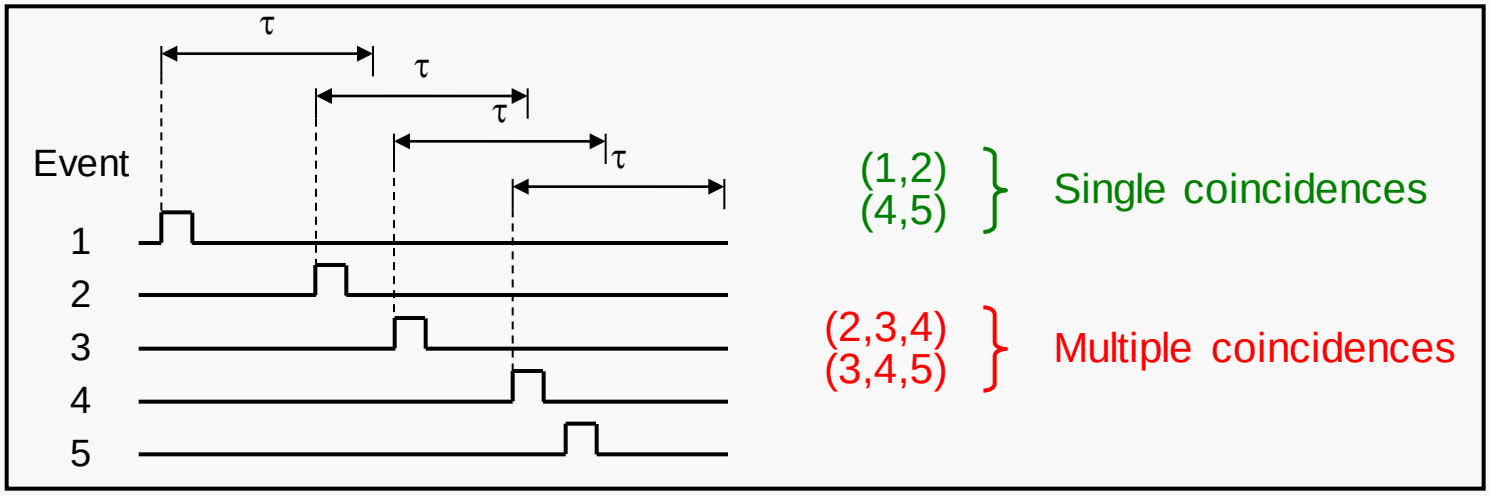
Data processing – Coincidence sorter

- Single time window coincidence sorter



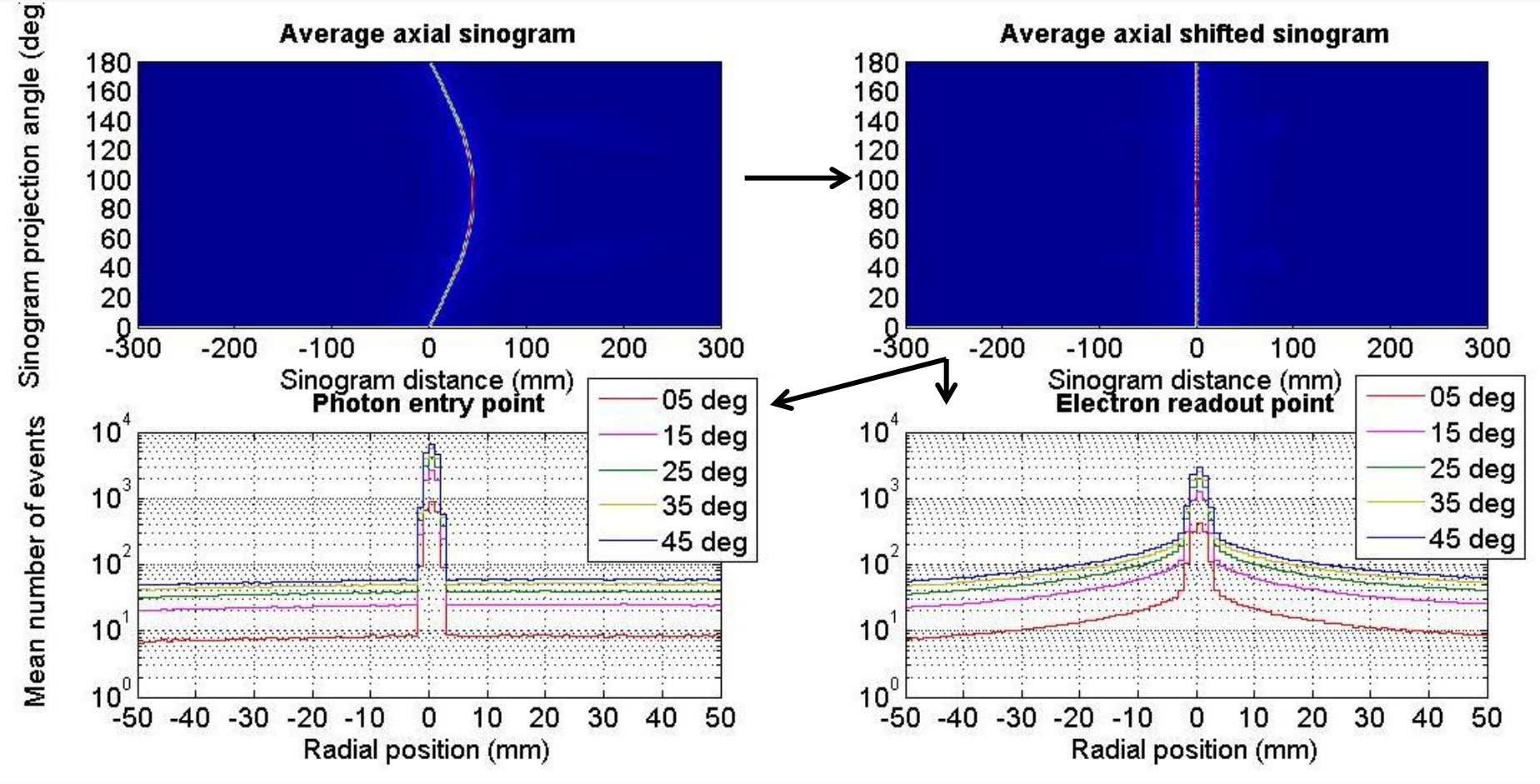
τ = 5 ns

- Multiple time window coincidence sorter



3. RPC-PET

Results – Scatter fraction (NEMA 2001)

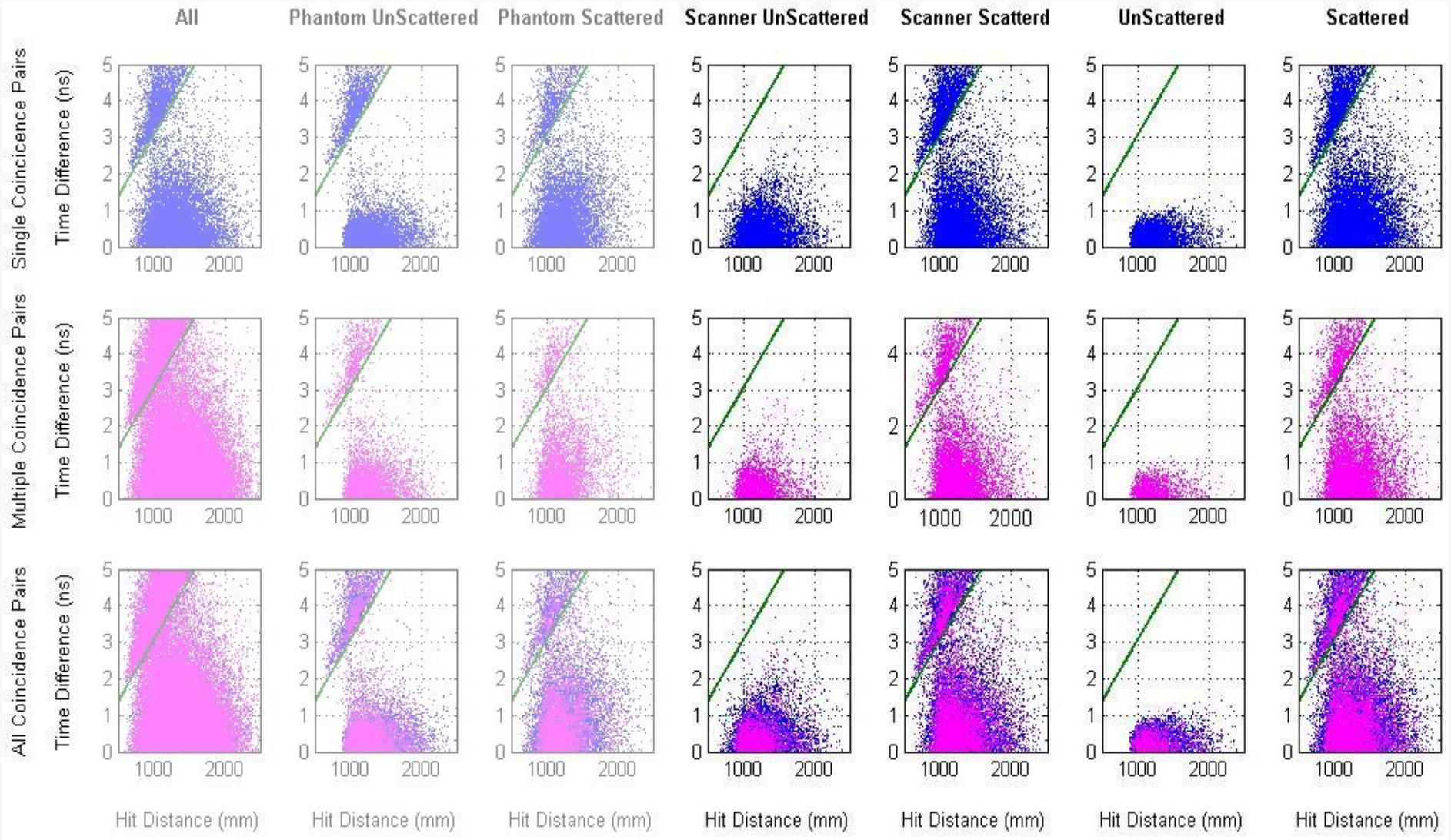


Detector scatter is responsible for some long-range diffusion

3. RPC-PET

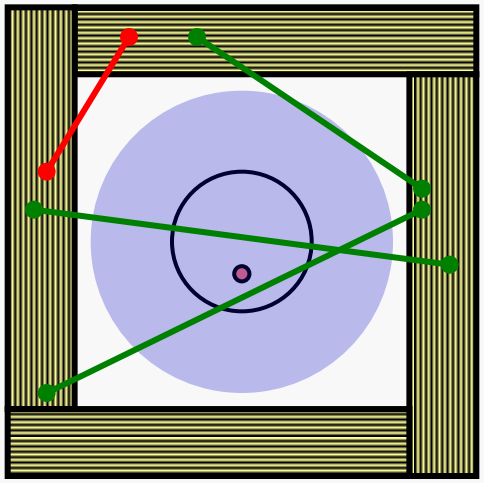
? Best trigger ?

Results – Time-Space patterns for coincidence

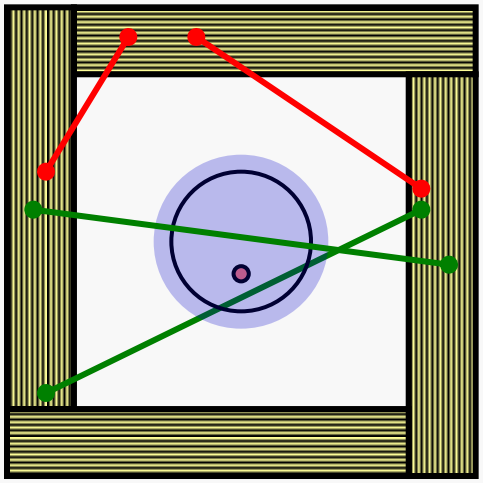


3. RPC-PET

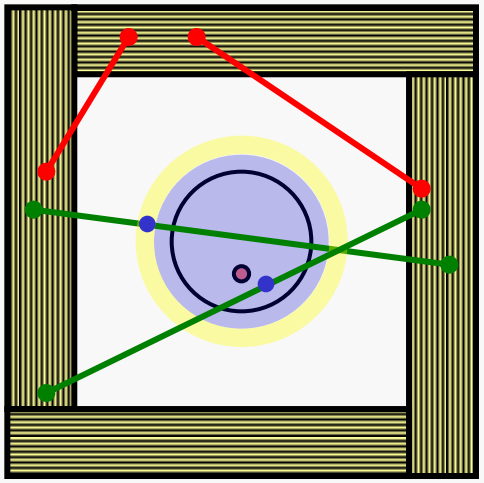
Results – Tested trigger strategies



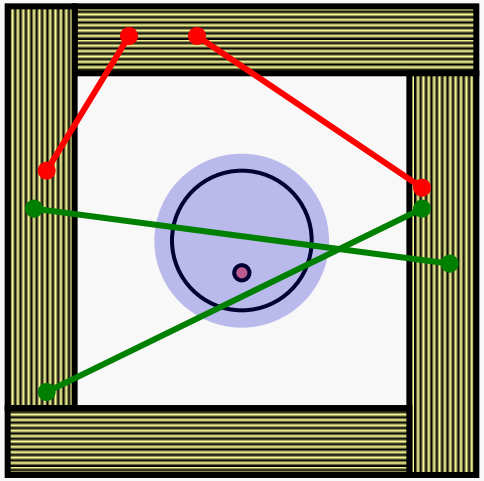
Bore rejection



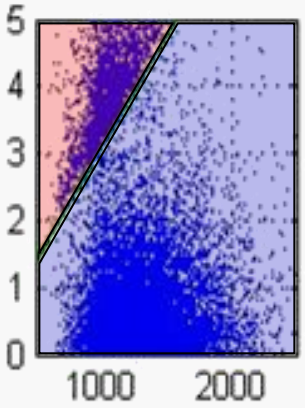
plus



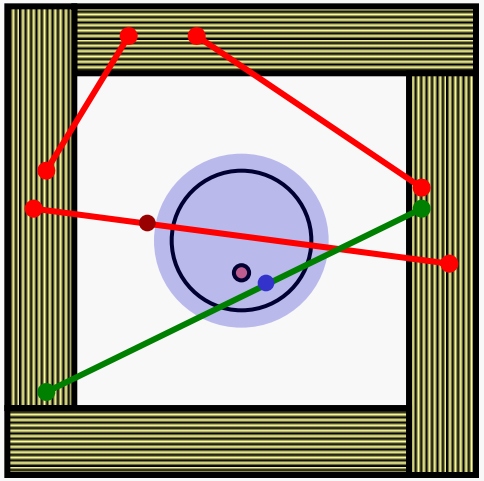
Geometric TOF rejection + 300 ps



Geometric rejection



Time-Space rejection

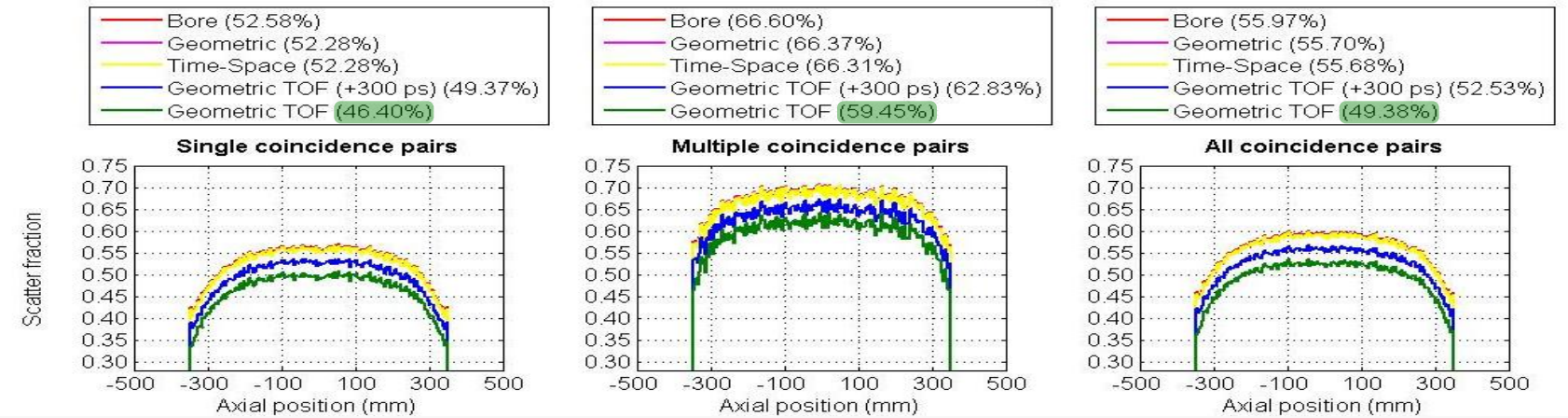


Geometric TOF rejection

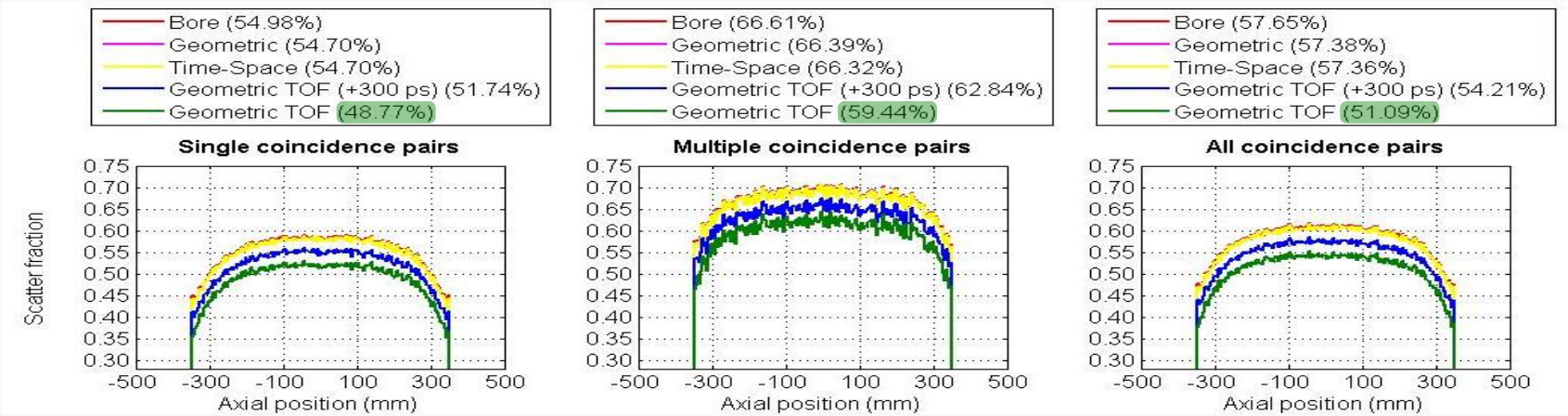
3. RPC-PET

Results – Scatter fraction (NEMA 2001)

Single time window coincidence sorter



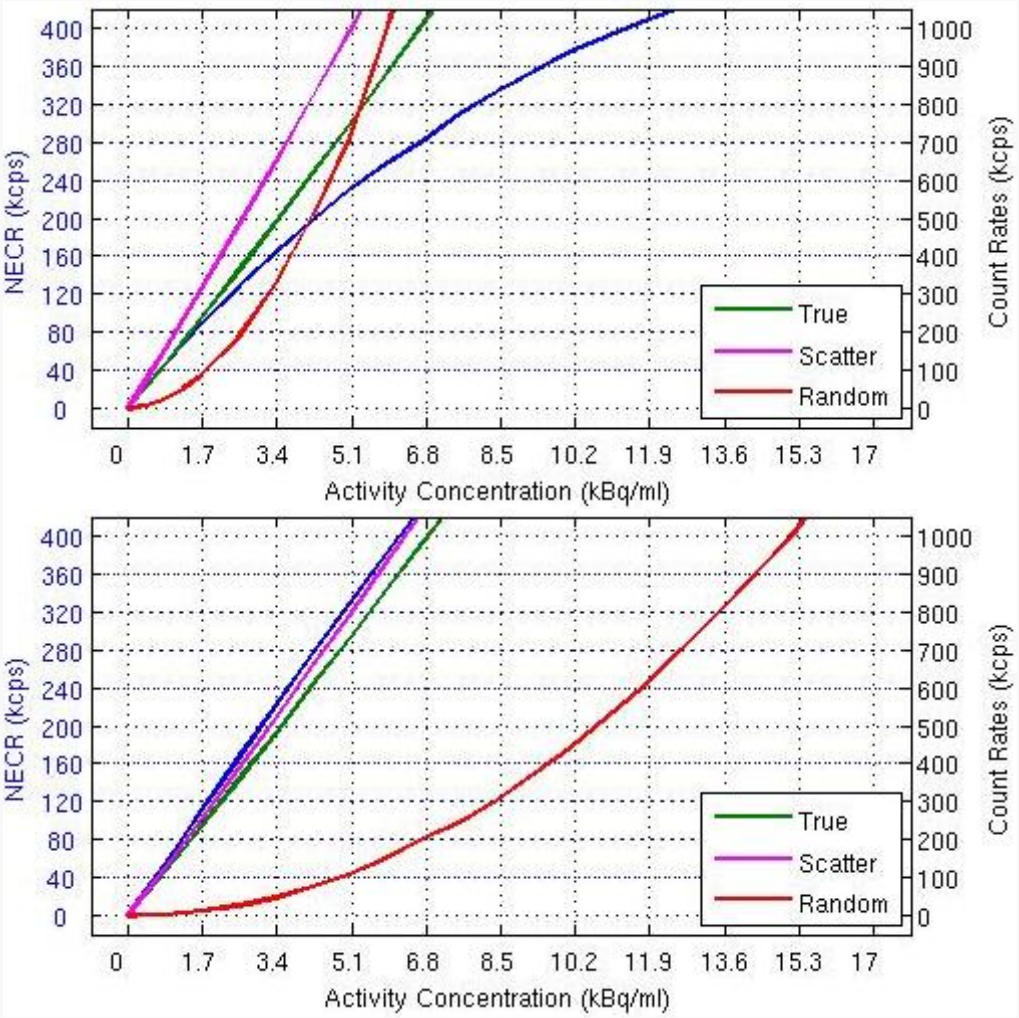
Multiple time window coincidence sorter



3. RPC-PET

Results – Count rates and NECR, with position pileup rejection (NEMA 2001)

0.0 μs dead time for position signal



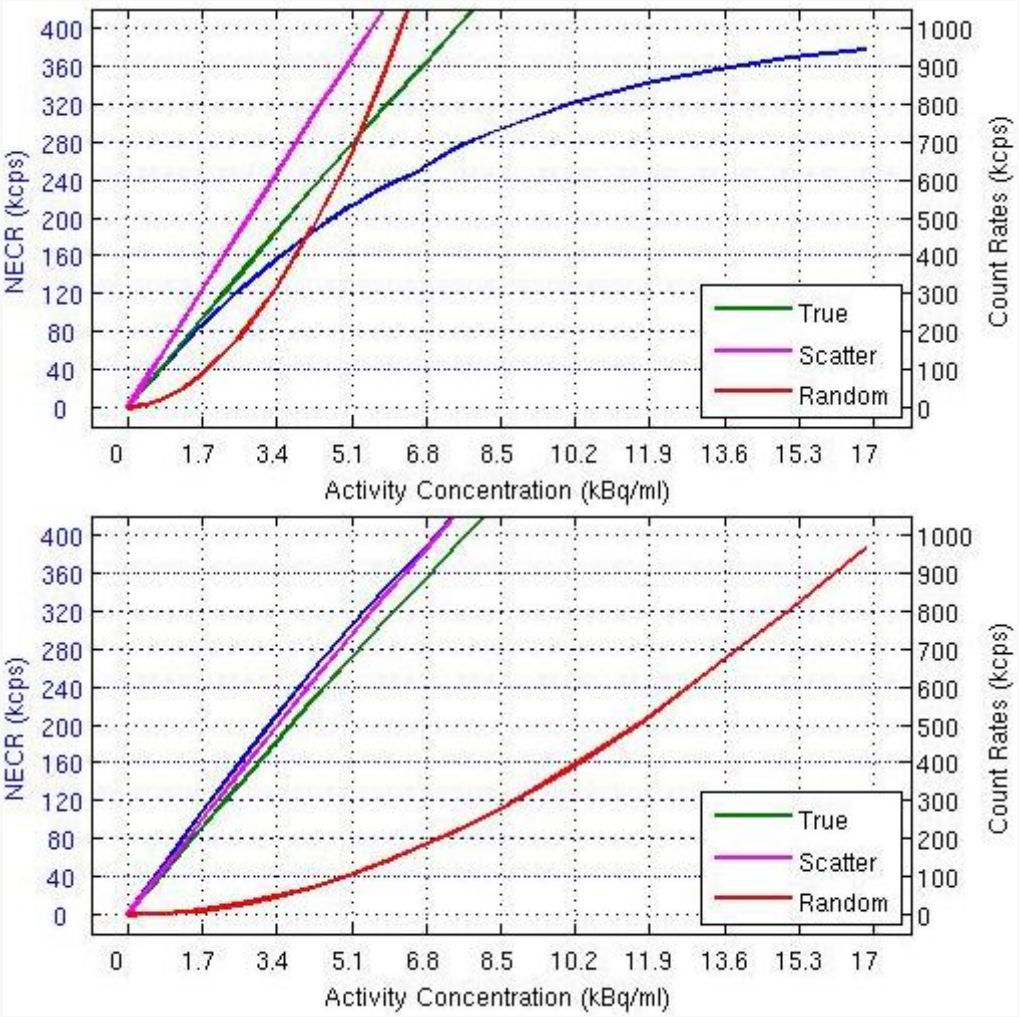
Geometric rejection

Geometric TOF rejection

3. RPC-PET

Results – Count rates and NECR, with position pileup rejection (NEMA 2001)

0.5 μs dead time for position signal



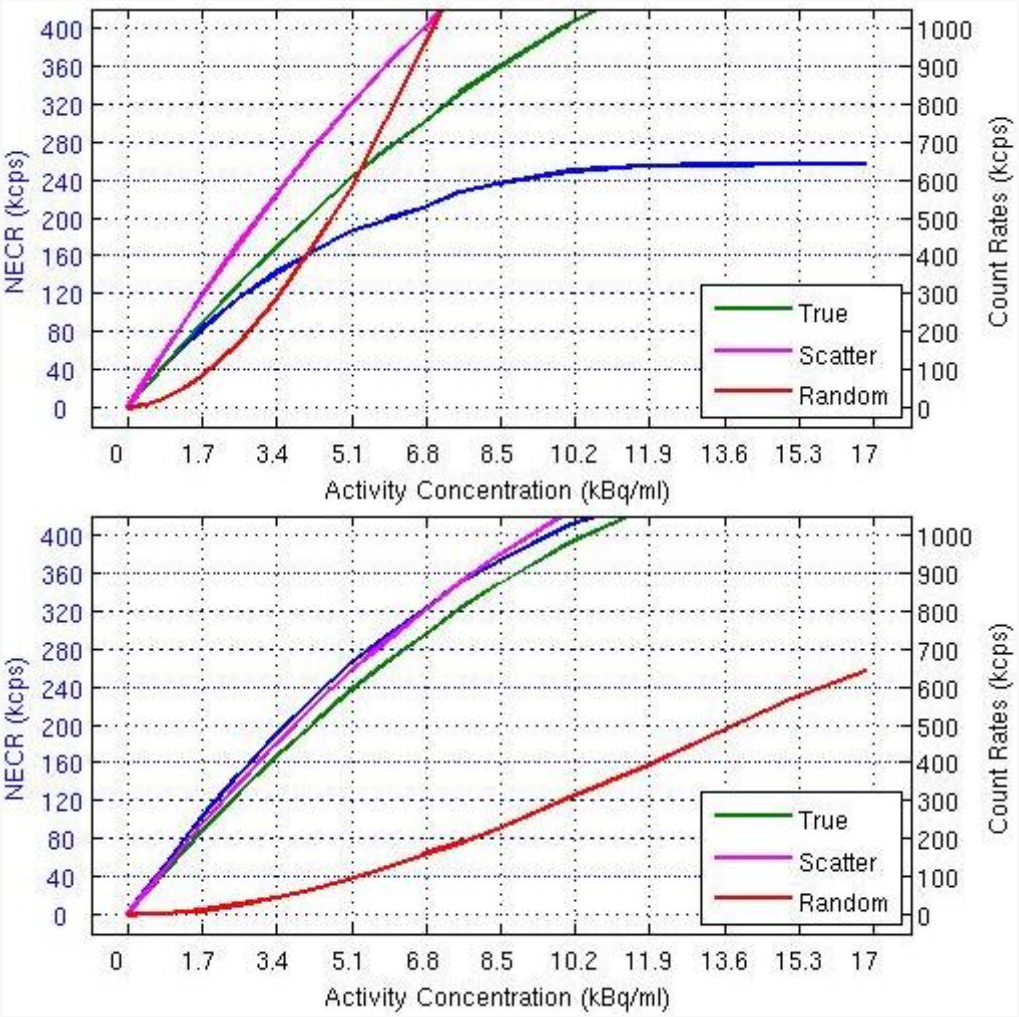
Geometric rejection

Geometric TOF rejection

3. RPC-PET

Results – Count rates and NECR, with position pileup rejection (NEMA 2001)

1.0 μs dead time for position signal



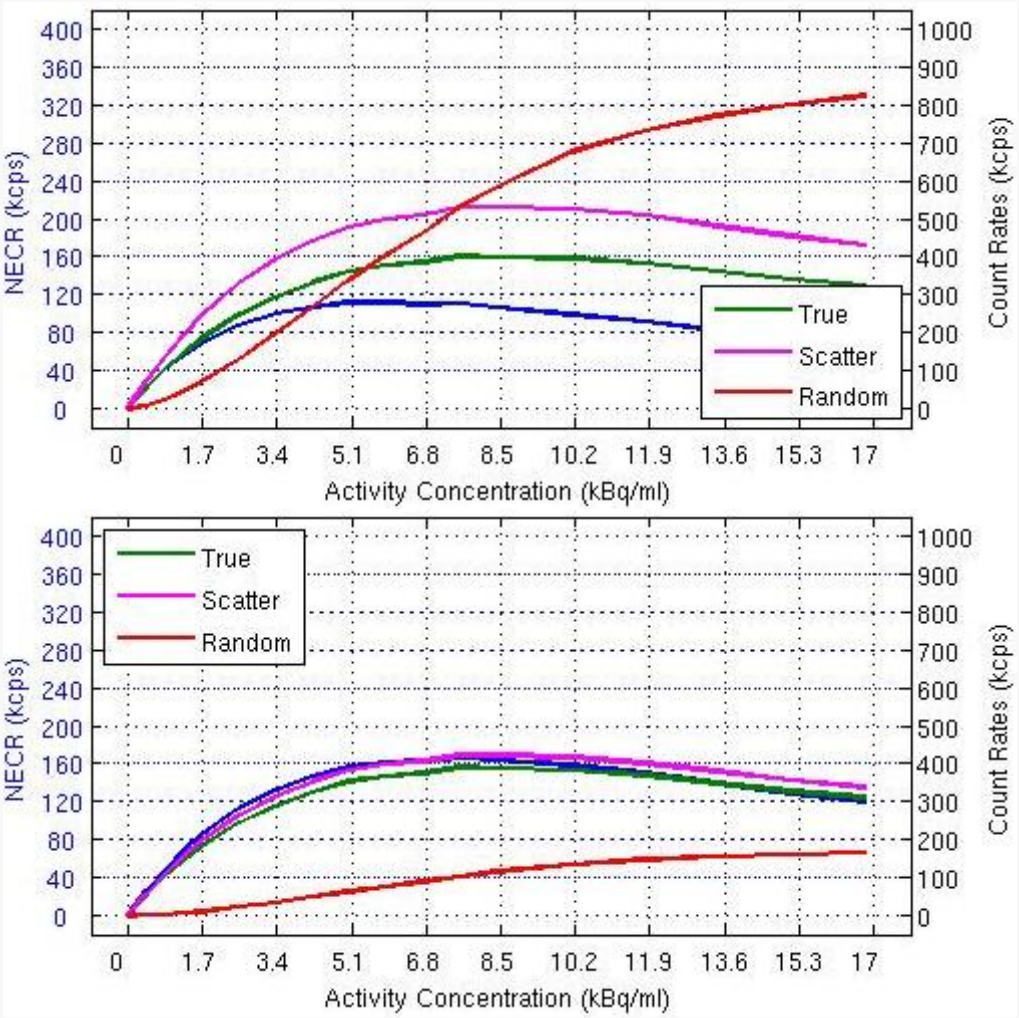
Geometric rejection

Geometric TOF rejection

3. RPC-PET

Results – Count rates and NECR, with position pileup rejection (NEMA 2001)

3.0 μs dead time for position signal



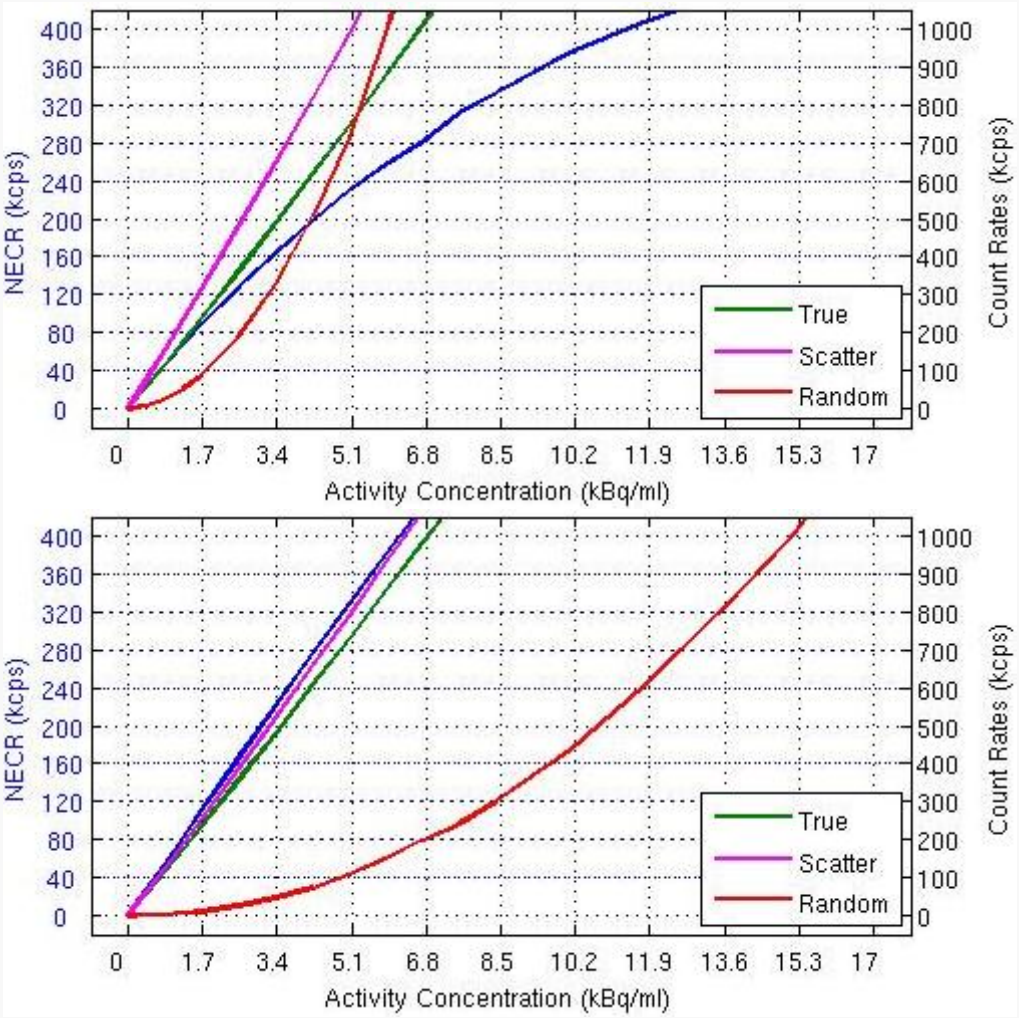
Geometric rejection

Geometric TOF rejection

3. RPC-PET

Results – Count rates and NECR, with coarse position (NEMA 2001)

Independent of dead time for position signal

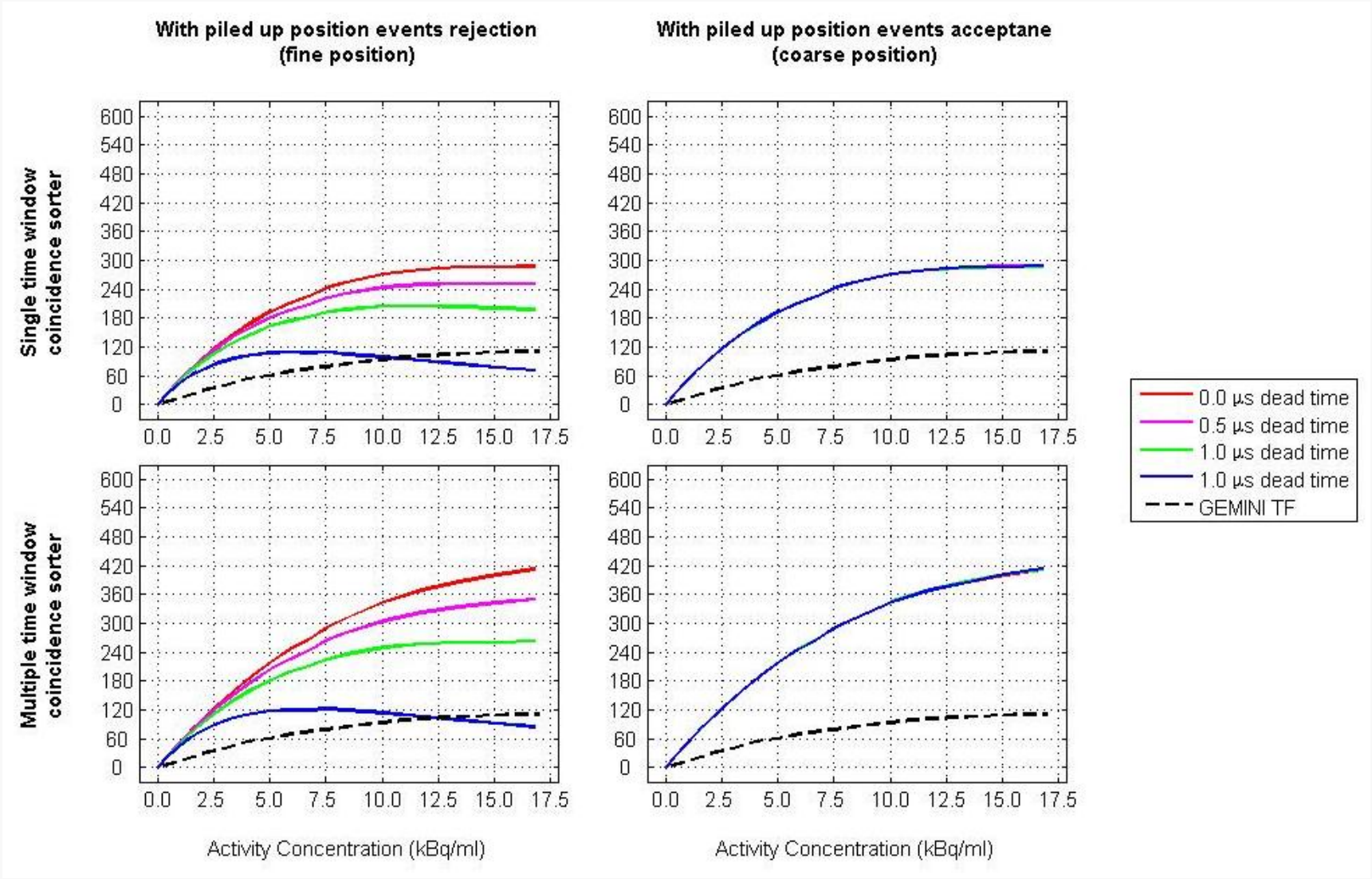


Geometric rejection

Geometric TOF rejection

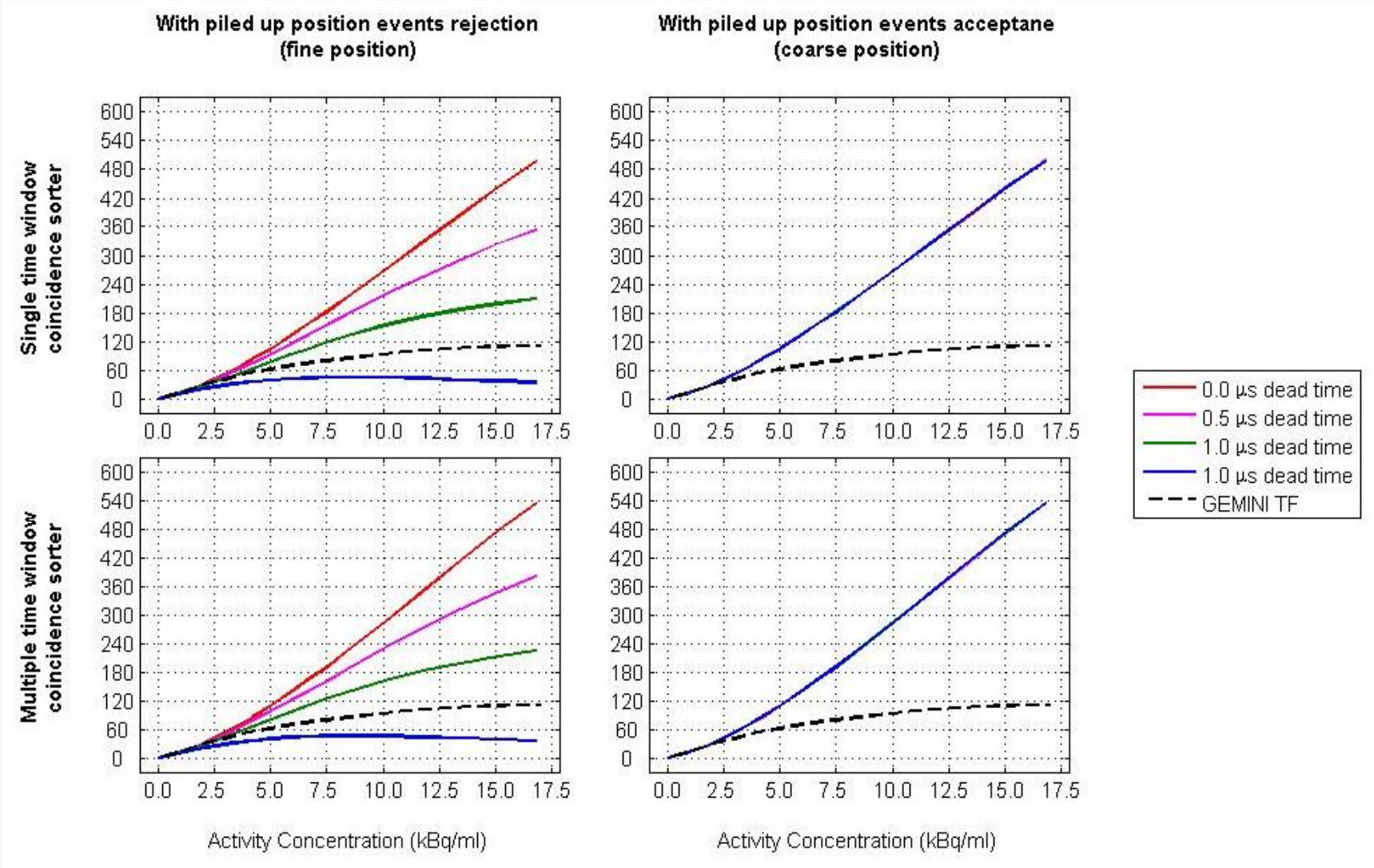
3. RPC-PET

Results – NECR for single coincidence pairs (NEMA 2001)



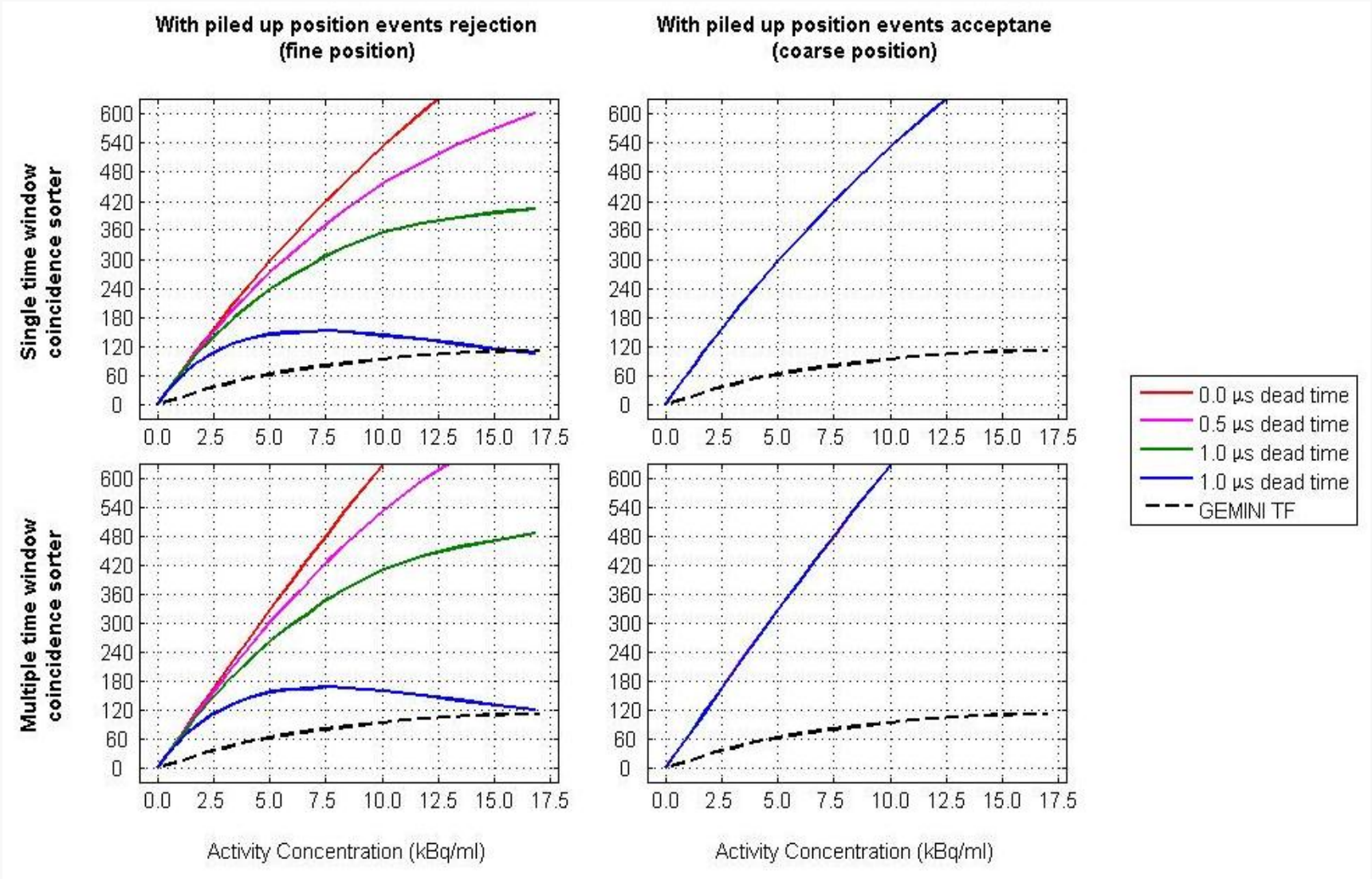
3. RPC-PET

Results – NECR for multiple coincidence pairs (NEMA 2001)



3. RPC-PET

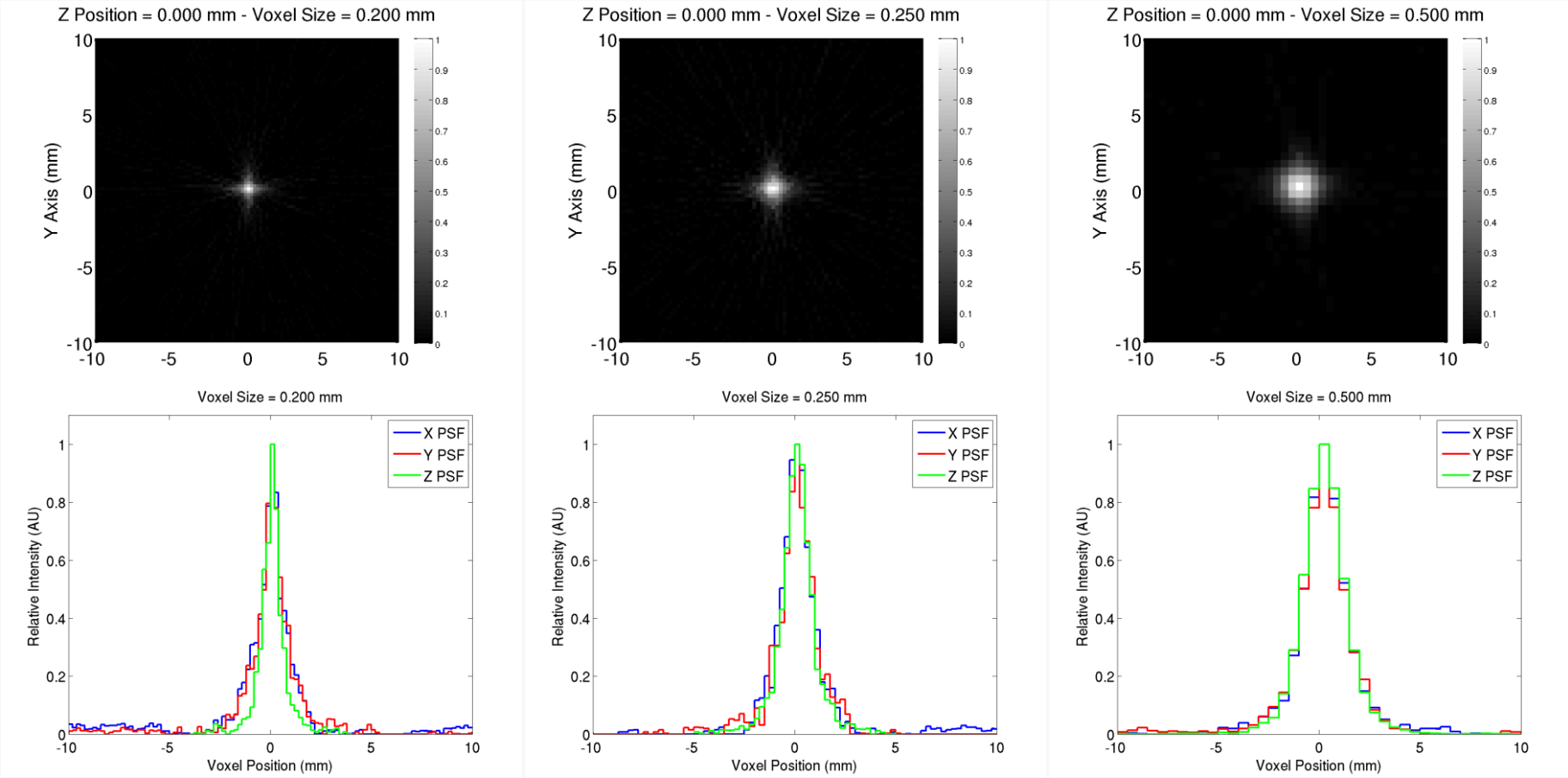
Results – NECR for all possible coincidence pairs (NEMA 2001)



3. RPC-PET

Results – Spatial resolution (NEMA 2001)

Only DOI	DOI + 1.0 mm Binning	DOI + 2.0 mm Binning



Mean = 0.8 mm	Mean = 1.4 mm	Mean = 2.1 mm

[M.Couceiro et al, 2012]

4. Conclusions

- Disadvantages in comparison to crystal based detectors
  - Much smaller detection efficiency (20% to 50%)
  - No energy resolution (although energy sensitivity)
- Previous simulations suggested that RPC-PET will have a significant improvement in sensitivity over current technology
- Current simulations suggest that RPC-PET has higher scatter fractions than those present in current crystal based PET scanners, which however do not compromise system performance, as measured by the NEMA NU-2 2001
- However, it is still necessary to test the spatial resolution at high count rates, and image quality as stated in NEMA NU-2 2001 protocol to conclude if coarse position policy can effectively be used to further increase NECR

Acknowledgments

- Laboratory for Advanced Computation (LCA) of the University of Coimbra, Portugal, for a very generous gift of computing time (300,000 hours)

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