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Positron Emission Tomography Simulation using GATE/GEANT4

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Hoang Thi Kieu Trang (Trang HOANG)

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Education

- **1998**: Bachelor in Nuclear Physics, University of Science, Vietnam National University, Vietnam
- **2003**: Master in Nuclear Physics, University of Science, Vietnam National University, Vietnam
- **2012**: Ph.D. in Experimental High Energy Physics, Florida State University, USA

Professional Experience

- **1998 – 2005**: Teaching Assistant, University of Sciences HCMC, Vietnam
- **2005 – 2007**: Ph.D. Student, Teaching Assistant, Florida State University, USA
- **2007 – 2012**: Ph.D. Student, Research Assistant based at Fermilab, Florida State University, USA
- **2013 – Present**: Lecturer, University of Science, Vietnam National University Ho Chi Minh City
- **2022 – 2024:** Project Manager, NuVirLab - Virtual Laboratory for Nuclear and Medical Physics

Research Interests

- Medical Image Processing
- Nuclear Medicine
- Monte Carlo Simulation
- Software Development (C++, python, web app)

Courses Taught

- Medical Image Processing
- Nuclear Medicine
- Radiation Physics
- Quantum Mechanics
- Modern Physics

Networking

- **2002 – Present**: Member of the Vietnam Nuclear Science and Technology Association
- **2014 – Present**: Member of the Vietnam Society for Medical Physics
- **2022 – Present**: Member of IEEE - Nuclear and Plasma Sciences Society

Outline

- What is Monte Carlo Simulation?
- How do you track particles in the Monte Carlo simulation?
- How does the PET system work?
- How do you simulate a PET imaging system?
- How do you reconstruct a PET image?

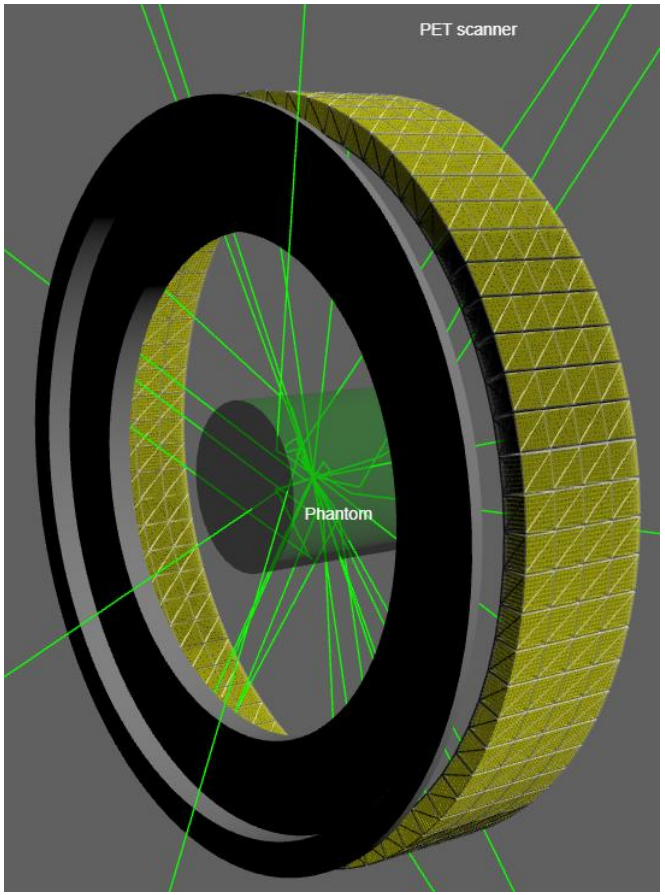
- **Hands-on exercise: PET simulation**
  - Experiment setup
  - Exercises

Introduction to Monte Carlo Simulation

What is Monte Carlo Simulation?

- **Monte Carlo simulation** is a computational technique used to model and analyze complex systems through random sampling

- **Simulation Capabilities**
  - Modeling System Geometry
  - Simulating Particle Interaction Processes



Introduction to Monte Carlo Simulation

What is needed to simulate an experimental system?

Popular Monte Carlo Simulation Codes:

- **GEANT4:** Widely used in high energy physics, astrophysics, and medical physics
- **MCNP(X)**: Effective for simulating the transport of neutron, electrons and positrons
- **EGSnrc**: Focused on radiation transport and dosimetry in medical physics
- **PENELOPE:** Used for simulating the transport of photons and electrons, particularly in medical applications
- **FLUKA**, **PHITS**, etc.

Introduction to Monte Carlo Simulation

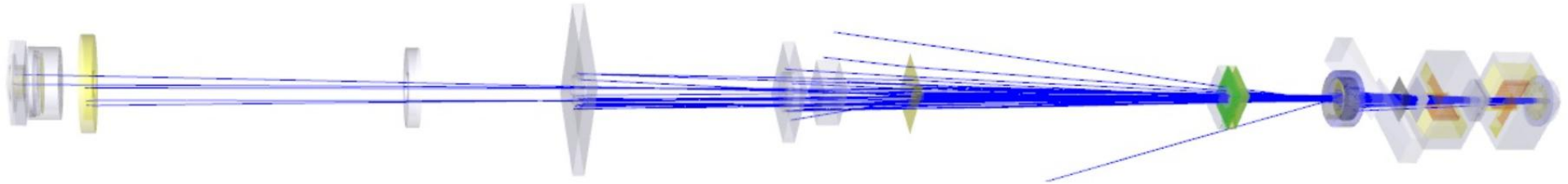
What is needed to simulate an experimental system?

Popular Monte Carlo Simulation Codes:

- **GEANT4:** Widely used in high energy physics, astrophysics, and medical physics

Requirements for Using GEANT4:

- Solid understanding of physics
- Strong programming skills
- Access to adequate computing power



Introduction to Monte Carlo Simulation

What is needed to simulate an experimental system?

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- **GEANT4:** Widely used in high energy physics, astrophysics, and medical physics

Custom Application Using Geant4 in Medical Physics

- Geant4-DNA - Geant4-DNA project
- G4MED - Geant4 Medical Physics in Japan
- G4NAMU - Geant4 North American Medical User Organization
- GAMOS - Geant4-based Architecture for Medicine-Oriented Simulations
- **GATE** - Geant4 Application for Tomographic Emission
- GHOST - Human Oncology Simulation Tool
- TOPAS - Geant4 Monte Carlo Platform for Medical Application

Introduction to Monte Carlo Simulation

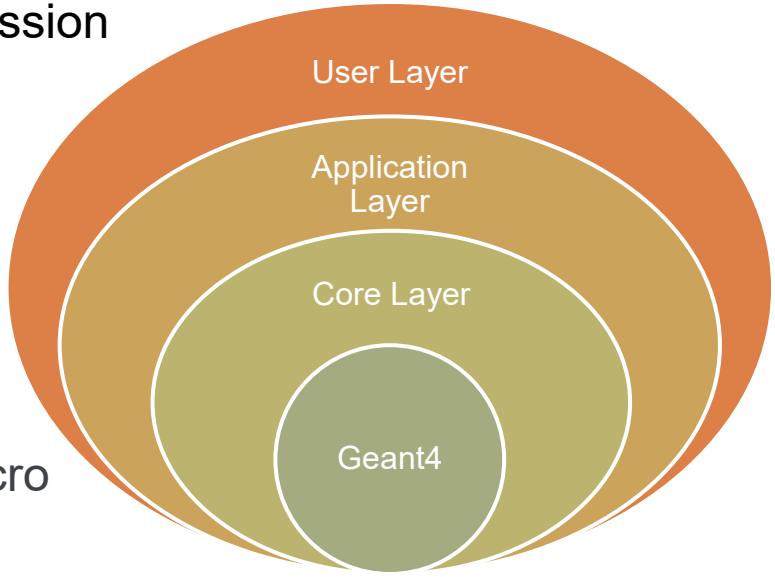
What is GATE?

GATE - Geant4 **A**pplication for **T**omographic **E**mission

- 2001 - 2004: first public release
- Written in C++

GATE encapsulates GEANT4 libraries

- GATE 9.4 (Geant4 11.2)
  - Does not require C++ programming
  - Control Monte Carlo simulations using macro language
- GATE 10 (Geant4 11.3) utilizes a python-based interface



GATE can simulate time dependent phenomena:

- System movements: SPECT, PET or CT detector (rotation/translation)
- Source decay kinetics

Introduction to Monte Carlo Simulation

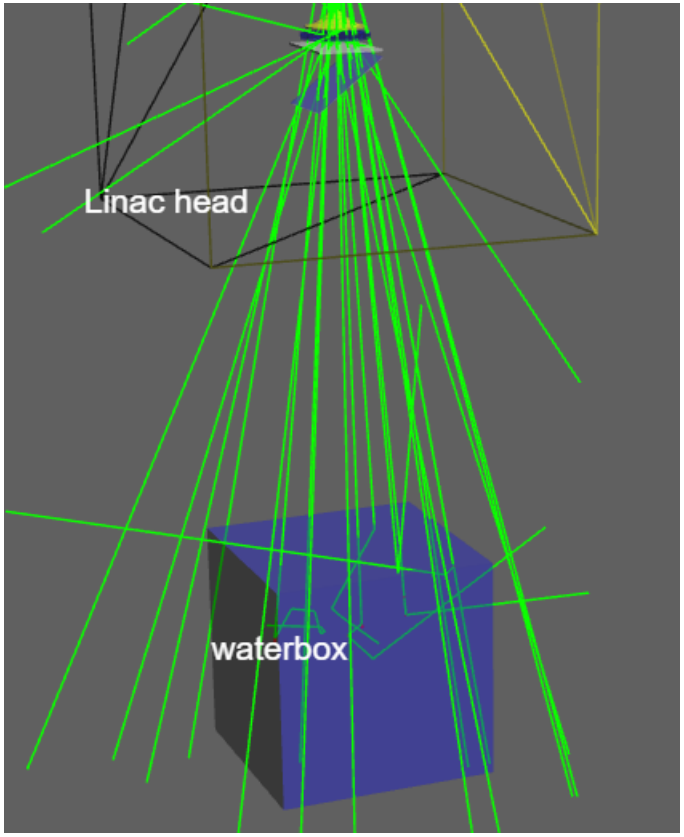
What are the applications of GATE in medical physics?

GATE supports simulations of:

- Emission Tomography
  - Positron Emission Tomography (PET),
  - Single Photon Emission Computed Tomography (SPECT)
- Computed Tomography (CT),
- Optical Imaging (Bioluminescence and Fluorescence)
- Radiotherapy

Introduction to Monte Carlo Simulation

How do you track particles in the Monte Carlo simulation?

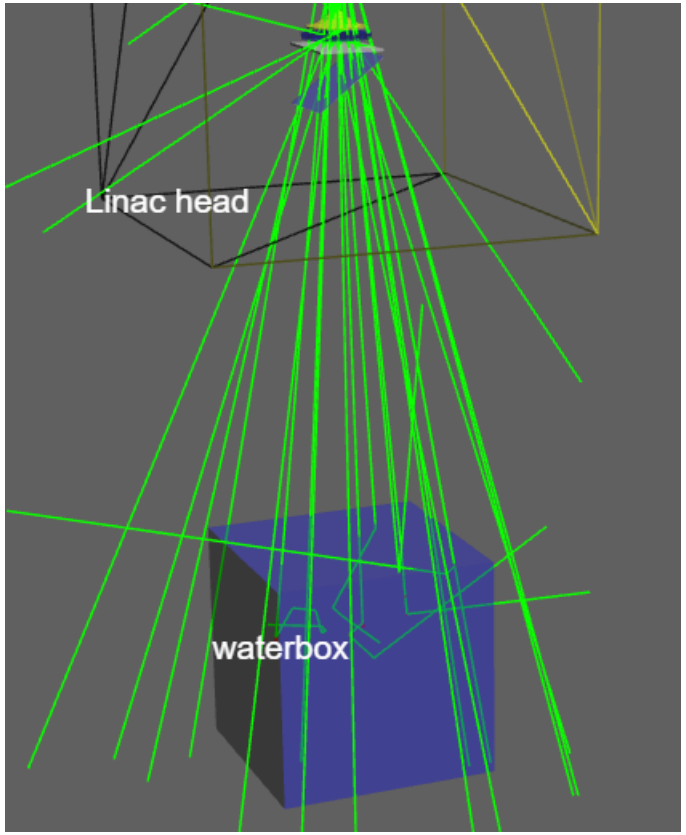


Introduction to Monte Carlo Simulation

How do you track particles in the Monte Carlo simulation?

Step 1: Initialization

- Define the simulation environment
  - Geometry
  - Materials
  - Initial conditions for the particles (e.g., photon, energy, beam shape, direction, etc).

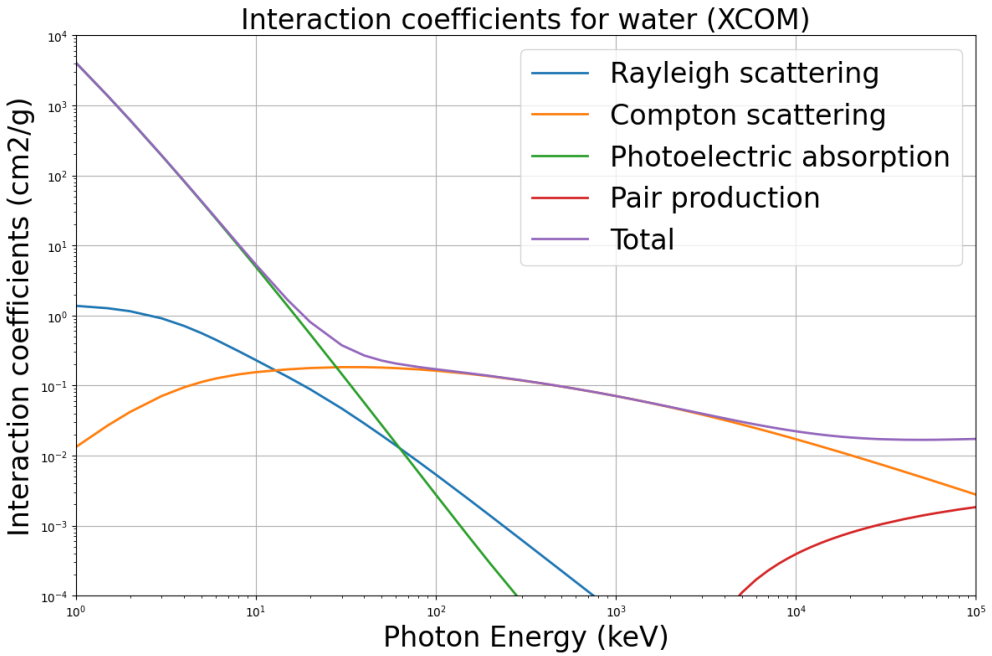


Introduction to Monte Carlo Simulation

How do you track particles in the Monte Carlo simulation?

Step 1: Initialization

- Select Interaction Modeling based on physical laws.
- Main processes of interaction of photons with matter:
  - Photoelectric absorption,
  - Compton scattering,
  - Rayleigh scattering,
  - Pair production

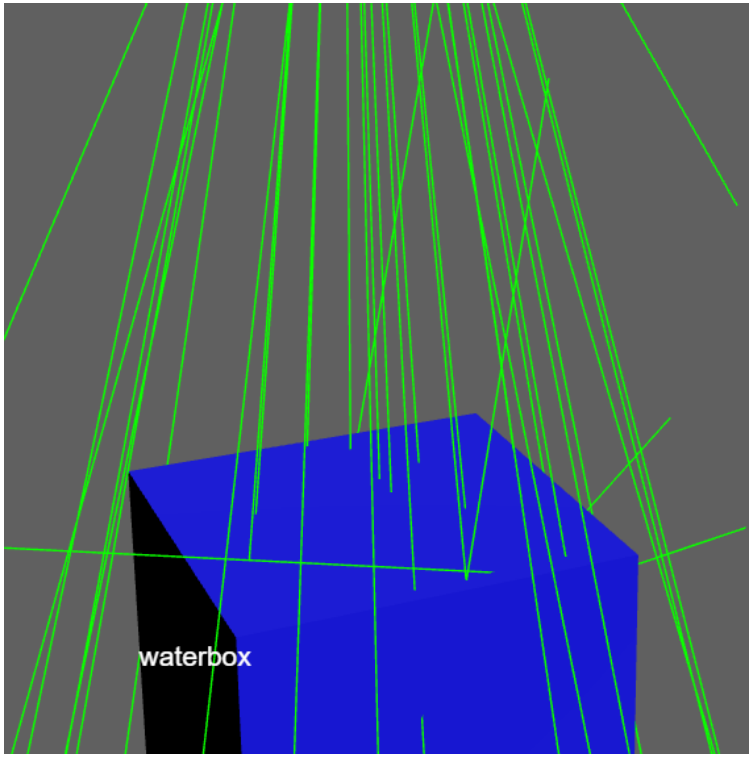


Introduction to Monte Carlo Simulation

How do you track particles in the Monte Carlo simulation?

Step 2: Particle Generation

- Create initial particles based on the defined parameters.
- This can include random sampling of positions and energies.

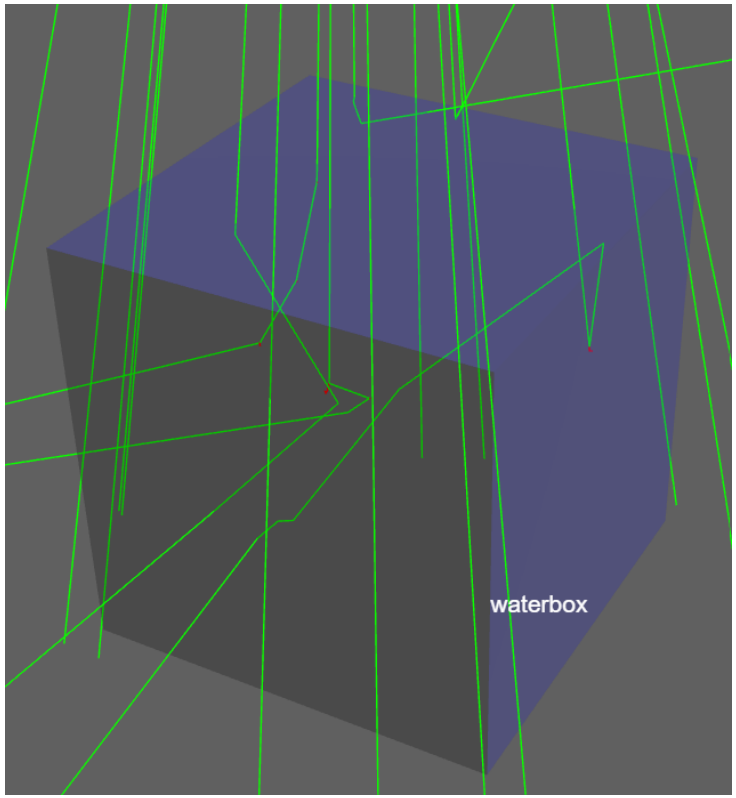


Introduction to Monte Carlo Simulation

How do you track particles in the Monte Carlo simulation?

Step 3: Step-by-Step Tracking

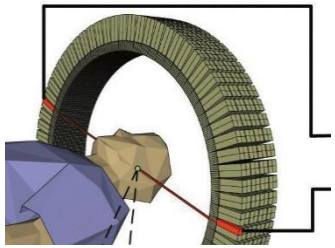
- **Calculate Step Length**: Determine how far the particle will travel before an interaction occurs.
- **Update Position**: Move the particle based on its velocity and the calculated step length.
- **Handle Interactions**: If an interaction occurs, update the particle's properties (e.g., energy loss, direction change) and possibly generate new secondary particles.
- **Boundary Conditions**: Check if the particle exits the defined geometry or interacts with a boundary. If it exits, you may record data (such as energy deposition) or terminate its simulation.



Introduction to Monte Carlo Simulation

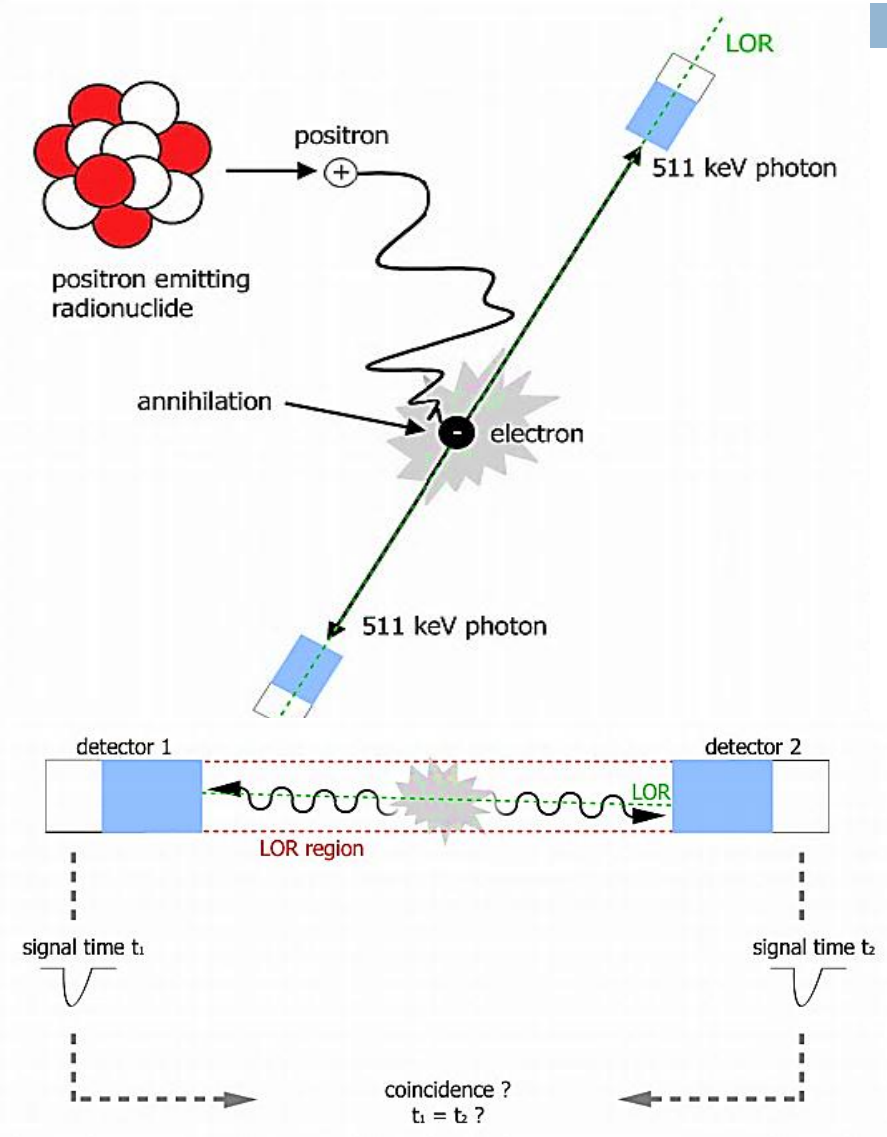
What are the applications of MC simulation in medical physics?

- **Radiotherapy:** MC simulations help calculate dose distributions for treatment techniques, ensuring accurate targeting of tumors while minimizing damage to surrounding tissues.
- **Medical Imaging:** MC simulations can model the interactions of photons and particles, improving image quality and reconstruction algorithms.
- **Dosimetry:** MC methods are employed to assess radiation doses received by patients during diagnostic procedures, ensuring safety and compliance with regulations.
- **Radiation Protection:** MC simulations evaluate radiation exposure in medical environments, helping to design safe protocols and shielding.



Positron Emission Tomography

How does the PET system work?



Coincidence annihilations events:

- Two gamma photons with an energy of 511 keV detected by opposing detectors nearly simultaneously.

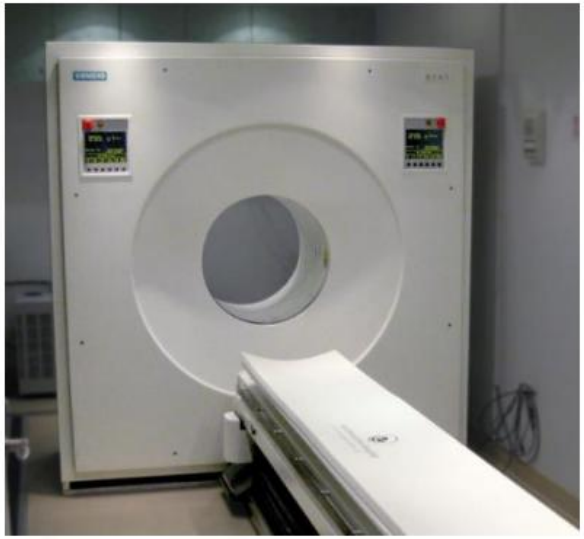
Properties of gammas from the annihilation events:

- **Energy:**
  - $E = 511\,\mathrm{keV} \pm \delta E$
    δE is the energy window.
- **Direction:**
  - Back-to-back emission:
    $\Delta\phi = 180 \circ \pm \delta\phi$
    $\delta\phi$ is the angle window.
- **Time Difference:**
  $\Delta t = 0 \pm \delta t$
  δt is the time window (approximately 0.3 – 0.5 ns).

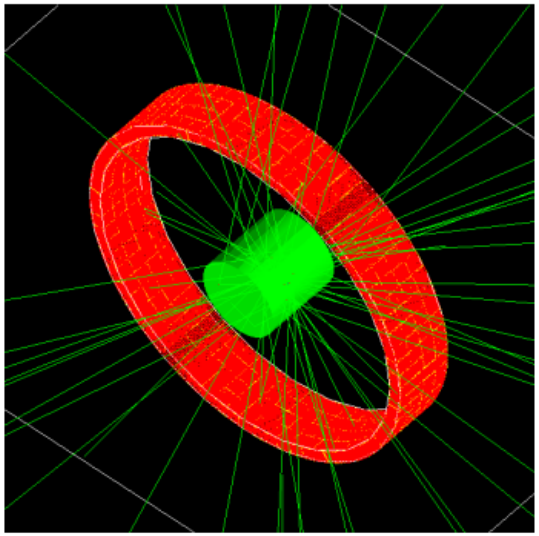
Positron Emission Tomography

How do you simulate a PET imaging system?

SIEMENS ECAT PET scanner



GATE ECAT PET scanner

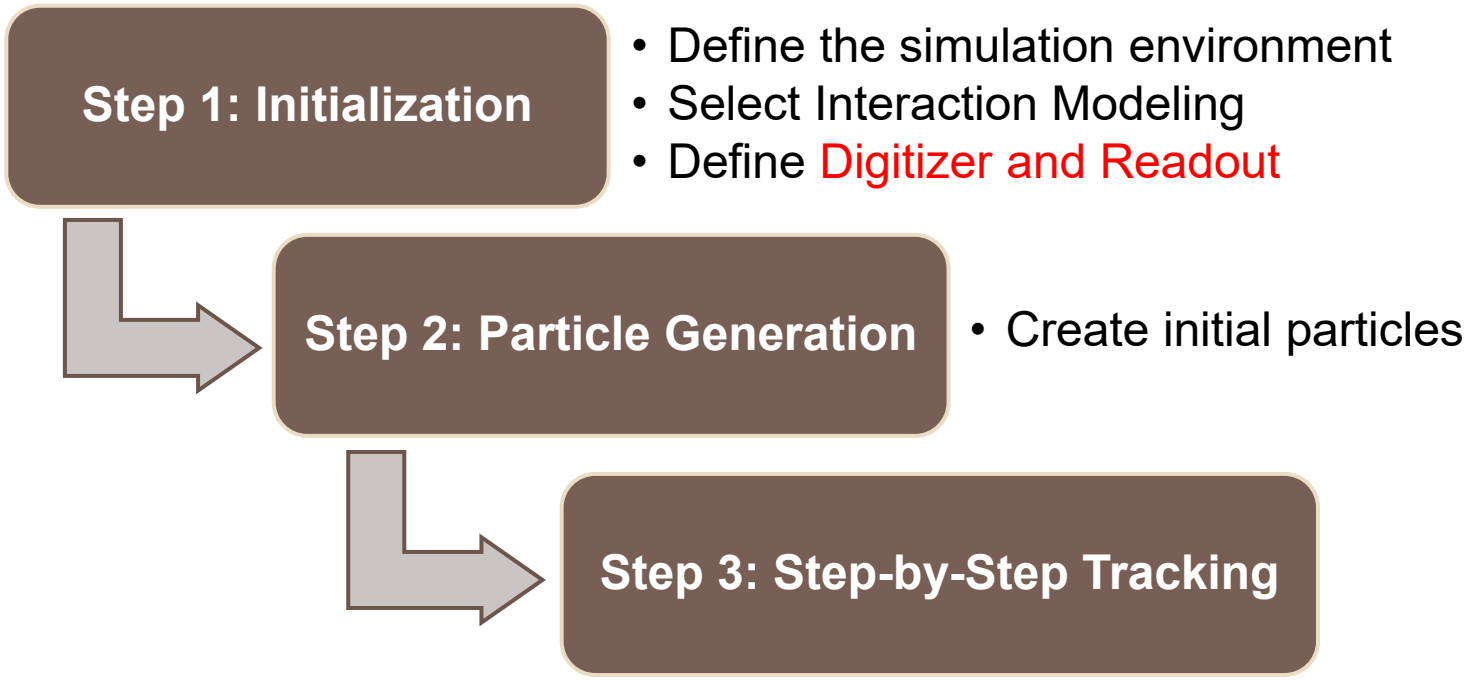


ECAT PET scanner

- ECAT uses block detector, consisting in an array of 8 x 8 crystals, read by 4 photomultipliers.
- The blocks are organized along an annular geometry to yield multi-ring detectors.

Positron Emission Tomography

How do you simulate a PET imaging system?



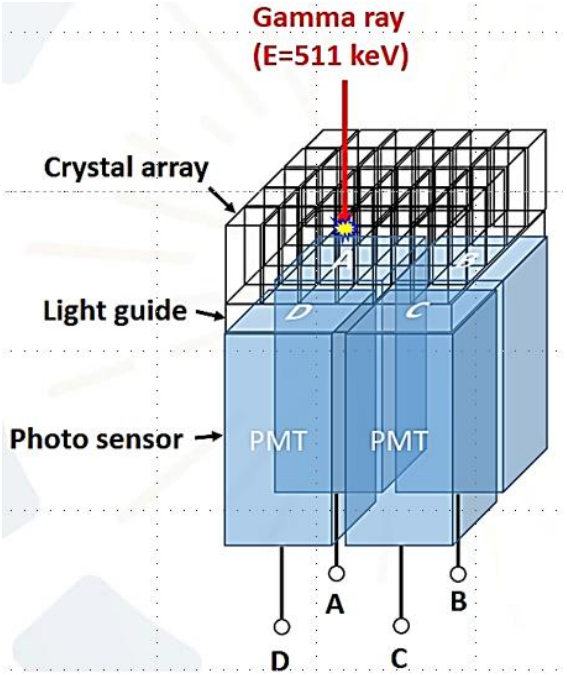
Positron Emission Tomography Simulation

Simulating a PET Scanner Using GATE

Define the PET geometry

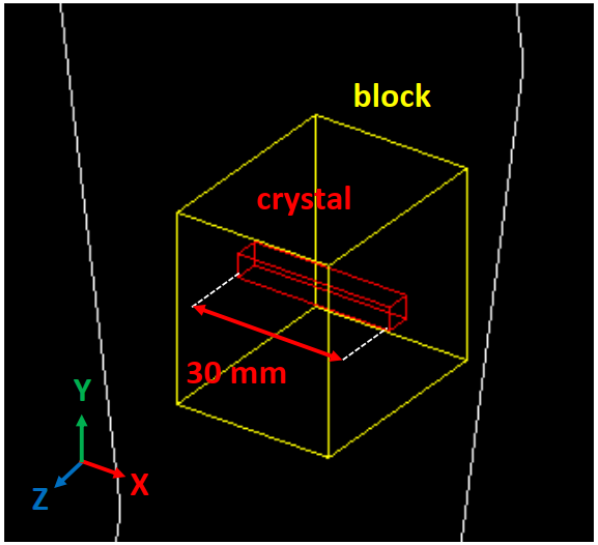
Geometry and material
- Scanner
- Phantom
- Source

```
#                CRYSTAL
/gate/block/daughters/name                  crystal
/gate/block/daughters/insert                box
/gate/crystal/geometry/setXLength           30 mm
/gate/crystal/geometry/setYLength           4.4 mm
/gate/crystal/geometry/setZLength           4.75 mm
/gate/crystal/setMaterial                   BGO
/gate/crystal/vis/setColor                  red
```



ECAT PET scanner

ECAT uses block detector, consisting in an array of 8 x 8 crystals, read by 4 photomultipliers.



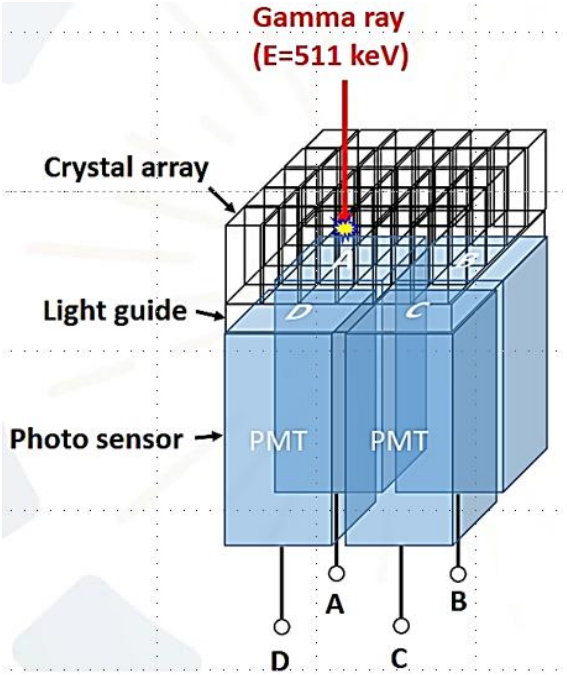
Positron Emission Tomography Simulation

Simulating a PET Scanner Using GATE

Define the PET geometry

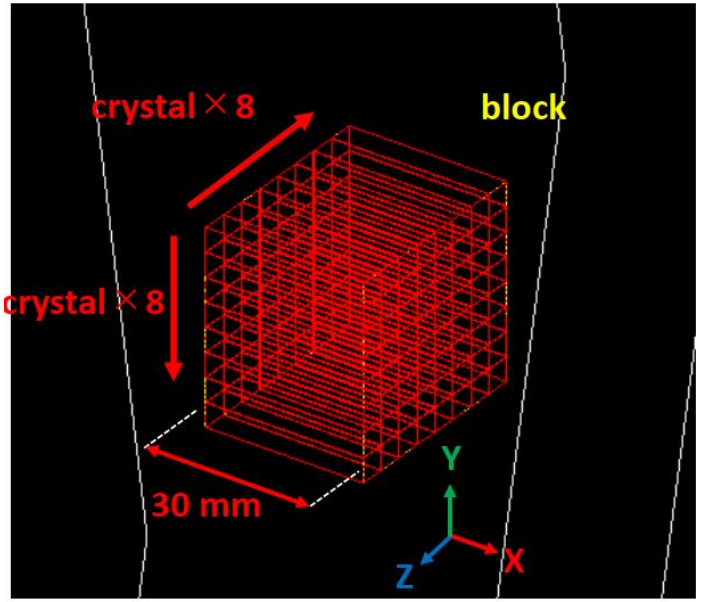
Geometry and material
- Scanner
- Phantom
- Source

```
#                CRYSTAL
/gate/crystal/repeaters/insert                    cubicArray
/gate/crystal/cubicArray/setRepeatNumberX         1
/gate/crystal/cubicArray/setRepeatNumberY         8
/gate/crystal/cubicArray/setRepeatNumberZ         8
/gate/crystal/cubicArray/setRepeatVector          0. 4.4942 4.85 mm
```



ECAT PET scanner

ECAT uses block detector, consisting in an array of 8 x 8 crystals, read by 4 photomultipliers.



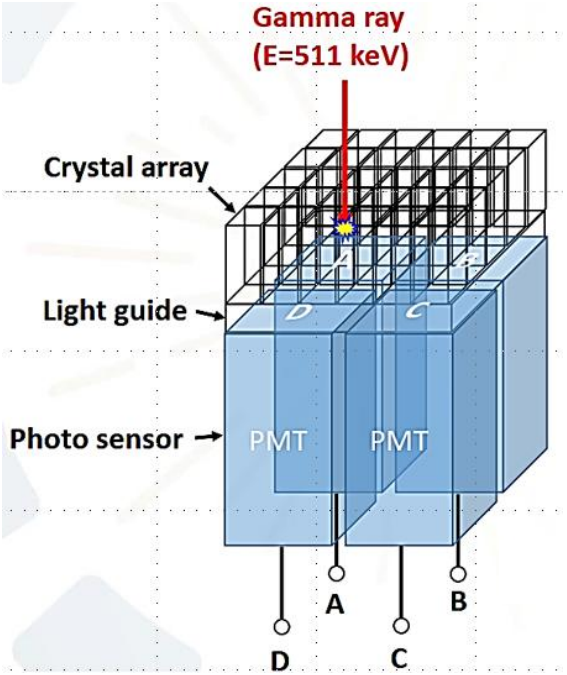
Positron Emission Tomography Simulation

Simulating a PET Scanner Using GATE

Define the PET geometry

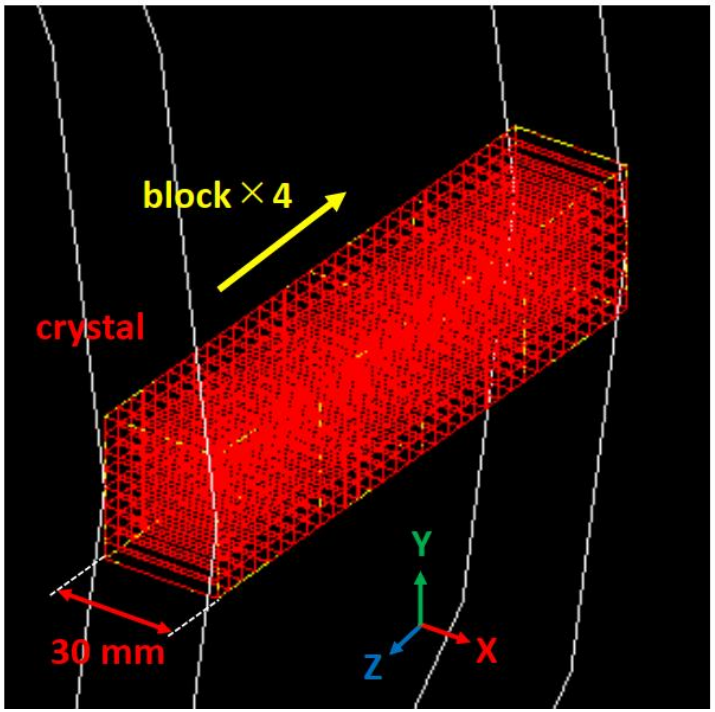
Geometry and material
- Scanner
- Phantom
- Source

```
#                  R E P E A T   BLOCK
/gate/block/repeaters/insert                linear
/gate/block/linear/setRepeatNumber          4
/gate/block/linear/setRepeatVector          0.  0.  38.8 mm
```



ECAT PET scanner

The blocks are organized along an annular geometry to yield multi-ring detectors.



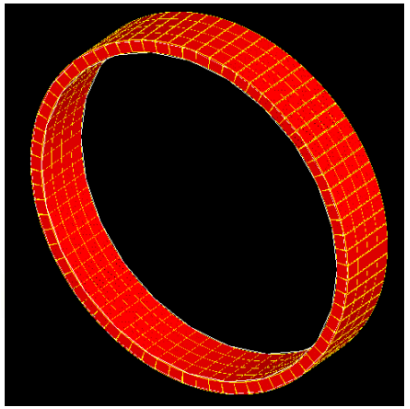
Positron Emission Tomography Simulation

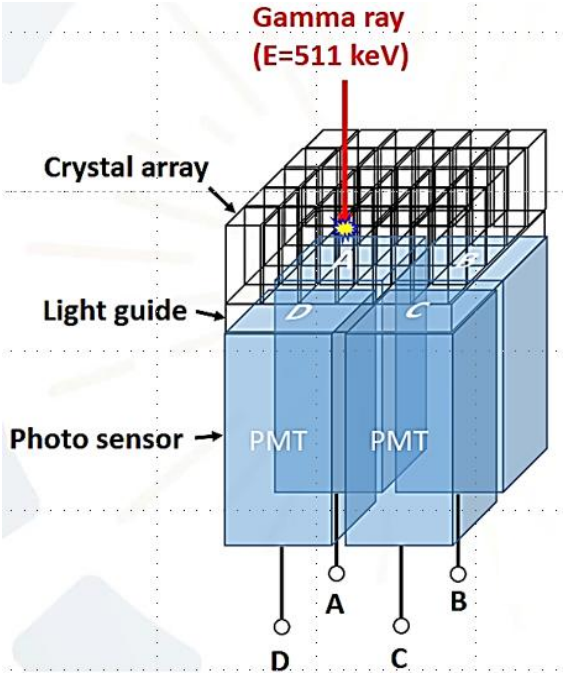
Simulating a PET Scanner Using GATE

Define the PET geometry

Geometry and material
- Scanner
- Phantom
- Source

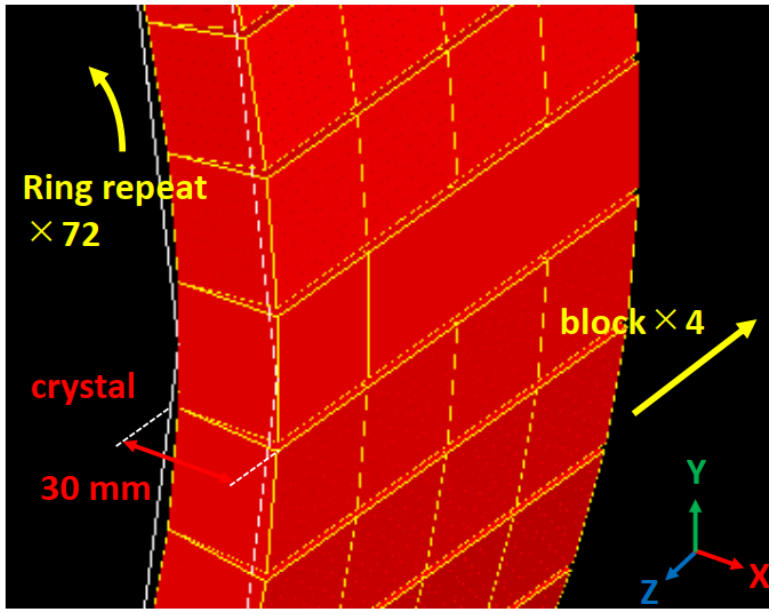
```
#                REPEAT   BLOCK
/gate/block/repeaters/insert          ring
/gate/block/ring/setRepeatNumber      72
```





ECAT PET scanner

The blocks are organized along an annular geometry to yield multi-ring detectors.
The scanner is equipped with 18,432 crystals organized into 288 blocks.

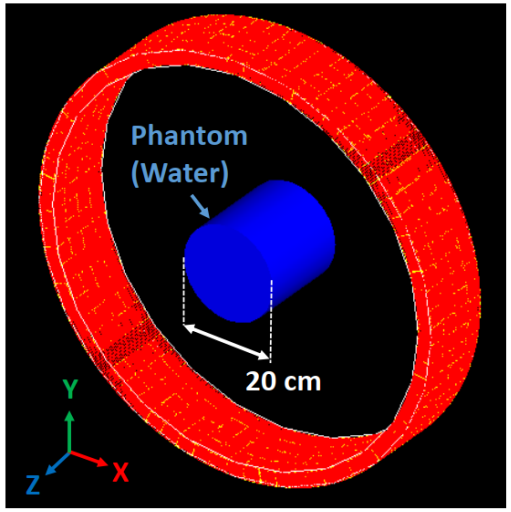


Positron Emission Tomography Simulation

Simulating a PET Scanner Using GATE

Define a phantom containing a source

Geometry and material
- Scanner
- Phantom
- Source




```
/gate/world/daughters/name                    Phantom
/gate/world/daughters/insert                  cylinder
/gate/Phantom/geometry/setRmax                10.  cm
/gate/Phantom/geometry/setRmin                0. cm
/gate/Phantom/geometry/setHeight              20. cm
/gate/Phantom/placement/setTranslation        0. 0. 0. cm
/gate/Phantom/setMaterial                     Water
/gate/Phantom/vis/setColor                    blue
/gate/Phantom/vis/forceSolid
/gate/Phantom/vis/setVisible                  1
```

```
/gate/source/addSource                                mySource_1
/gate/source/mySource_1/gps/type                      Volume
/gate/source/mySource_1/gps/shape                     Cylinder
/gate/source/mySource_1/gps/radius                    0.5 mm
/gate/source/mySource_1/gps/halfz                     100 mm
/gate/source/mySource_1/gps/centre                    0. 0. 0. cm
/gate/source/mySource_1/gps/particle                  e+
/gate/source/mySource_1/gps/energytype                Fluor18
/gate/source/mySource_1/setForcedUnstableFlag         true
/gate/source/mySource_1/setForcedHalfLife             6586 s
```

Water cylinder phantom with a cylinder F-18 source at the center of the phantom

Positron Emission Tomography Simulation

Simulating a PET Scanner Using GATE

Select the Physics Model

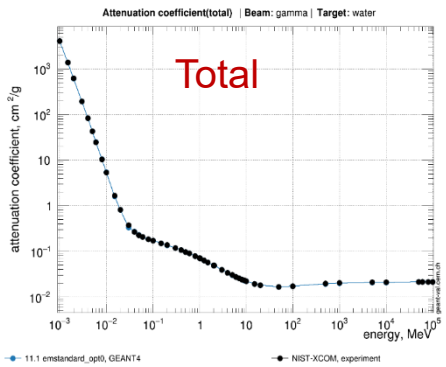
Electromagnetic Processes:

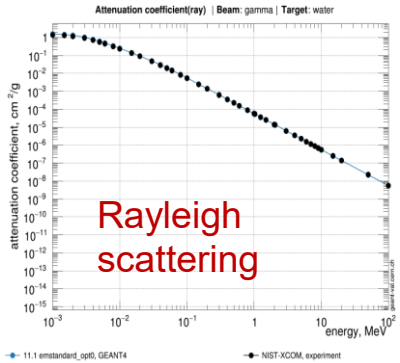
- Rayleigh scattering, photoelectric effect, Compton scattering
- Bremsstrahlung (charged particle)

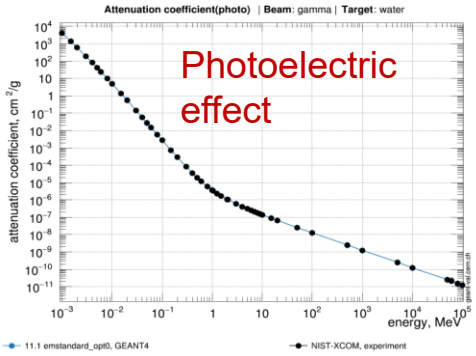
```
#=====================================================
# P H Y S I C S
#=====================================================
/gate/physics/addPhysicsList          emstandard_opt4
```

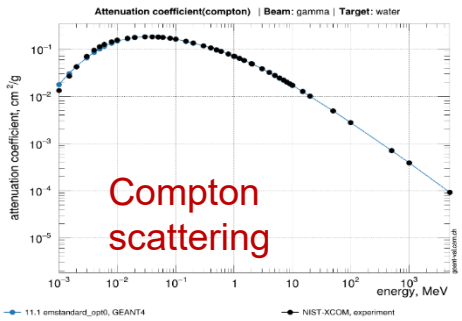
Electromagnetic standard

Attenuation of photon in water - GEANT4 emstandard_opt4 (line) vs. NIST-Xcom (dot)









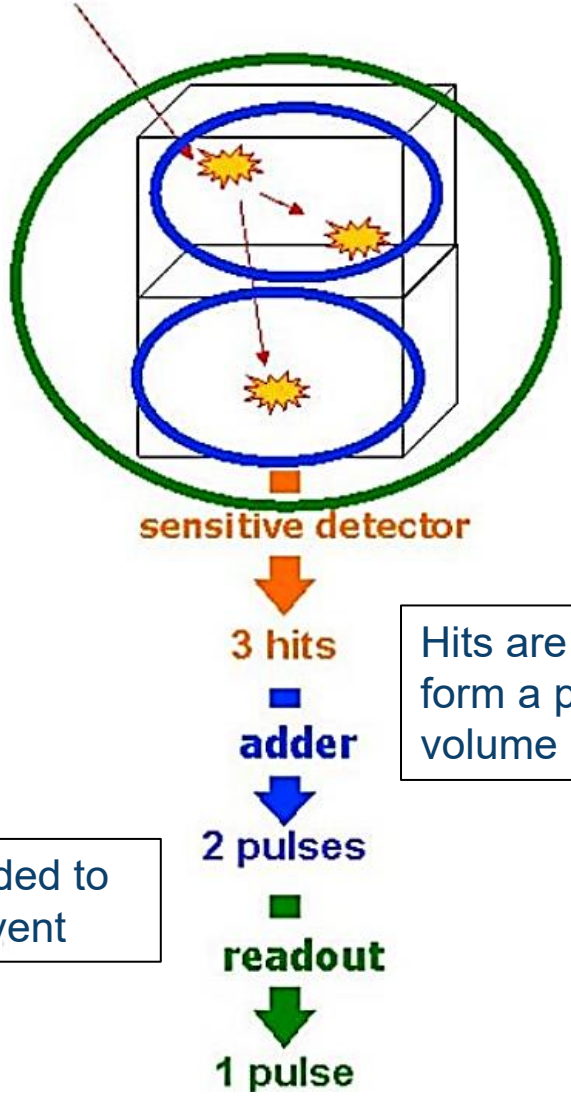
Positron Emission Tomography Simulation

Simulating a PET Scanner Using GATE

Defind Digitizer and Readout

```
#====================
# D I G I T I Z E R
#====================
# Adder
/gate/digitizer/Singles/insert                adder

# Readout (block = Depth 1)
/gate/digitizer/Singles/insert                readout
/gate/digitizer/Singles/readout/setDepth  1
```



Digitizer collects the hits inside the Sensitive Detector

Hits are added to form a pulse per volume

The pulses are added to form a “Singles” event

Positron Emission Tomography Simulation

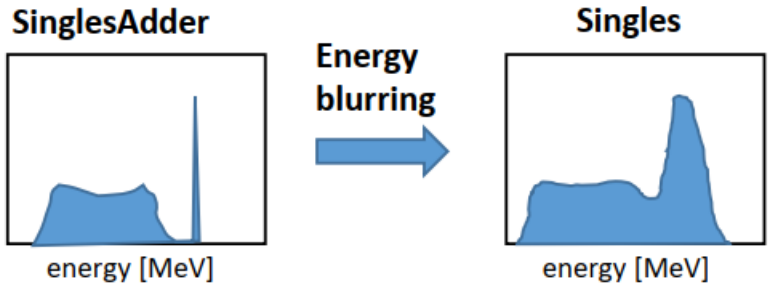
Simulating a PET Scanner Using GATE

Defind Digitizer and Readout

```
# Energy blurring
/gate/digitizer/Singles/insert                          blurring
/gate/digitizer/Singles/blurring/setResolution          0.26
/gate/digitizer/Singles/blurring/setEnergyOfReference   511. keV
```

Energy resolution (26%)

Energy blurring of **26%** with respect to **511 keV** is applied as the **pulses** are added to form a **Singles event**

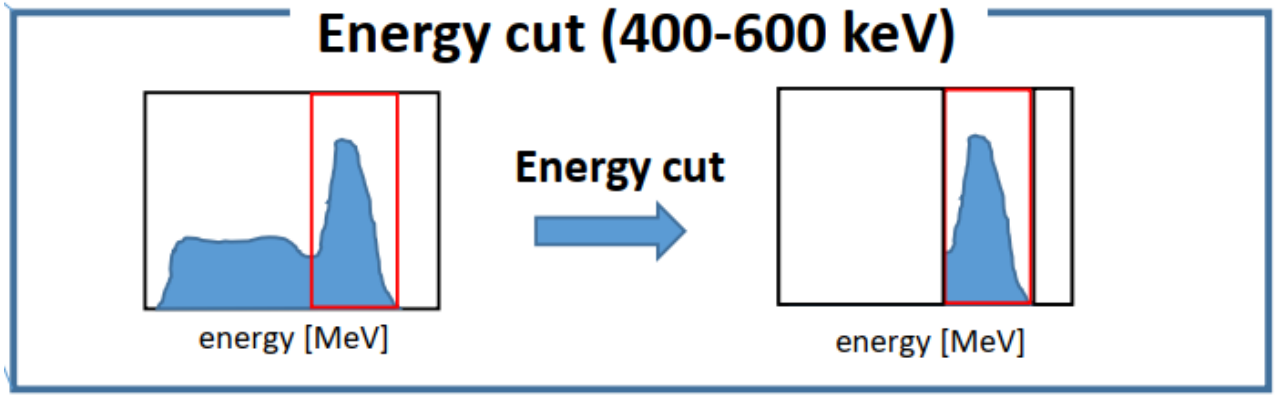


Positron Emission Tomography Simulation

Simulating a PET Scanner Using GATE

Defind Digitizer and Readout

```
# Energy cut
/gate/digitizer/Singles/insert                          thresholder
/gate/digitizer/Singles/thresholder/setThreshold        400. keV
/gate/digitizer/Singles/insert                          upholder
/gate/digitizer/Singles/upholder/setUphold              600. keV
```

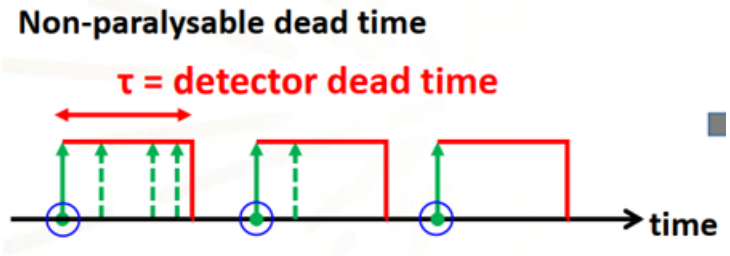


Positron Emission Tomography Simulation

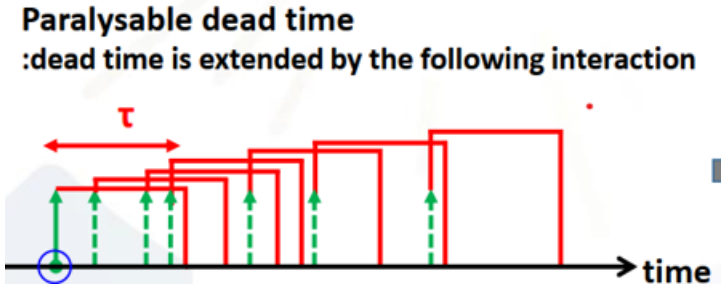
Simulating a PET Scanner Using GATE

Defind Digitizer and Readout

```
#    DEAD  TIME
/gate/digitizer/Singles/insert                          deadtime
/gate/digitizer/Singles/deadtime/setDeadTime            3000. ns
/gate/digitizer/Singles/deadtime/setMode                paralysable
/gate/digitizer/Singles/deadtime/chooseDTVolume         block
```



Number of incomming photons: 7
Number of signals: 3



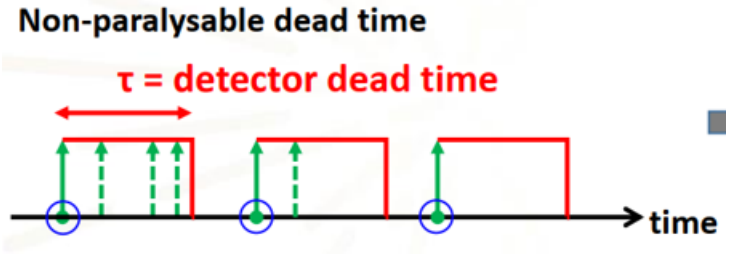
Number of incomming photons: 7
Number of signals: 1

Positron Emission Tomography Simulation

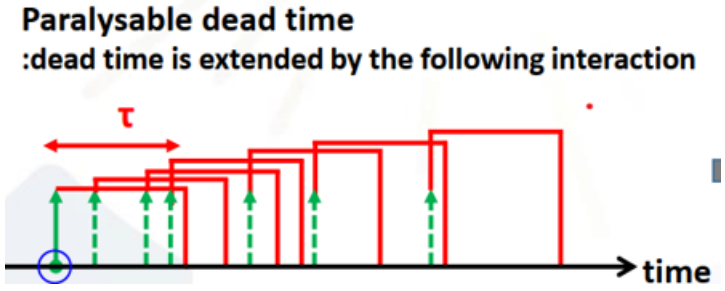
Simulating a PET Scanner Using GATE

Defind Digitizer and Readout

```
#    DEAD  TIME
/gate/digitizer/Singles/insert                          deadtime
/gate/digitizer/Singles/deadtime/setDeadTime            3000. ns
/gate/digitizer/Singles/deadtime/setMode                paralysable
/gate/digitizer/Singles/deadtime/chooseDTVolume         block
```



Number of incomming photons: 7
Number of signals: 3



Number of incomming photons: 7
Number of signals: 1

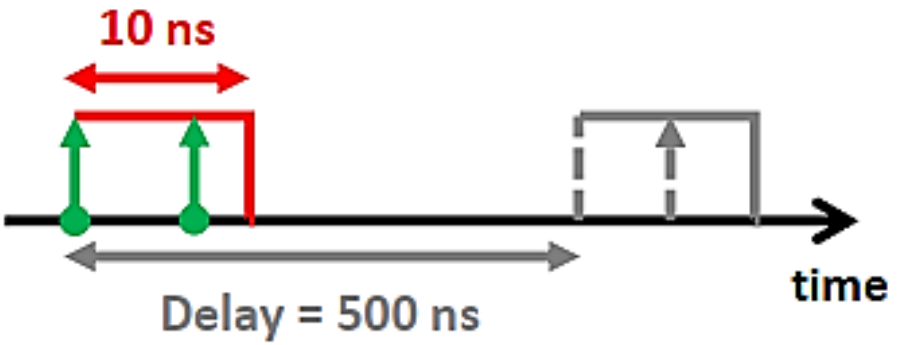
Positron Emission Tomography Simulation

Simulating a PET Scanner Using GATE

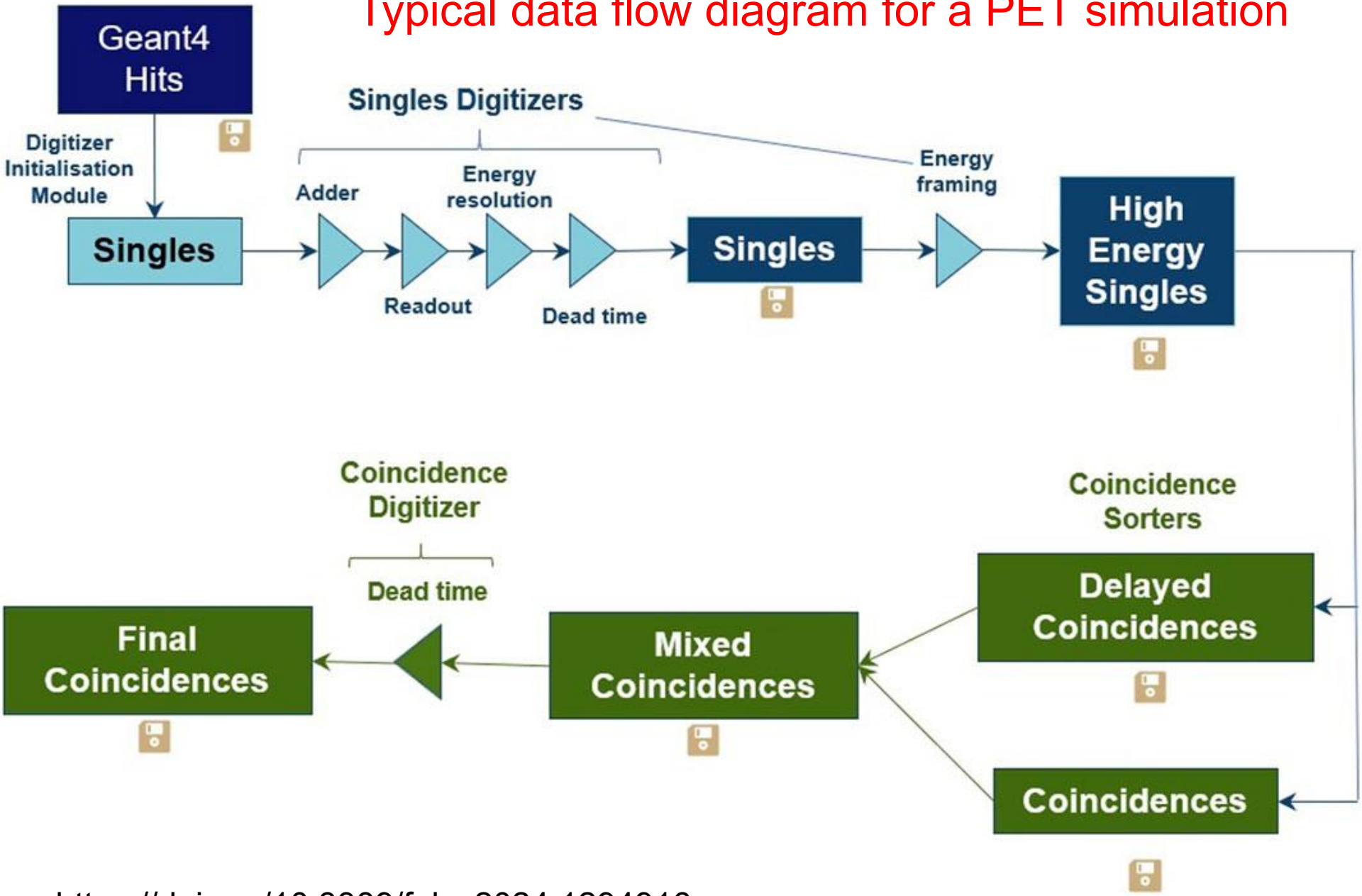
Defind Digitizer and Readout

```
# Coincidence window
/gate/digitizer/Coincidences/setWindow      10. ns
/gate/digitizer/Coincidences/setOffset      0. ns
/gate/digitizer/Coincidences/describe

# Delay window
/gate/digitizer/name                        delay
/gate/digitizer/insert                      coincidenceSorter
/gate/digitizer/delay/setWindow             10. ns
/gate/digitizer/delay/setOffset             500. ns
/gate/digitizer/delay/describe
```



Typical data flow diagram for a PET simulation



https://doi.org/10.3389/fphy.2024.1294916

Positron Emission Tomography

Simulating a PET Scanner Using GATE

Step 1: Initialization

- Define the simulation environment
- Select Interaction Modeling
- Define Digitizer and Readout

Step 2: Particle Generation

- Create initial particles

```
# ====================================
# RANDOM SEED
# ====================================
# JamesRandom Ranlux64 MersenneTwister
/gate/random/setEngineName        Ranlux64
/gate/random/setEngineSeed        auto
/gate/random/verbose              1
```

```
# Static-image (No Dynamic)
/gate/application/setTimeSlice    1 s
/gate/application/setTimeStart    0. s
/gate/application/setTimeStop     10 s
```

$$\#\text{of Run} = \frac{setTimeStop - setTimeStart}{setTimeSlice}$$

Positron Emission Tomography

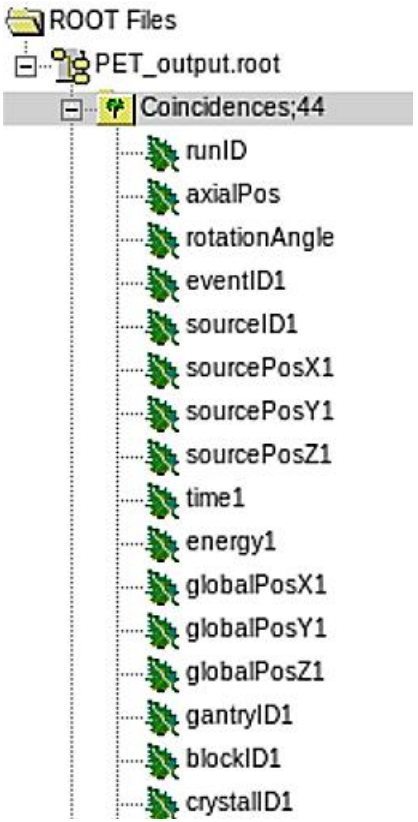
How do you simulate a PET imaging system?

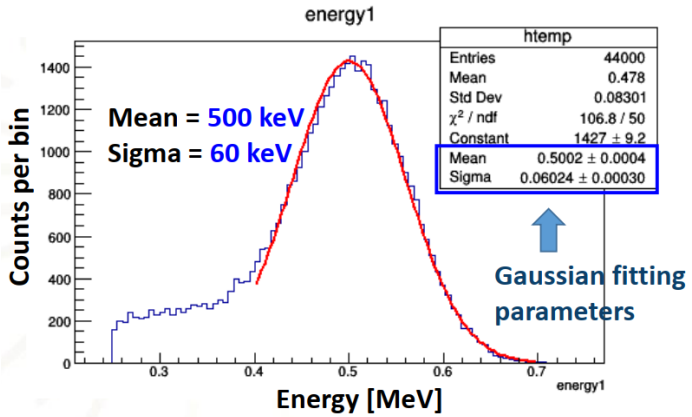
Step 1: Initialization

Step 2: Particle Generation

Step 3: Step-by-Step Tracking

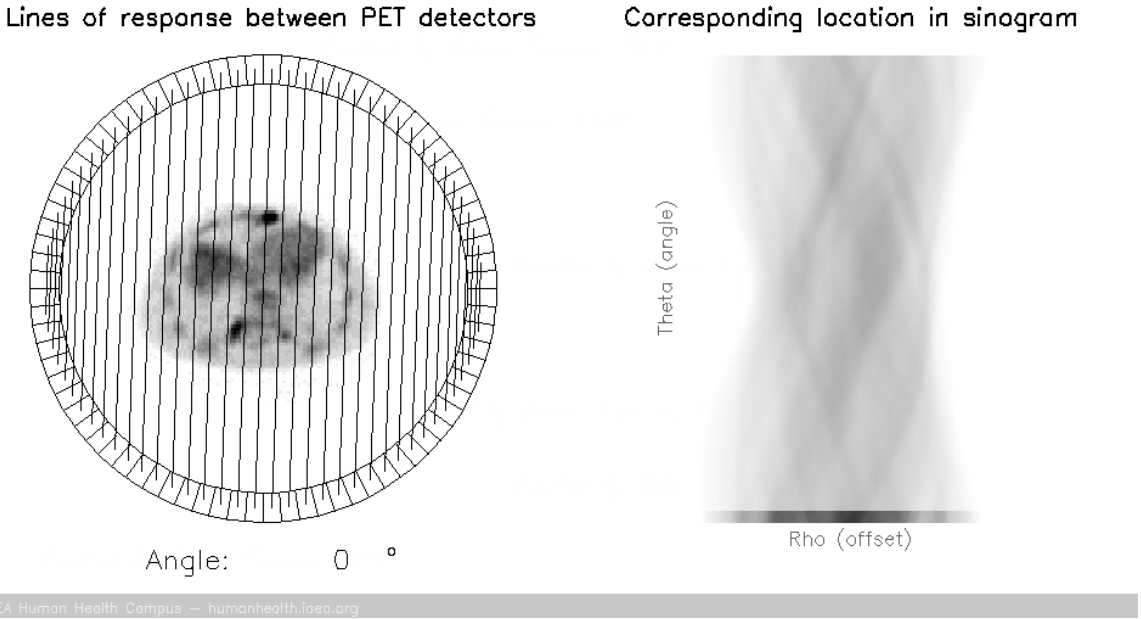
Simulation output is saved in the root file (list mode)
Energy, position, time,

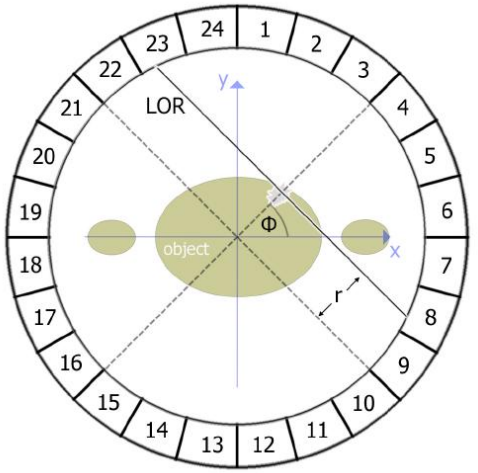




Positron Emission Tomography

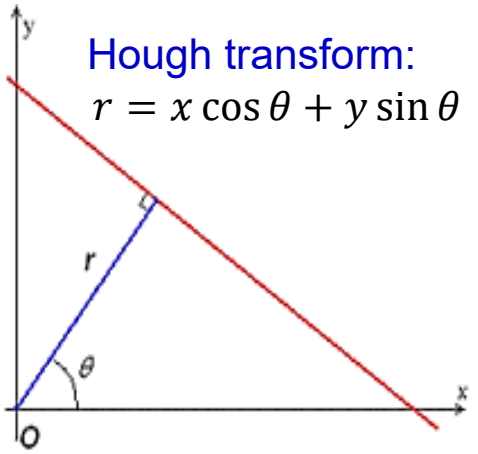
How do you reconstruct a PET image?





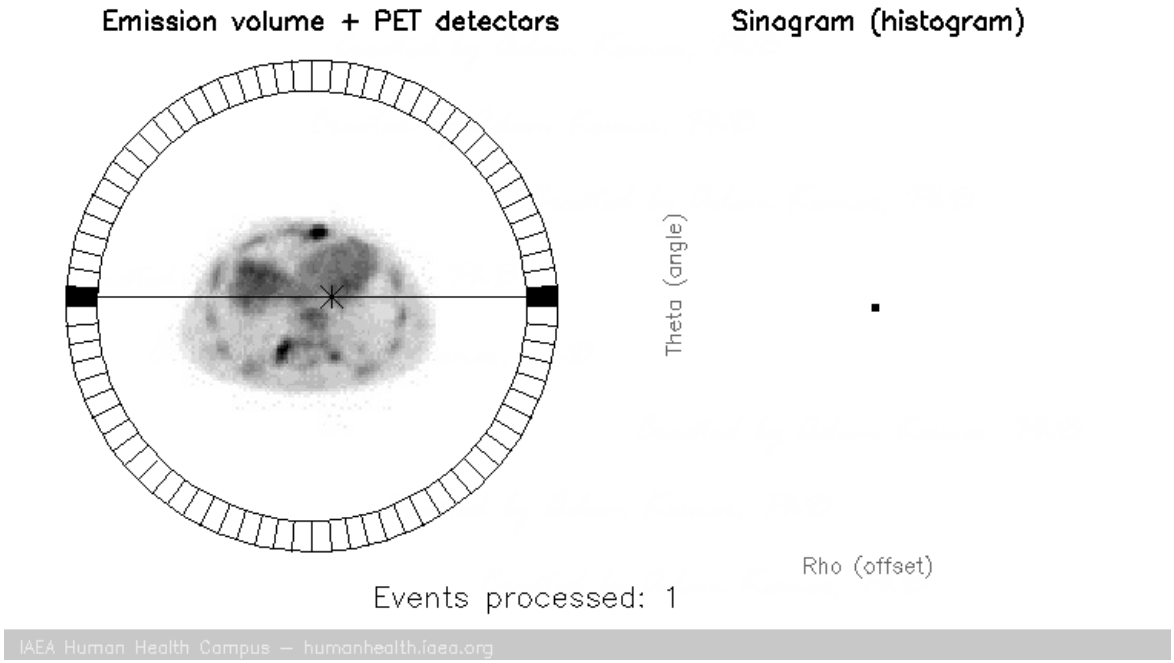
Sinogram: the angle specific histogram store detected events.

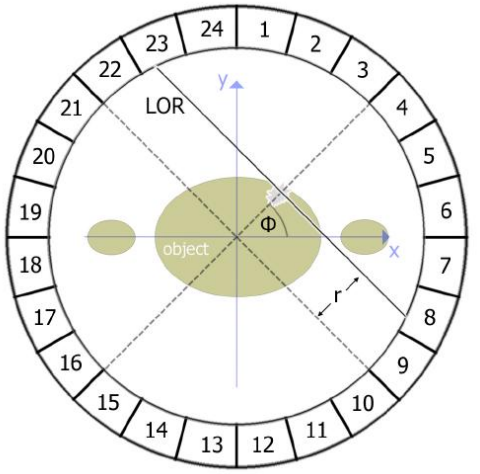
- Every event is sorted using the angle and offset characteristic to its detection.
- Each LOR has a corresponding angle and offset to indicate its location in the sinogram.



Positron Emission Tomography

How do you reconstruct a PET image?



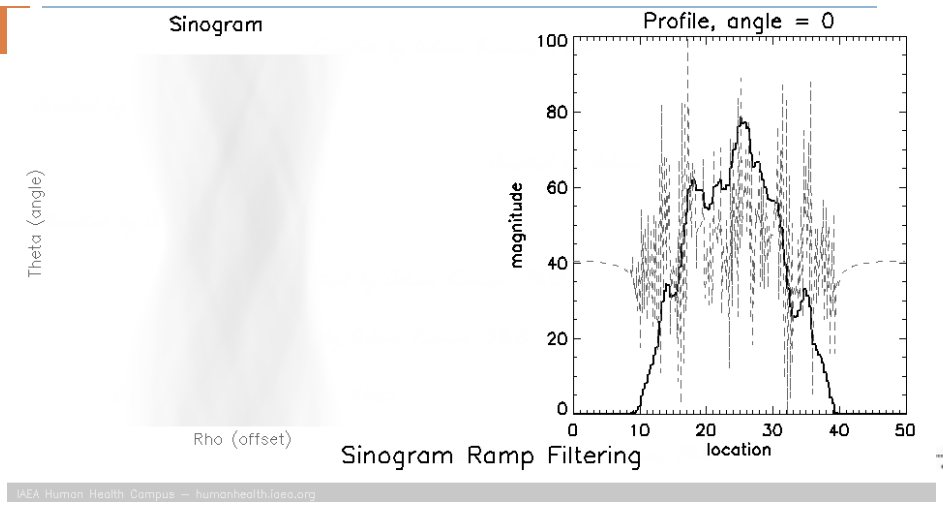


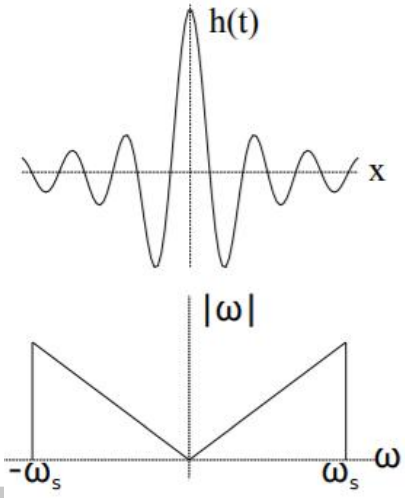
Back Projection:

- The image is constructed from the sum of all projections

Positron Emission Tomography

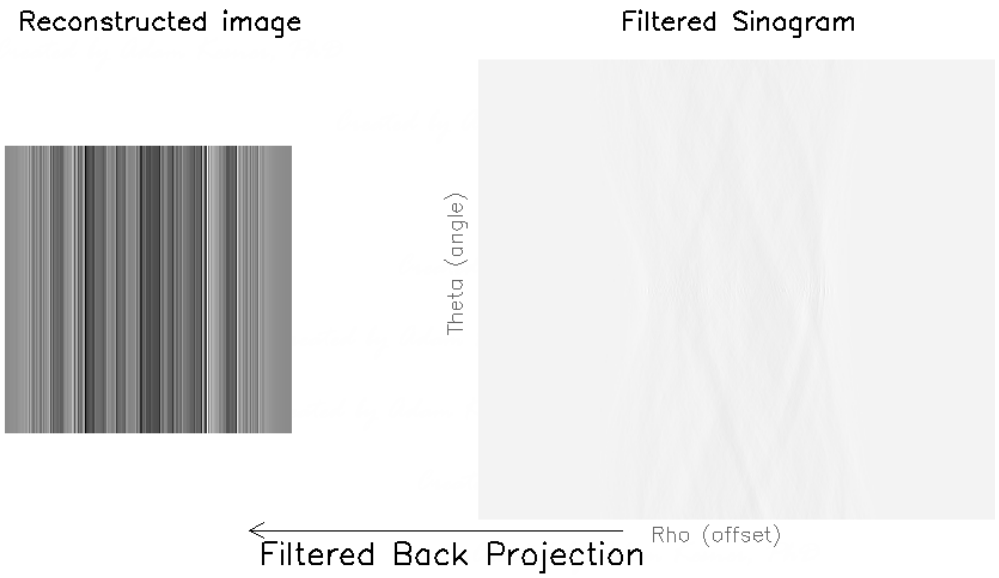
How do you reconstruct a PET image?





Ramp filter:

- A high-pass filter,
- Enhances edges and sharp details in the image, while suppressing the low-frequency blurring.



- **Filtered back projection:** The sinogram data are filtered and then back-projected to recover an accurate image

Summary

- Monte Carlo simulation is a computational technique used to model and analyze complex systems through random sampling
- GATE is a Geant4-based simulation platform for medical physics
  - design of new medical imaging devices,
  - optimize of acquisition protocols,
  - develop / assess image reconstruction algorithms and correction techniques,
  - dosimetry
- Simulation workflow
  - Setup scanner (geometry, materials, physics, sensitive detector)
  - Simulation: generating and tracking optical photons
- Image reconstruction
  - The image is constructed from the sum of all projections (back-projection)
  - Corrections: absorption, decay time

Literatures

- Cherry S.R., Dahlbom M. (2006) PET: Physics, Instrumentation, and Scanners. In: Phelps M.E. (eds) PET. Springer, New York, NY
- IAEA, Nuclear Medicine Physics: A Handbook for Teachers and Students, 2014, chương 12-15
- IAEA, Human Health Campus, 3D image reconstruction

https://humanhealth.iaea.org/HHW/MedicalPhysics/NuclearMedicine/ImageAnalysis/3Dimagereconstruction/index.html

- Adam Kesner and Ida Häggström (2019), Kesner-Häggström Fundamentals of Medical Image Reconstruction Explained with Animations Lecture
- Rafael C. Gonzalez, Digital image processing, 2008
- ECSE-4540 Intro to Digital Image Processing Rich Radke, Rensselaer Polytechnic Institute
  - DIP Lecture 18: Reconstruction from parallel projections and the Radon transform

https://www.youtube.com/watch?v=ZgcD4C-4u0Q&list=PLuh62Q4Sv7BUf60vkjePfcOQc8sHxmnDX&index=21

Thank you for your attention

Medical Physics is not only involved in medicine and physics, but it also includes mathematics, biology, chemistry, computer science, and arts