Virtual IEEE NPSS Workshop on Applications of Radiation Instrumentation 2020

PET imaging
Demostration & Simulation

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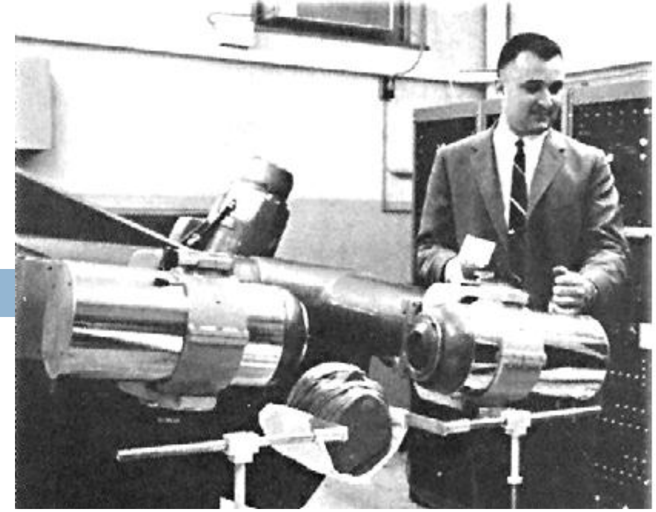
9-11 November 2020 - Jarkata, Indonesia

Outline

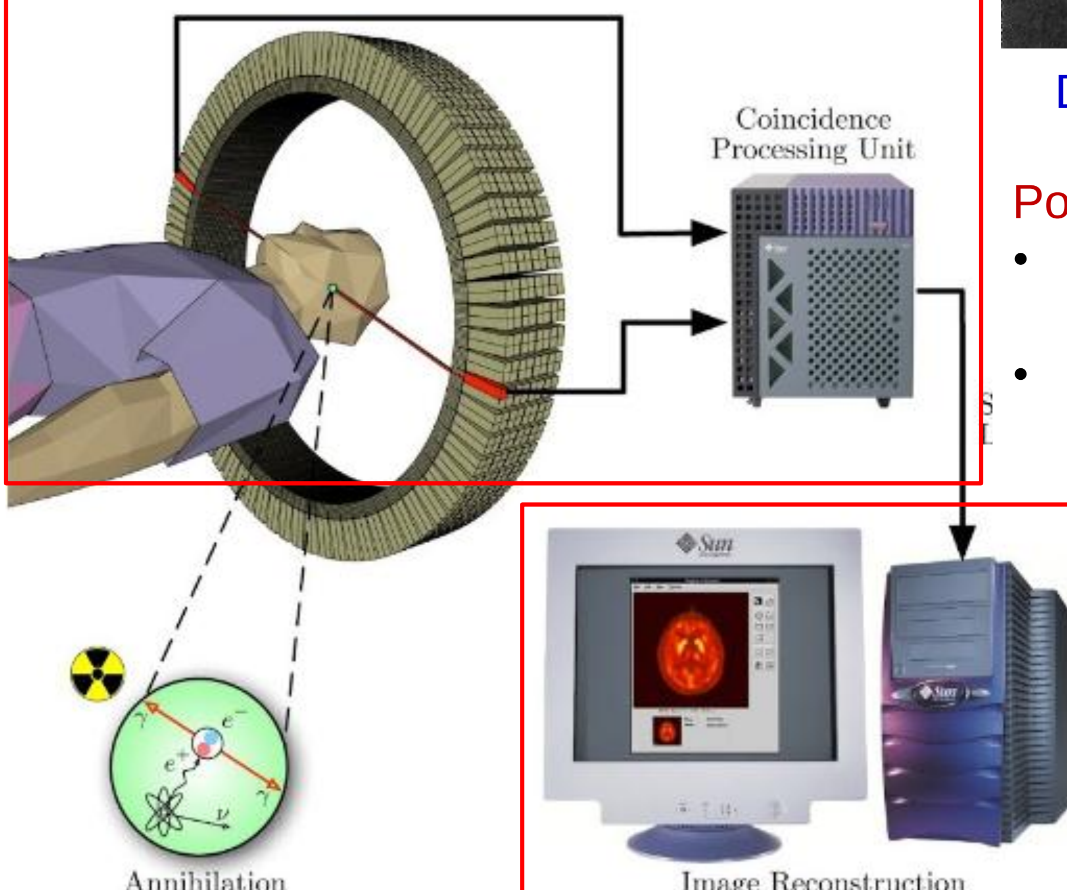
- PET imaging
  - Coincidence annihilation events
  - Line of response & Sinogram
  - Image reconstruction
    - Back projection & Filtered back projection
- PET Simulation
  - Geant4/Gate simulation toolkit
  - Simulation setting
  - ROOT data analysis

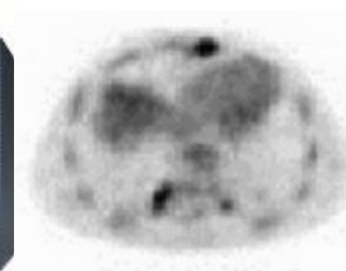
PET
Positron Emission Tomography



David Kuhl – 'Father' of PET scanning

Data Acquisition





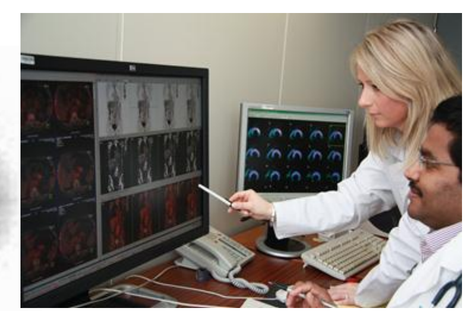
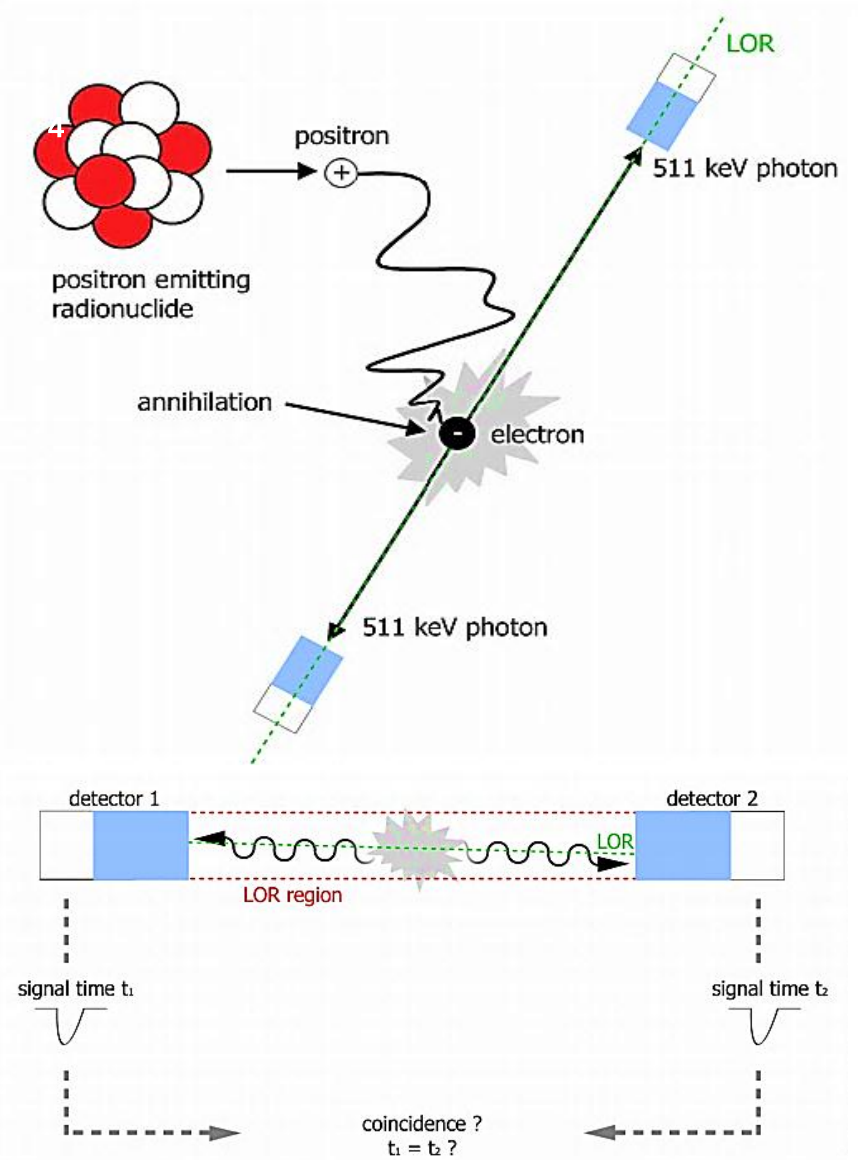


Image Reconstruction and Visualization

Positron Emission Tomography (PET)

- shows the radioactivity distribution within the body
- virtualizes functional processes inside the patient.

Positron-electron annihilation



Coincidence annihilation events:

- Two gammas with the energy of 511 keV detected by opposite detectors nearly at the same time

Gammas from the e^+e^- annihilation events:

- Energy:

  $E = 511\ \text{keV} \pm \delta E$

  δE: energy window

  (δE ~ 100 keV)

- Direction: back-to-back

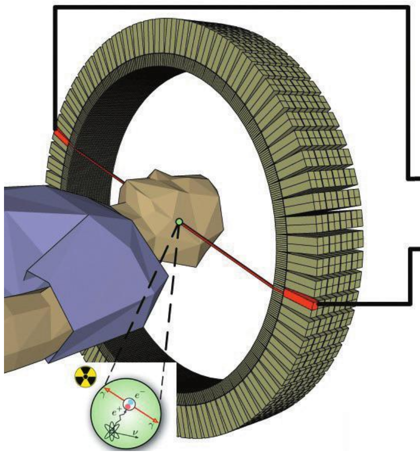
  $\Delta\phi = 180° \pm \delta\phi$

  $\delta\phi$: angle window

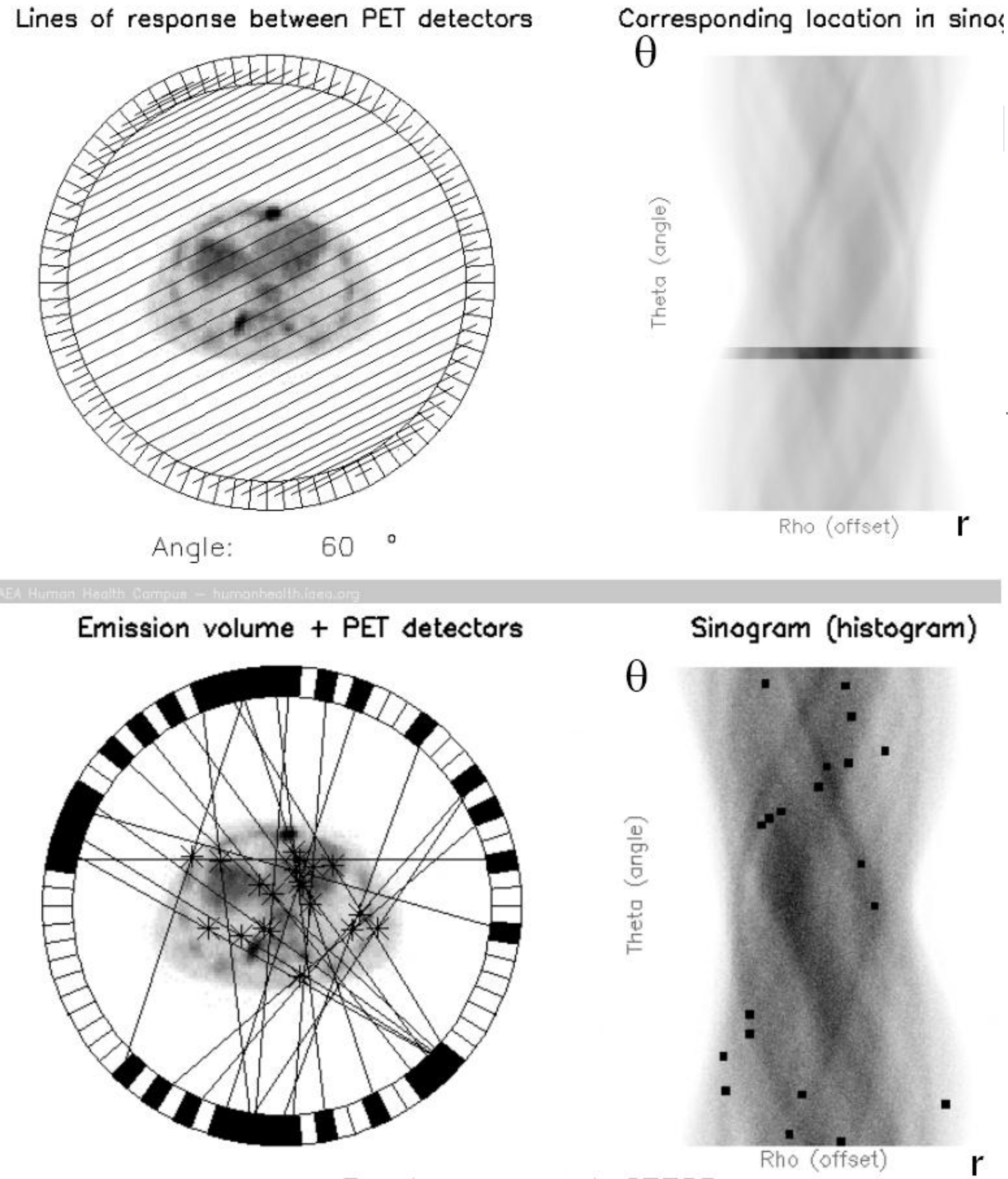
- Time difference:

  $\Delta t = 0 \pm \delta t$

  δt: time window (~ 0.3 – 0.5 ns)



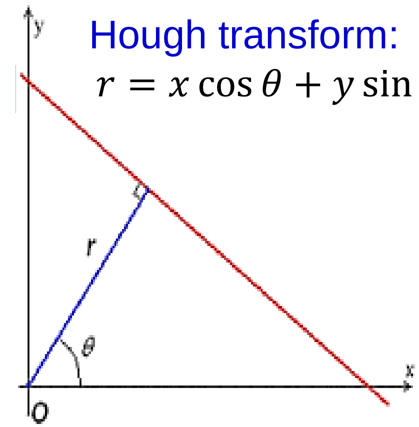
Line of Response & Sinogram

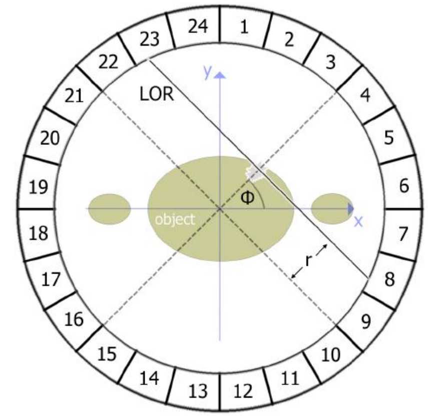


Adam Kesner, Ida Häggström, IAEA Human Health Campus

Hough transform:

$$r = x\cos\theta + y\sin\theta$$





Line of Response (LOR):

- The line between the two front faces of the detectors each time a coincidence is detected between the two scintillation detectors.

Sinogram:

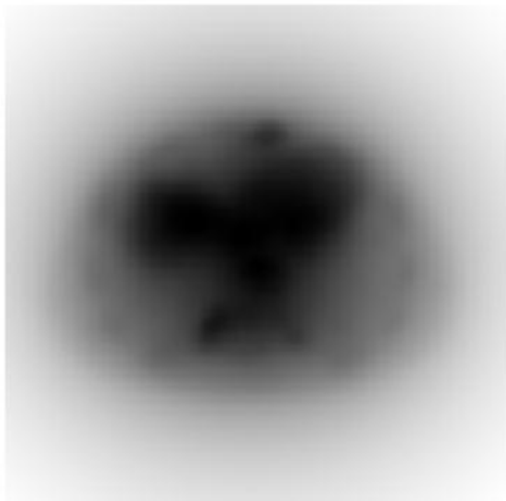
- The angle specific histrogram store detected events.
- Every event is sorted using the angle and offset charactoristic to its detection.
- Each LOR has a corresponding angle and offset to indicate its location in the sinogram.

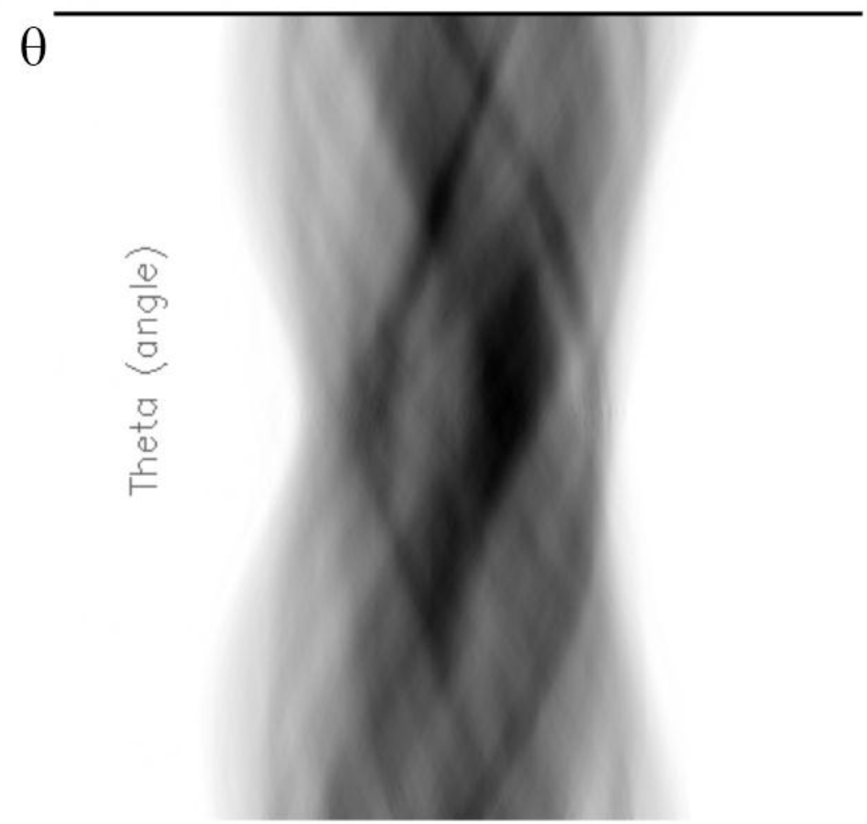
Image reconstruction – Back projection

Reconstructed image

Sinogram

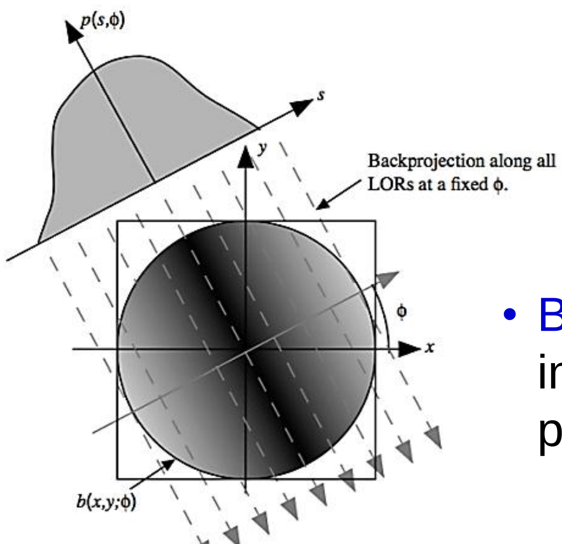
The image reconstructed with back-projection algorithm has '1/r blurring effect'





Back Projection

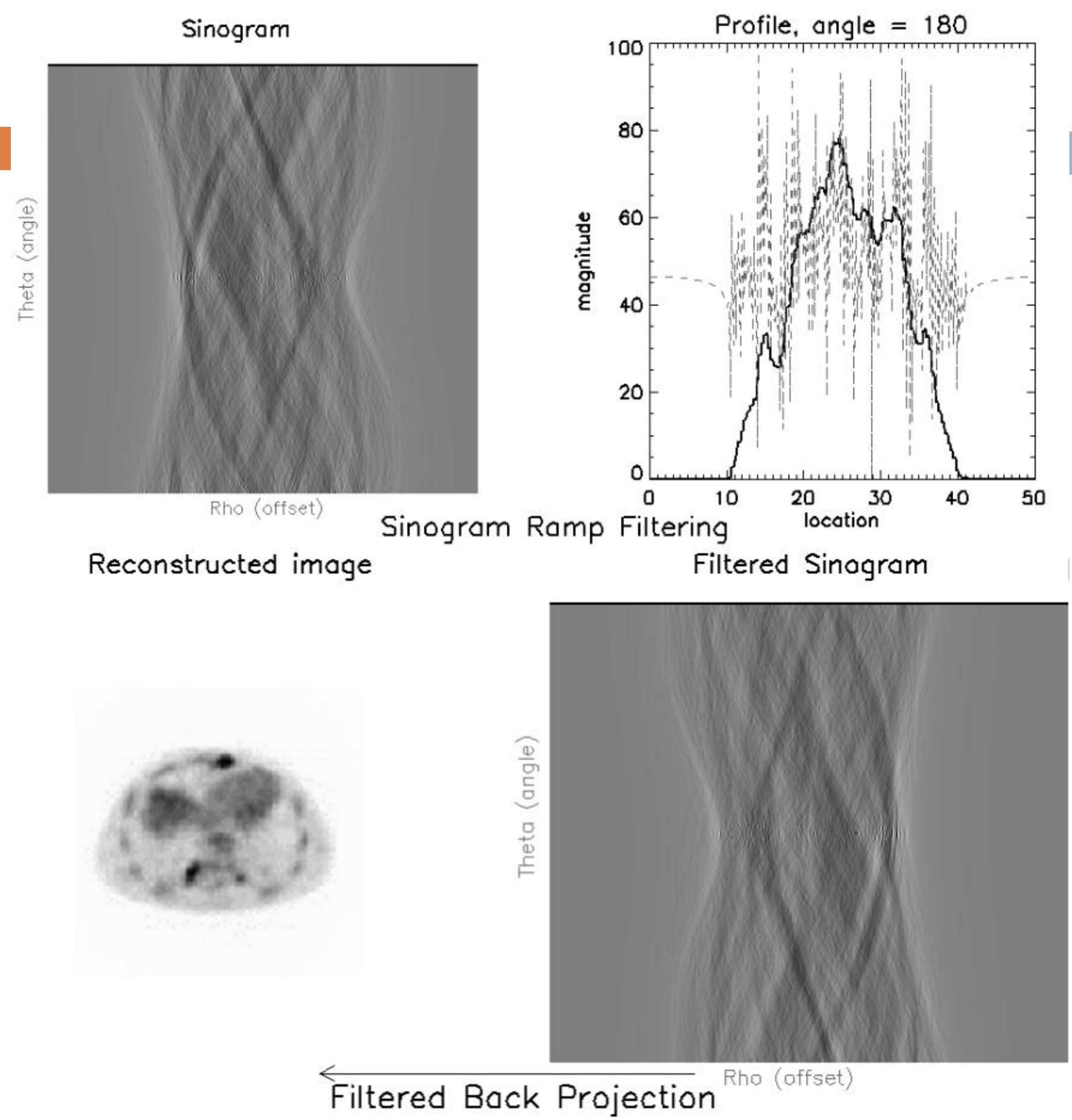
r (offset)

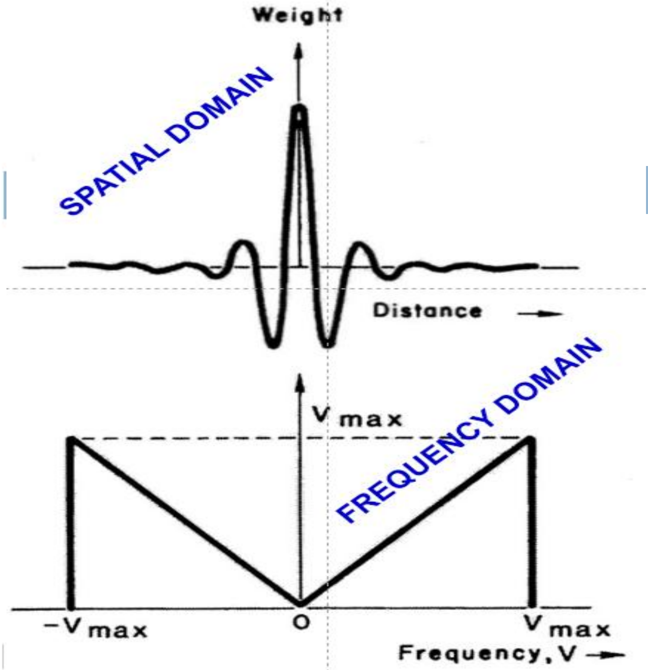


- Back-projection is to smear the measured profiles across the image space. The image is constructed from the sum of all projections.

Adam Kesner, Ida Häggström, IAEA Human Health Campus

Image reconstruction – Filtered back projection





Ramp filter:

- high pass filter
- minimize blurring
- maximize contrasts

Filtered back projection:

- The sinogram is filtered and then back-projected to recover an accurate image

PET Simulation

GEANT4/GATE simulation toolkit

EduGate: PET simulation

- Simulation setup for a simple PET system
- Data flow

ROOT output and data analysis

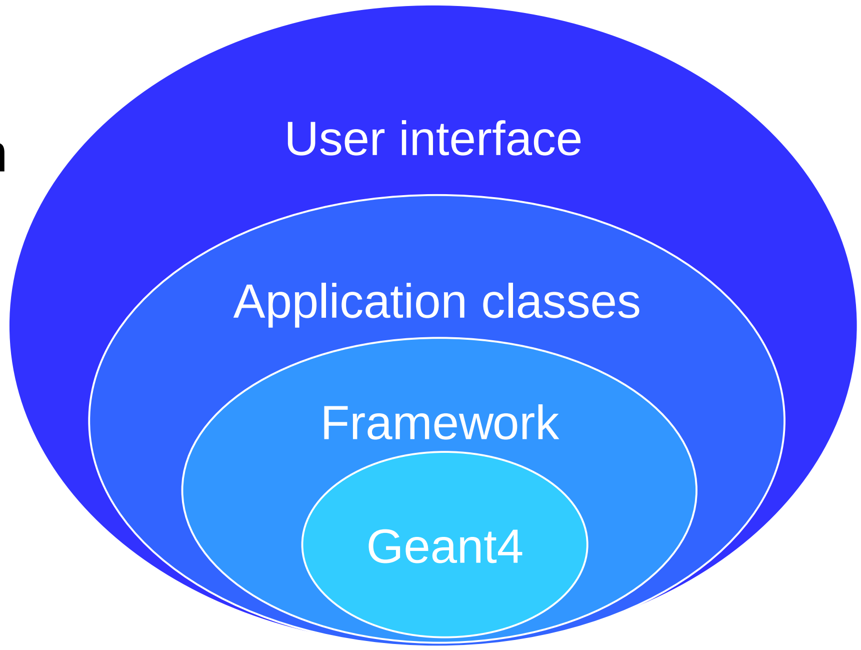
- Energy spectra
- Coincidences and Scatters

GATE/GEANT4 Simulation Toolkit

- Monte Carlo simulation softwares for PET imaging:
  - GATE/Geant4 platform
  - SimSET, PeneloPET (Penelope), SORTEO, Eidolon (MCNP), PETSIM, Geant4, or GAMOS (Geant4)
- Gate is a simulation platform for nuclear medicine based on Geant4.
  - define all paramaters of the simulation by scripting commands
- vGate 9.0 – a virtual machine equipped with necessary softwares for running GATE simulations
  - Ubuntu LTS 18.04 on Virtual Box (40GB virtual HD)
  - GATE 9.0 and Geant4 10.06.1
  - Root 6.14.00

Geant4
Application for
Tomographic
Emission

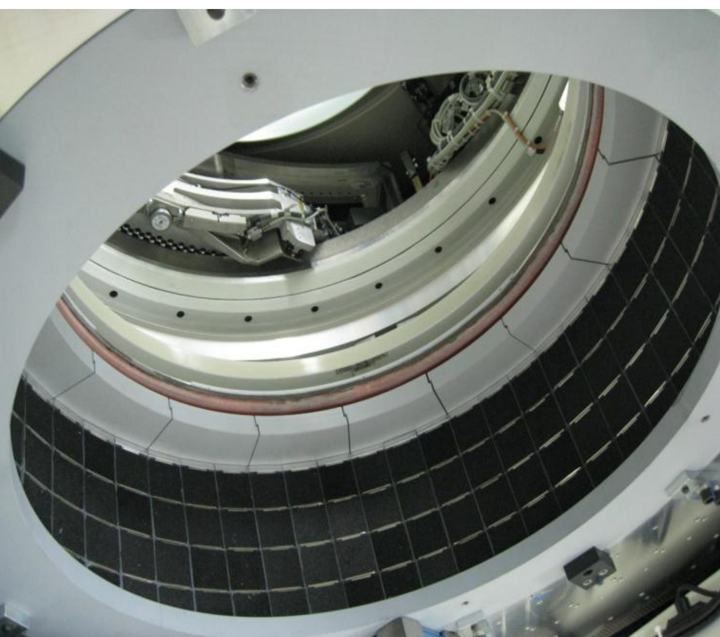
OpenGate Collaboration

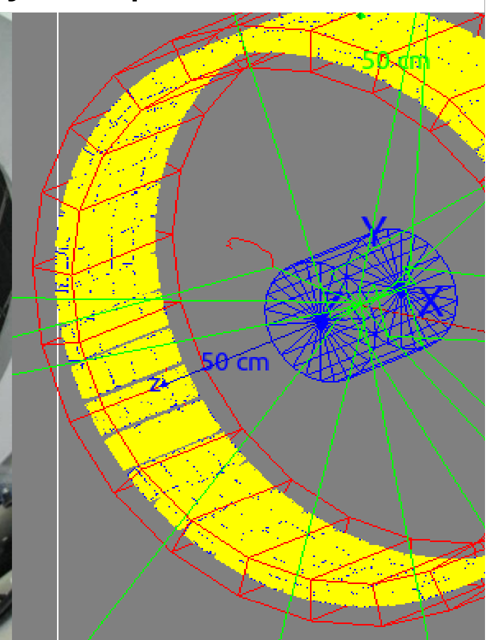


D. Lazaro, V. Breton, GATE a simulation platform for nuclear medicine based on GEANT4

Simple PET scanner

PET/CT scanner at Cho Ray Hospital, 2019





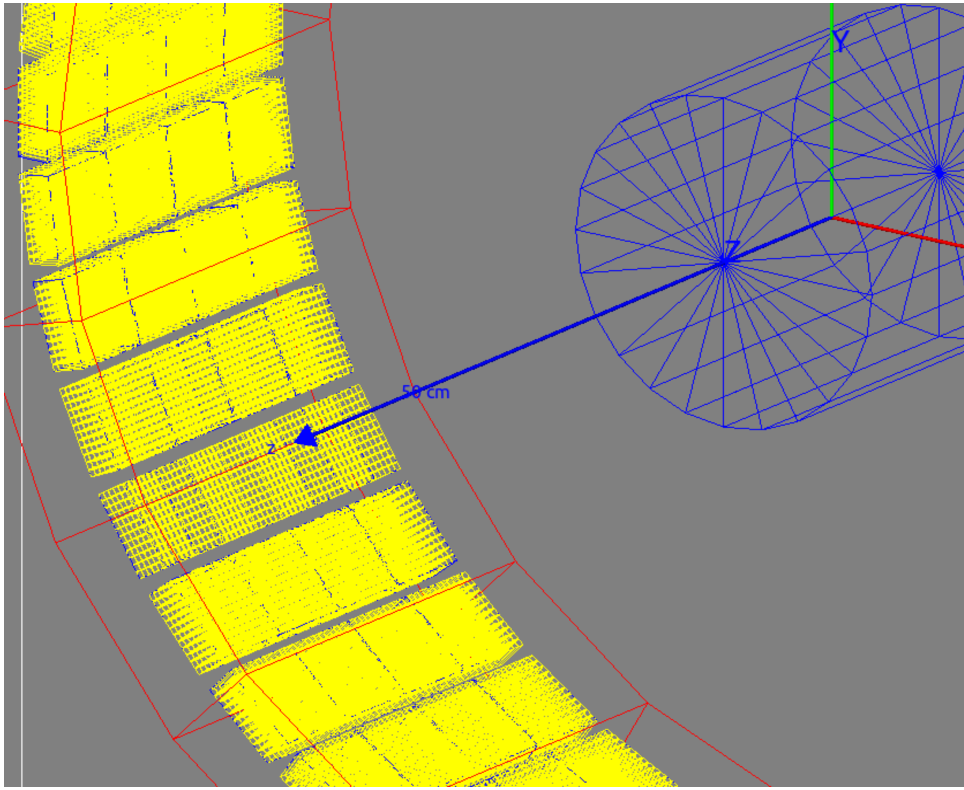
Objective:

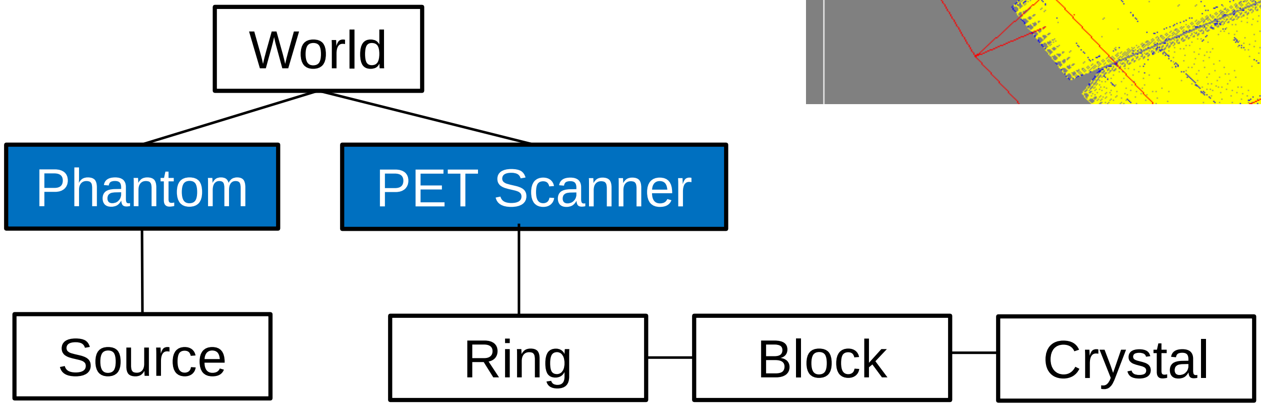
- This experiment simulates a PET scanner composed of 04 rings of crystal blocks (46 blocks per ring).
- Each block contains 12x12 crystal units. Each unit has the size of 4x4x20 mm^3.
- A cylindrical water phantom locates at the center of the scanner.
- There is a ^{18}F source with a radiation activity of 1 MBq (1 million decays per second, ~ 27 μCi) in the phantom.

PET simulation setup

Simulation setup

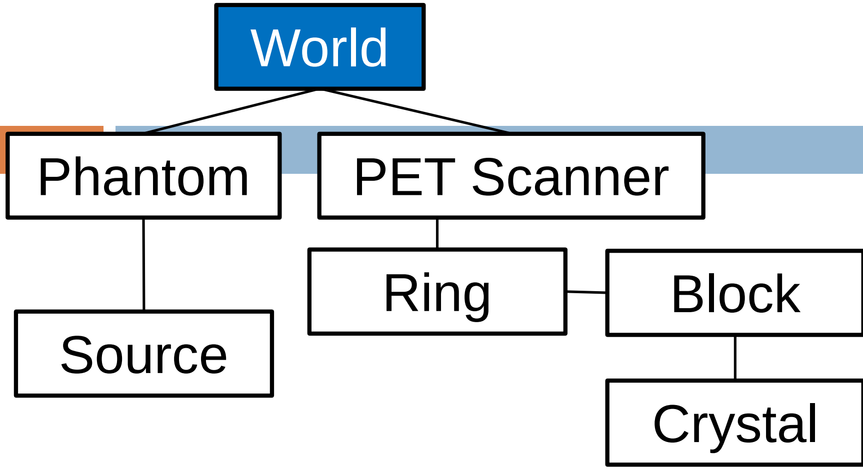
- geometry construction
  - scanner, phantom and sources
- physical processes
- acquisition time





Example macros: https://gitlab.in2p3.fr/davidsarrut/gate-exercices/-/tree/master/pet/mac

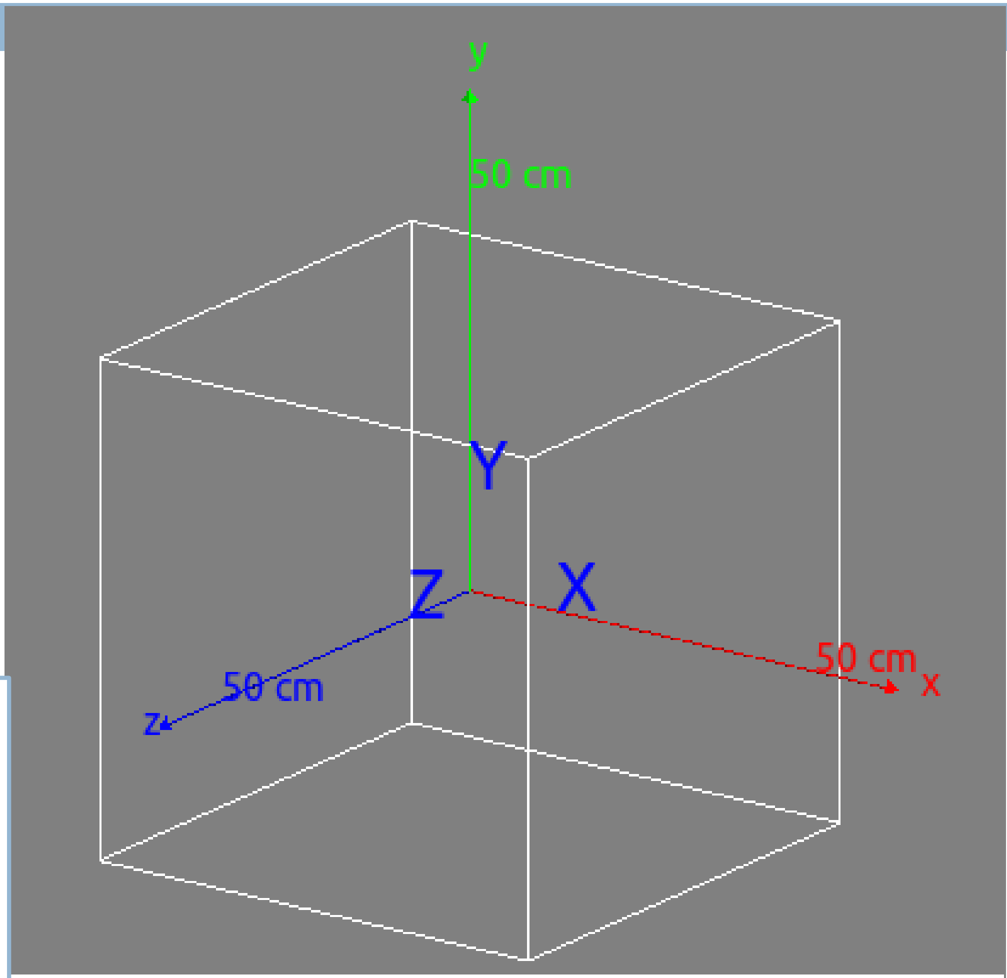
Geometry construction



World:

- Size (x y z): 4 m x 4 m x 4 m
- Material: Air

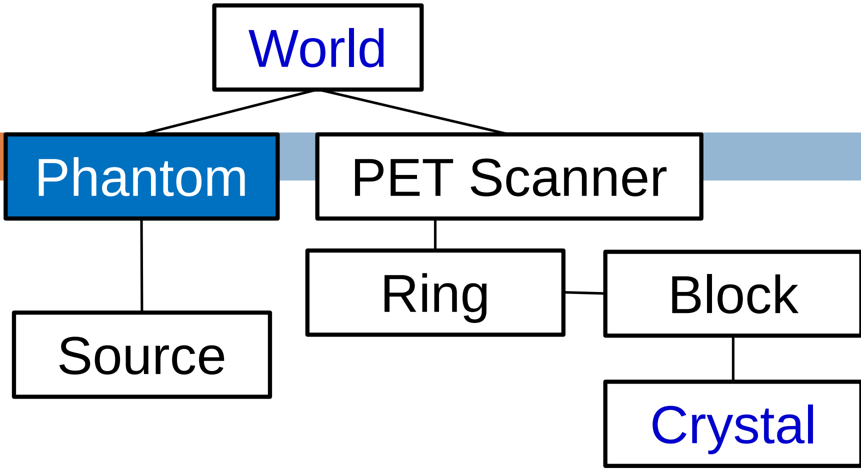
```
# World (world.mac)
/gate/world/geometry/setXLength 4 m
/gate/world/geometry/setYLength 4 m
/gate/world/geometry/setZLength 4 m
/gate/world/setMaterial Air
```



Simulation world, 4 x 4 x 4 m^3 (white box)

Example macros: https://gitlab.in2p3.fr/davidsarrut/gate-exercices/-/tree/master/pet/mac

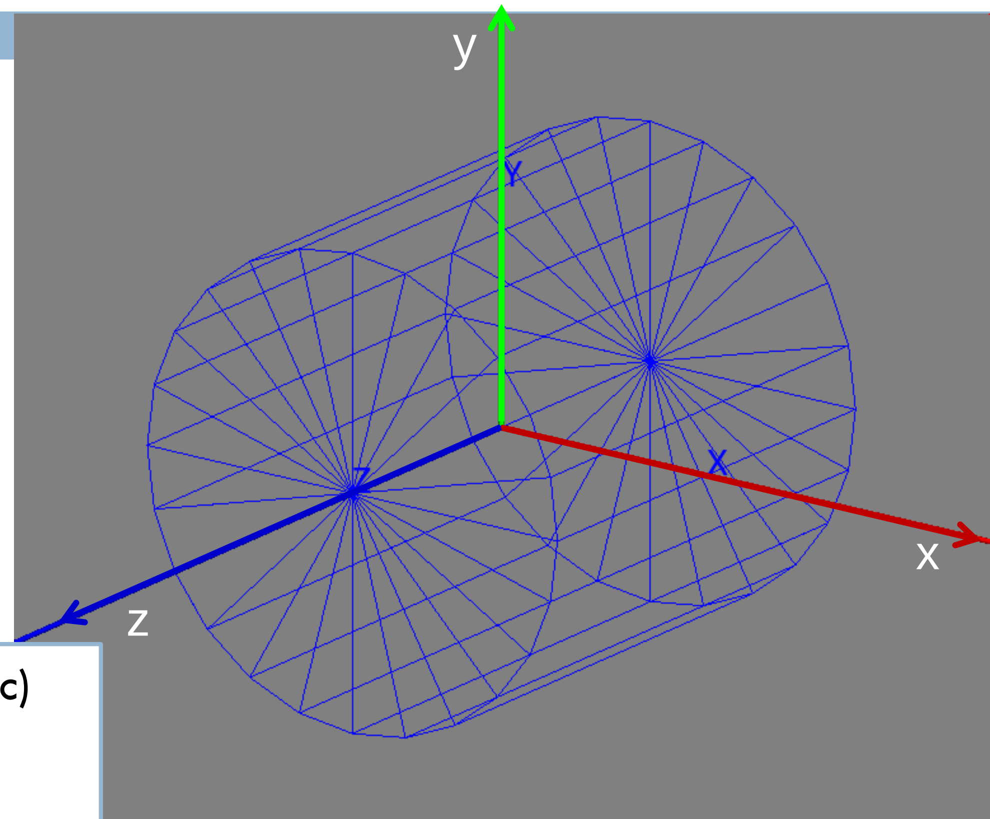
Geometry construction



Cylindrical phantom:

- Radius: 10 cm; Height: 20 cm
- Material: water

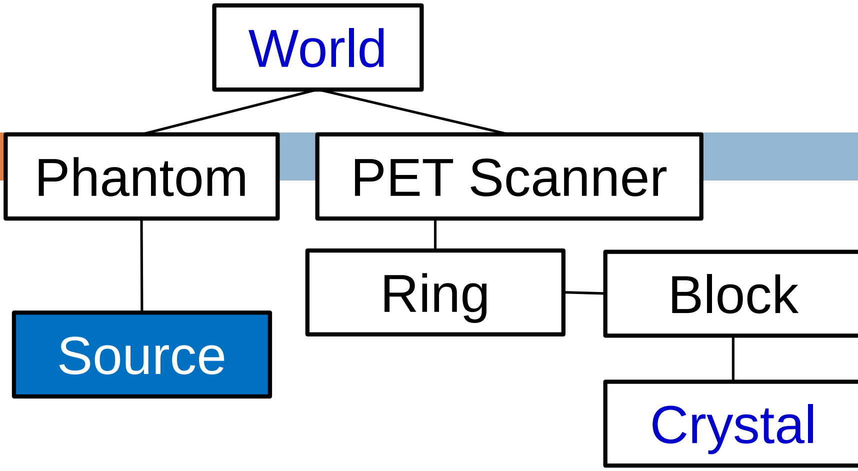
```
# Cylindrical phantom (cylindrical_phamtom.mac)
/gate/world/daughters/name        phantom
/gate/world/daughters/insert      cylinder
/gate/phantom/geometry/setRmin     0.0 cm
/gate/phantom/geometry/setRmax     10.0 cm
/gate/phantom/geometry/setHeight   20. cm
/gate/phantom/setMaterial          water
```



Cylindrical phantom (blue frame)

Example macros: https://gitlab.in2p3.fr/davidsarrut/gate-exercices/-/tree/master/pet/mac

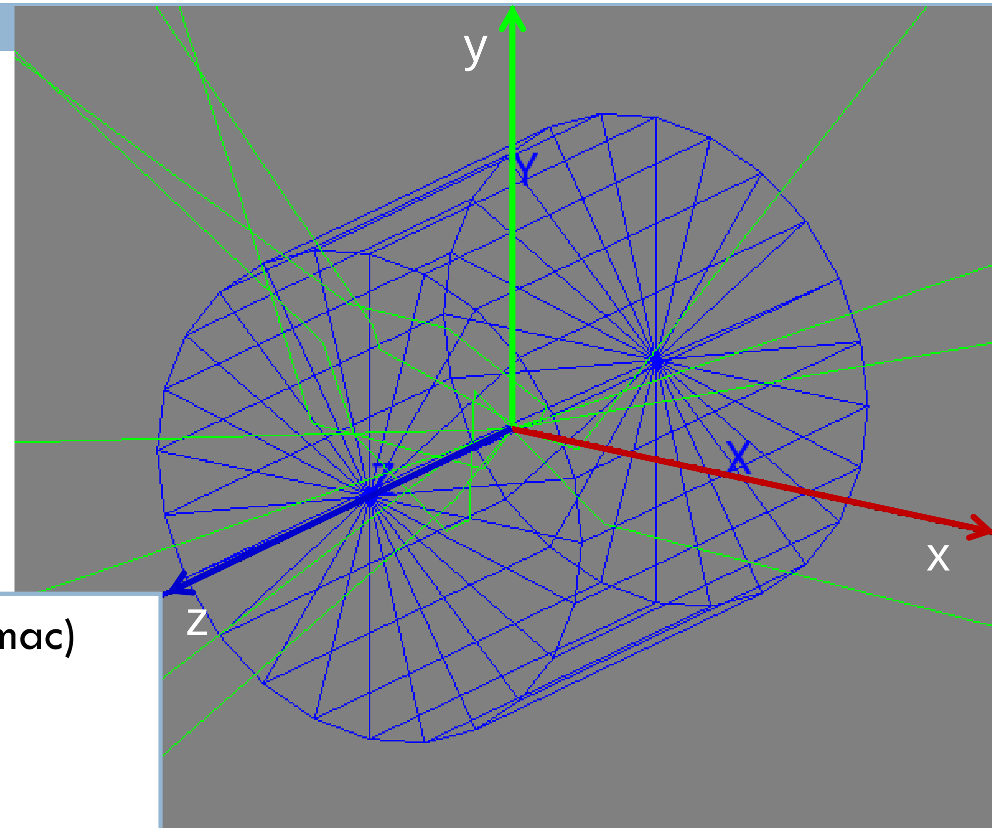
Geometry construction



Source in phantom:

- Radionuclide: [Flourine-18]
- Radioactivity: 1 MBq

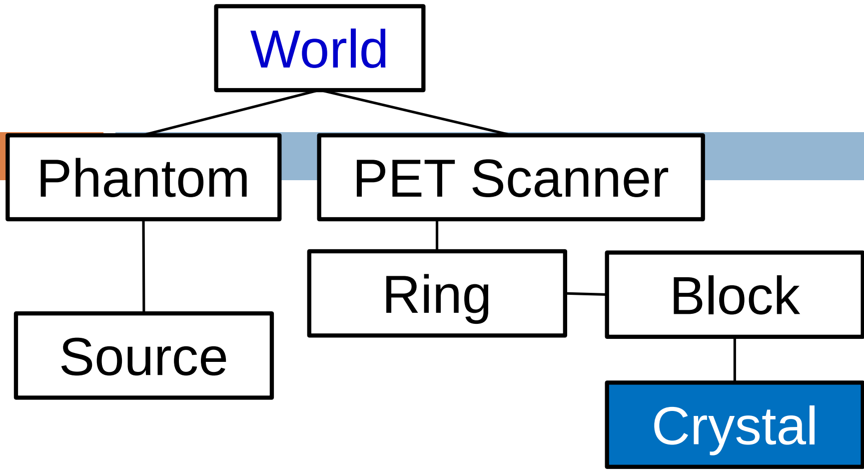
```
# Fluorine-18 positron emission source (sources.mac)
/gate/source/addSource          f18
/gate/source/f18/gps/particle  e+
/gate/source/f18/setForcedHalfLife 6586.2 s
/gate/source/f18/setActivity      10 Bq (test geometry)
/gate/source/f18/gps/shape     Cylinder
/gate/source/f18/gps/radius     0.5 mm
/gate/source/f18/gps/halfz      0.5 mm
```



A source at phantom center
(the green lines show photon paths)

Example macros: https://gitlab.in2p3.fr/davidsarrut/gate-exercices/-/tree/master/pet/mac

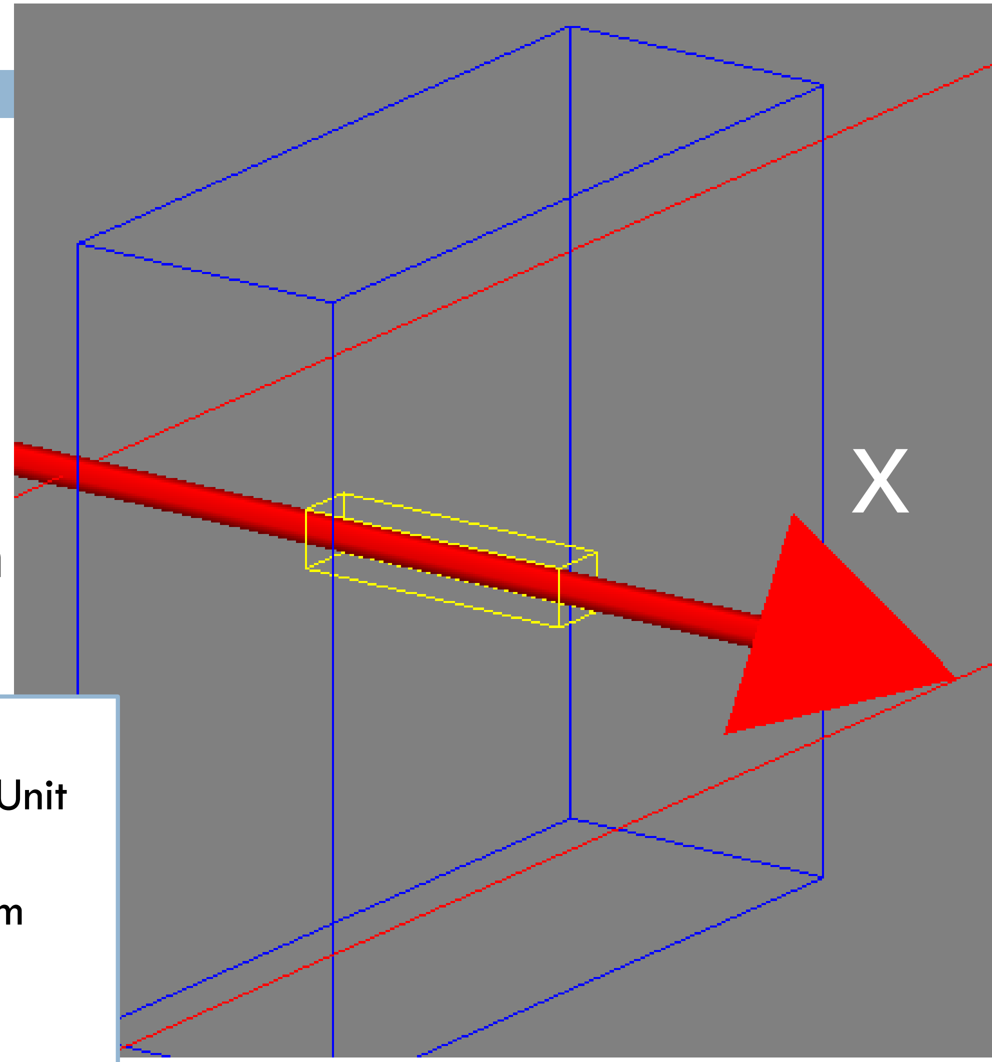
Geometry construction



PET scanner - Crystal unit:

- Size (x y z): 4 mm x 4 mm x 20 mm
- Material: LSO

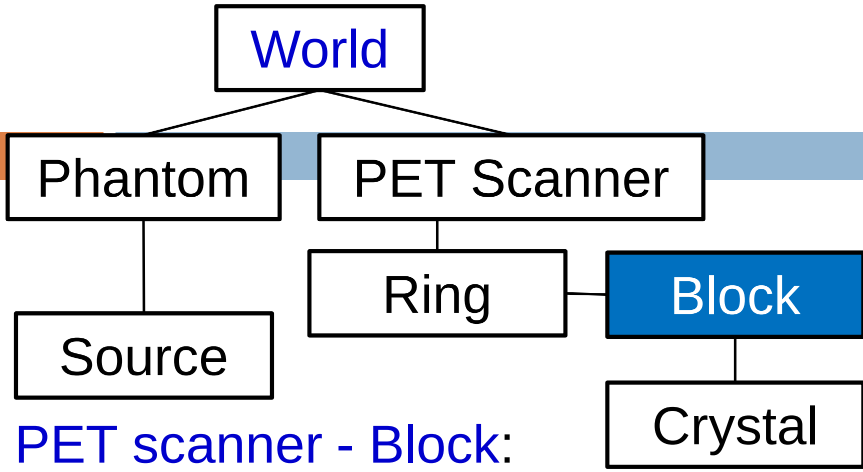
```
# Crystal (pet_head.mac)
/gate/blockDetector/daughters/name  crystalUnit
/gate/blockDetector/daughters/insert  box
/gate/crystalUnit/geometry/setXLength 20. mm
/gate/crystalUnit/geometry/setYLength 4. mm
/gate/crystalUnit/geometry/setZLength 4. mm
/gate/crystalUnit/setMaterial   LSO
```



Crystal unit (yellow box)

Example macros: https://gitlab.in2p3.fr/davidsarrut/gate-exercices/-/tree/master/pet/mac

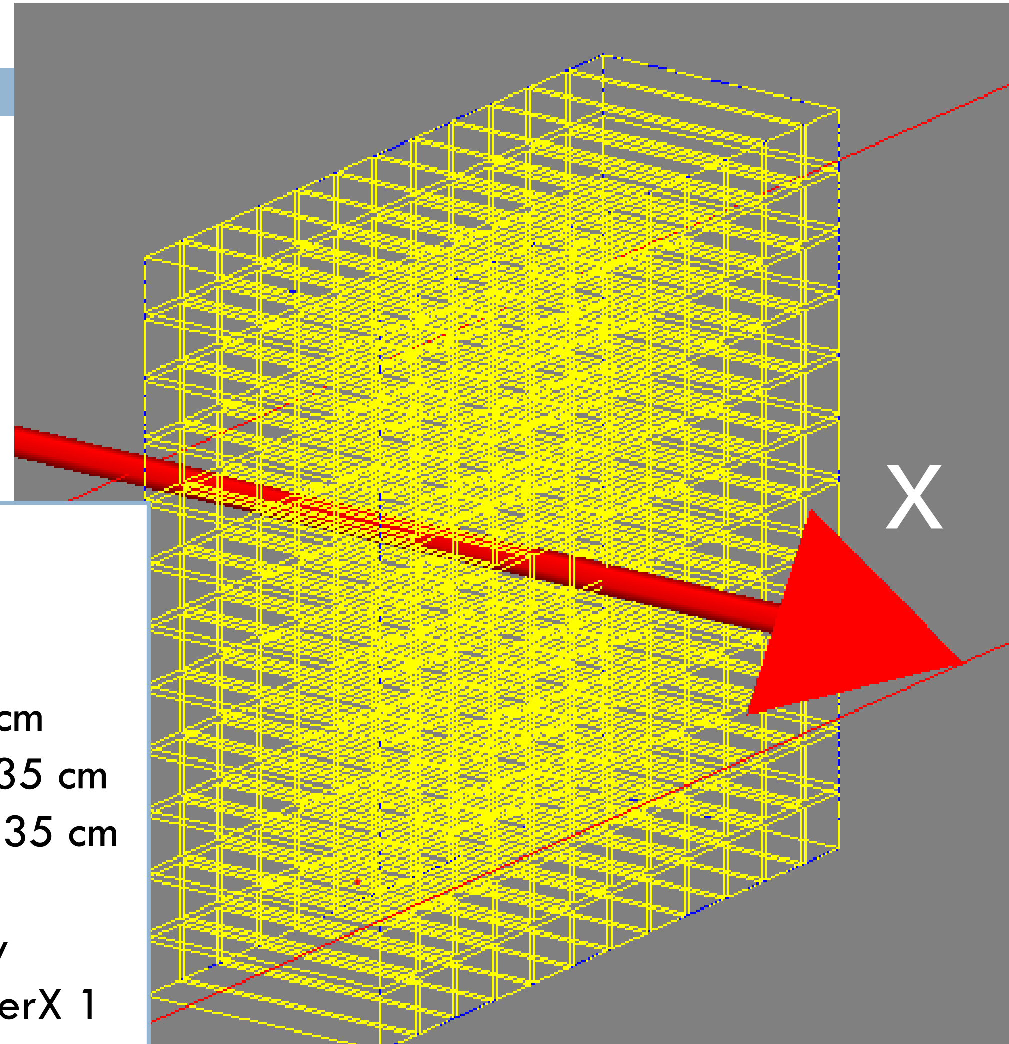
Geometry construction



PET scanner - Block:

- An array of 12 x 12 crytal units

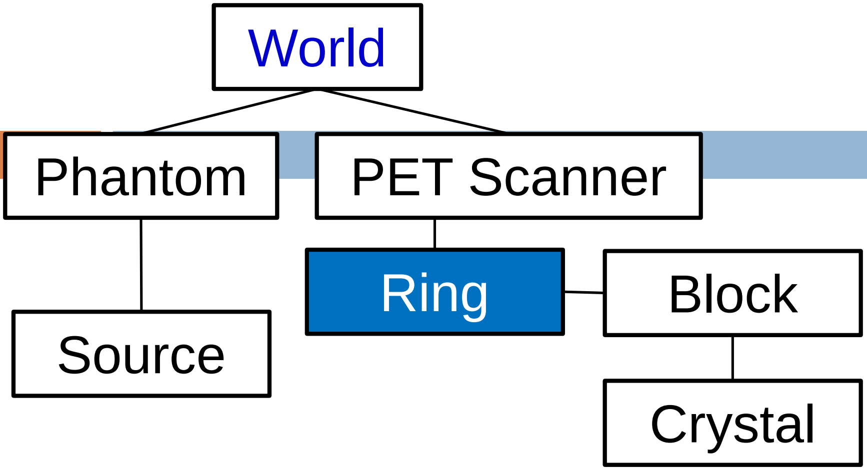
```
# Block (pet_head.mac)
/gate/ecat/daughters/name   blockDetector
/gate/ecat/daughters/insert   box
/gate/blockDetector/geometry/setXLength 2 cm
/gate/blockDetector/geometry/setYLength 5.35 cm
/gate/blockDetector/geometry/setZLength  5.35 cm
# Repeat the crytal units
/gate/crystalUnit/repeaters/insert  cubicArray
/gate/crystalUnit/cubicArray/setRepeatNumberX 1
/gate/crystalUnit/cubicArray/setRepeatNumberY 12
/gate/crystalUnit/cubicArray/setRepeatNumberZ 12
```



A block of a 12x12 crystal array (yellow)

Example macros: https://gitlab.in2p3.fr/davidsarrut/gate-exercices/-/tree/master/pet/mac

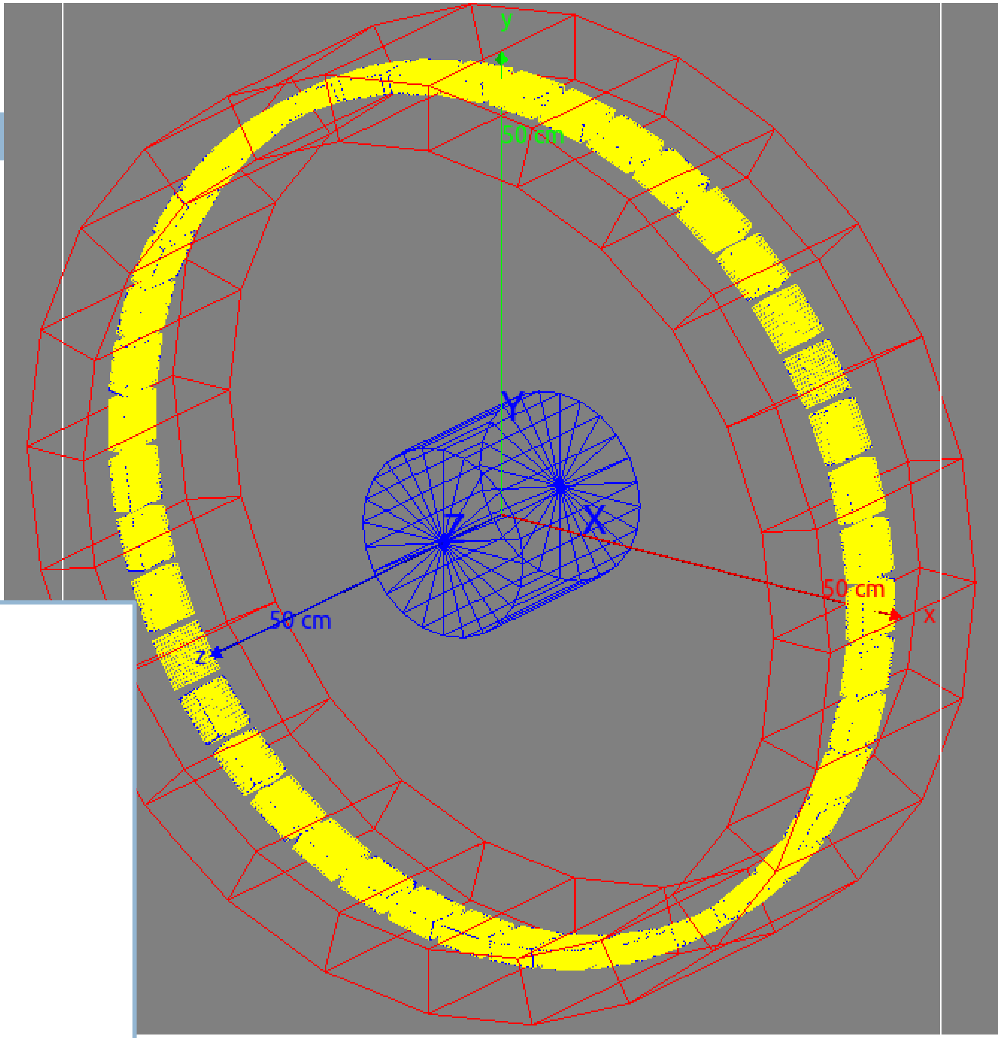
Geometry construction



PET scanner - Ring:

- 01 ring of 46 blocks

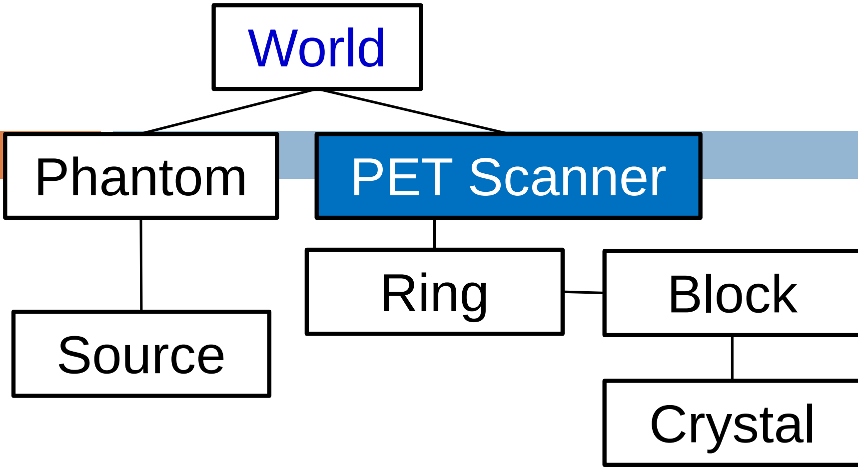
```
# Ring  (pet_head.mac)
/gate/world/daughters/name  ecat
/gate/world/daughters/insert  cylinder
/gate/ecat/geometry/setRmax  50 cm
/gate/ecat/geometry/setRmin   43 cm
/gate/ecat/geometry/setHeight  25 cm
# Repeat the blocks
/gate/blockDetector/repeaters/insert   ring
/gate/blockDetector/ring/setRepeatNumber 46
```



A ring of a 46 blocks (yellow)

Example macros: https://gitlab.in2p3.fr/davidsarrut/gate-exercices/-/tree/master/pet/mac

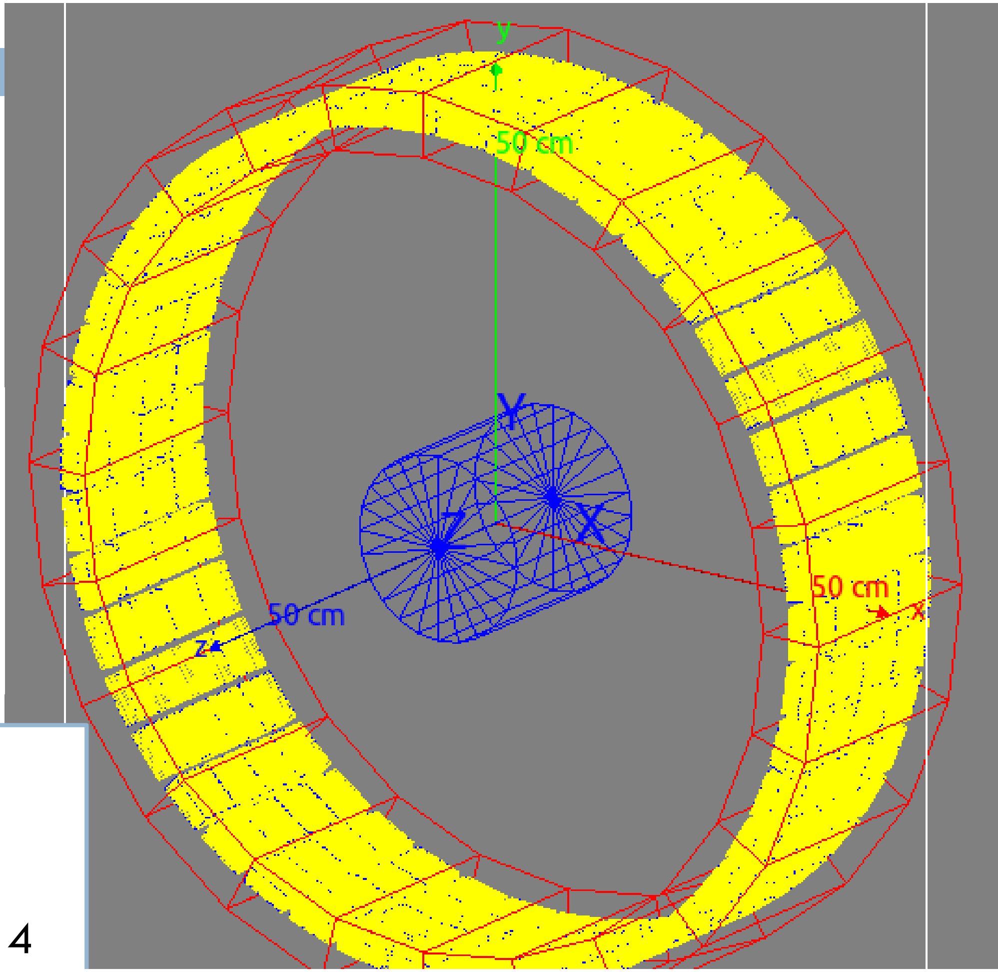
Geometry construction



PET scanner - Rings:

- 04 rings
- 46 blocks per ring
- 26496 crystal units

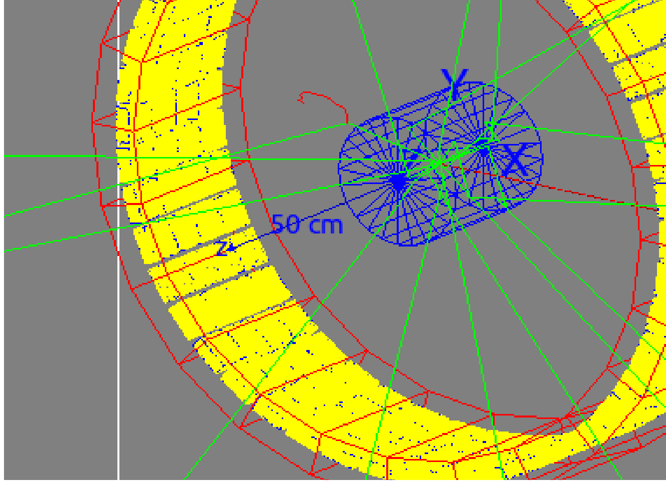
```
# 4 Rings  (pet_head.mac)
# Repeat the ring
/gate/blockDetector/repeaters/insert   linear
/gate/blockDetector/linear/setRepeatNumber 4
```



Simple PET scanner with 4 rings of crystals (yellow)

Example macros: https://gitlab.in2p3.fr/davidsarrut/gate-exercices/-/tree/master/pet/mac

Physical processes



Physics list: choices of all the particles that will be used in the simulation application together with the list of physics processes assigned to each individual particles.

- Particles: photon, electron and positron
- Physical processes: emstandard_opt4

Models used for gamma processes for Geant4 EM_Opt4

Gamma
Rayleigh scattering
- LivermoreRayleigh 0-100 TeV

Photoelectric scattering
- LivermorePhElectric 0-100 TeV

Compton scattering
- LowEPComptonModel 0-20 MeV
- KleinNishina 20 MeV-100 TeV

Gamma conversion
- BetheHeitler5D 0-100 TeV

Electron
Coulomb scattering
- eCoulombScattering 100 MeV-10 TeV

Multiple scattering
- GoudsmitSaunderson 0-100 MeV
- WentzelVIUni 100 MeV-100 TeV

Pair production
-ePairProd 0-100 TeV

Ionisation
- LowEnergyIoni 0-100 keV
- MollerBhabha 100 keV-100 TeV

Bremsstrahlung
- eBremSB 0-1 GeV
- eBremLPM 1 GeV-100 TeV14

Positron
Coulomb scattering
- eCoulombScattering 100 MeV-100 TeV

Multiple scattering
- GoudsmitSaunderson 0-100 MeV
- WentzelVIUni 100 MeV-100 TeV

Pair production
-ePairProd 0-100 TeV

Ionisation
- LowEnergyIoni 0-100 keV
- MollerBhabha 100 keV-100 TeV

Annihilation
- eplus2gg 0-100 TeV

Bremsstrahlung
- eBremSB 0-1 GeV
- eBremLPM 1 GeV-100 TeV

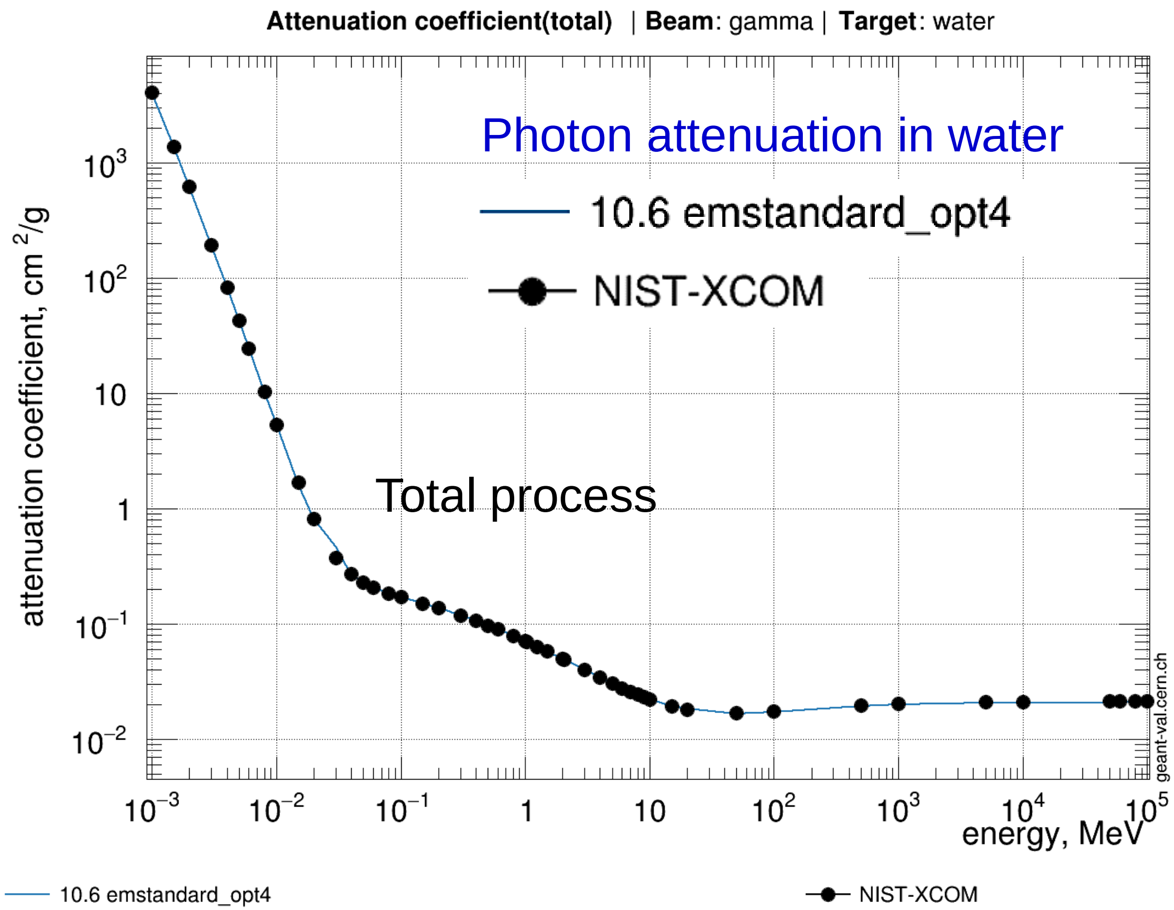
The chosen physics list needs to be validated for a given application

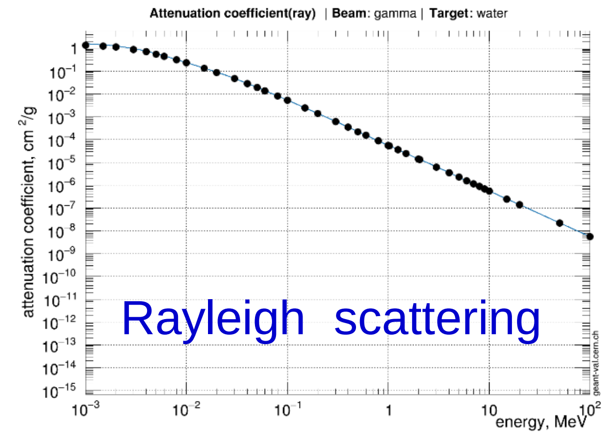
Geant4: EM Opt4
Geant4 Electromagnetic physics constructors
Geant4 Validation Portal: https://geant-val.cern.ch/layouts

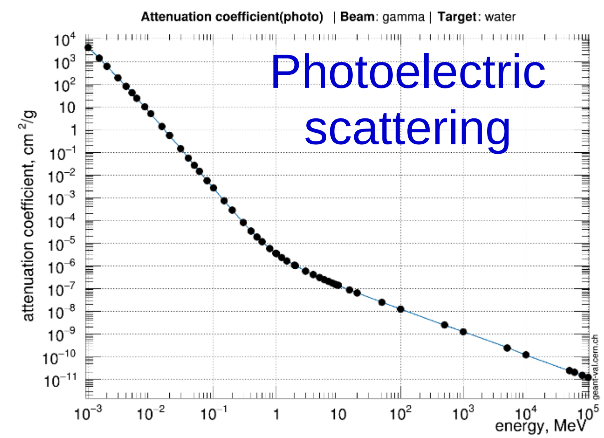
Geant4 validation

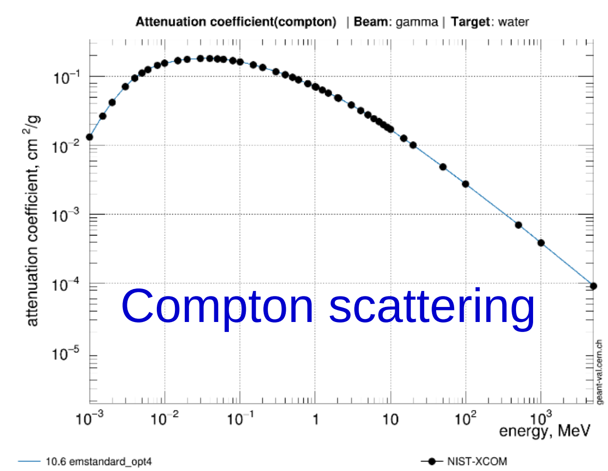
Comparison between values computed with GEANT4 10.6 and NIST-XCOM values

Physics list: emstandard_opt4



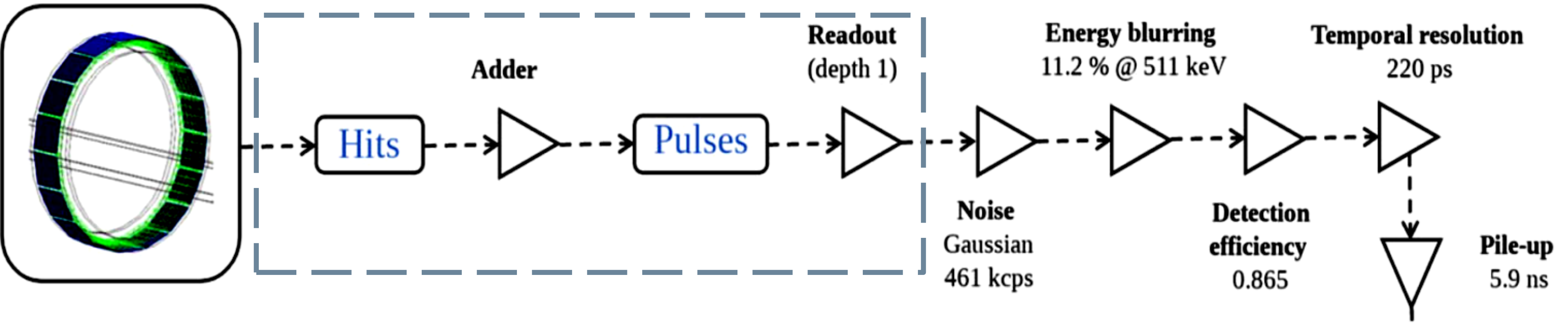






Geant Validation Portal: https://geant-val.cern.ch/layouts

Data flow - Digitizer and readout



Setup: Input: macro file

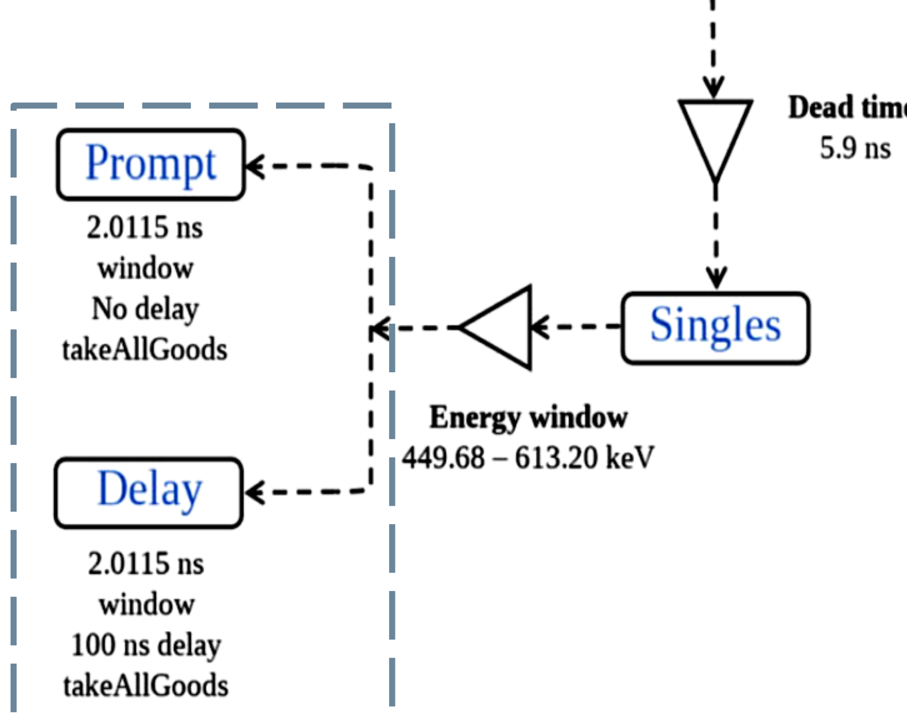
- Define scanner, phantom, source ...

Simulation

- Generate particles
- Simulate interactions and track particles' projections

Digitizing and readout

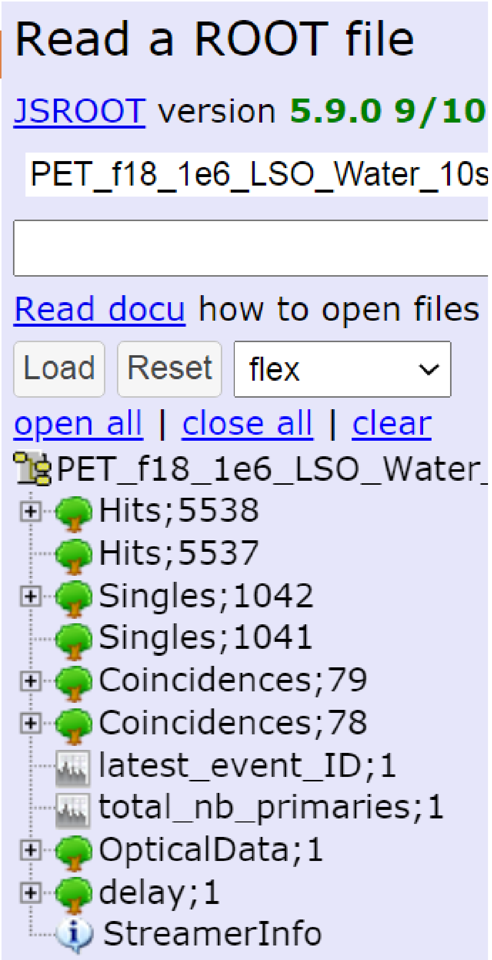
- Digitizer filters data to minic Front End Electronics
- Output: ROOT file stores information for Hits, Singles and Coincidences

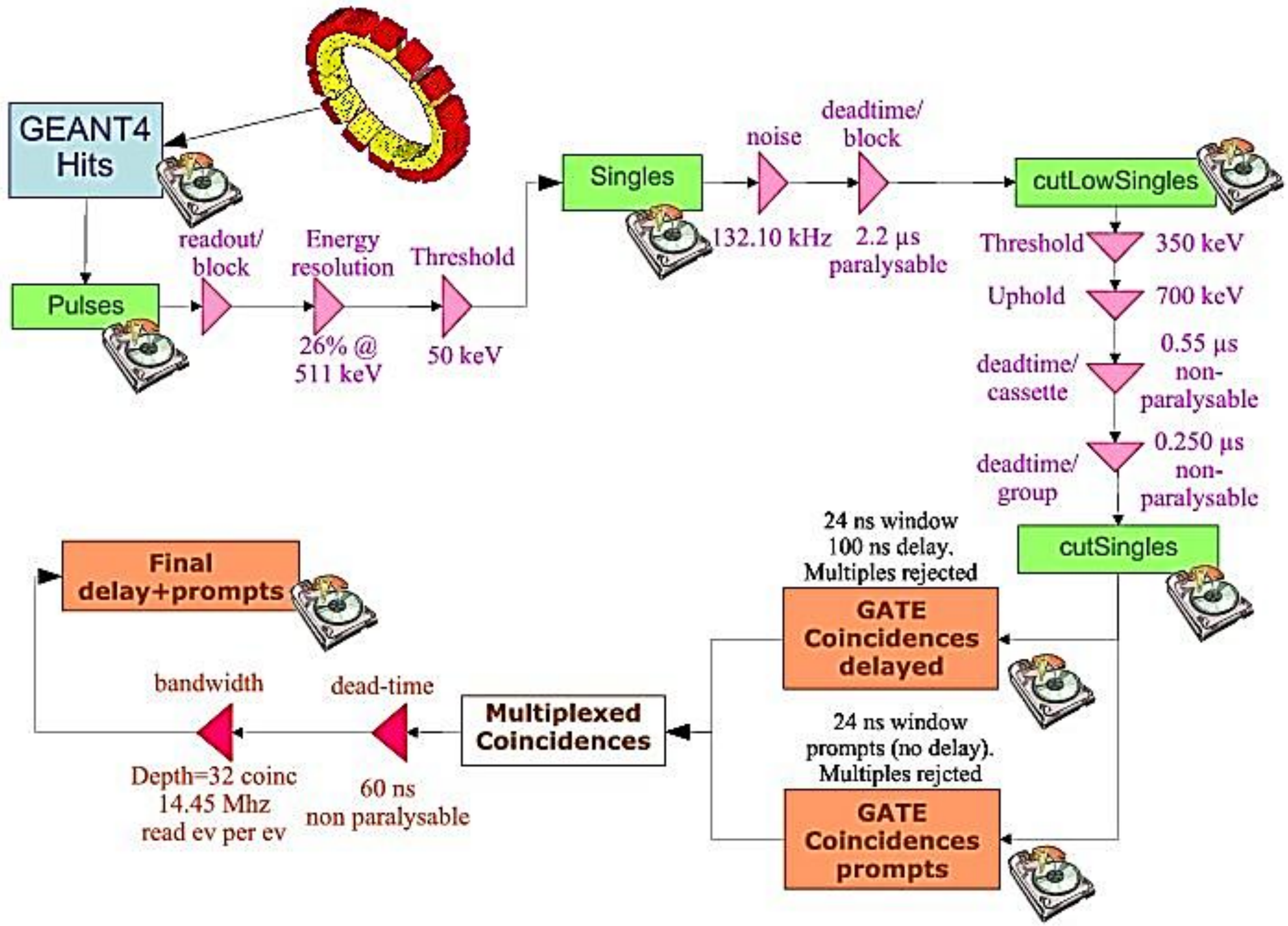


Salvadori, J., Labour, J., Odille, F., Marie, P. Y., Badel, J. N., Imbert, L., & Sarrut, D. (2020). Monte Carlo simulation of digital photon counting PET. *EJNMMI physics*, *7*, 1-19

Root file – Data analysis

JSROOT: https://root.cern.ch/js/latest/



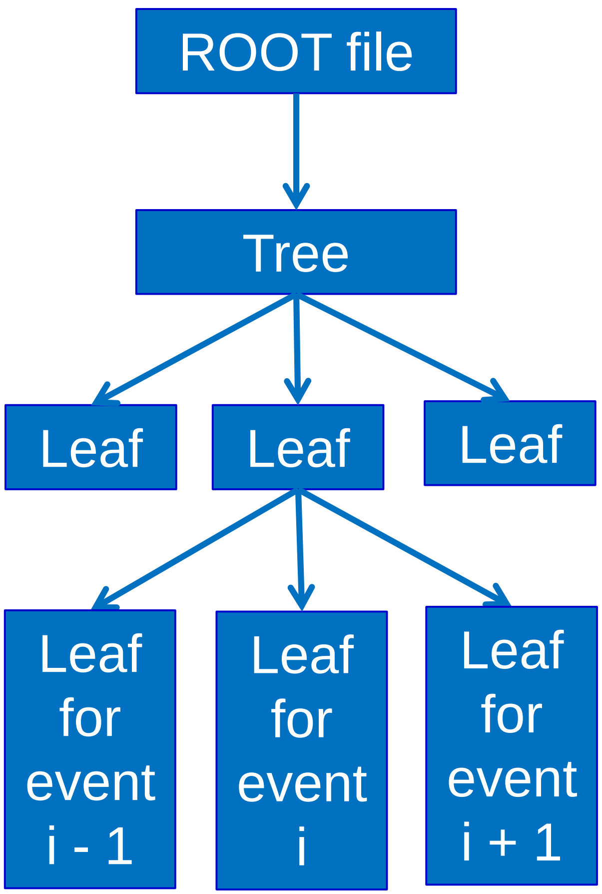


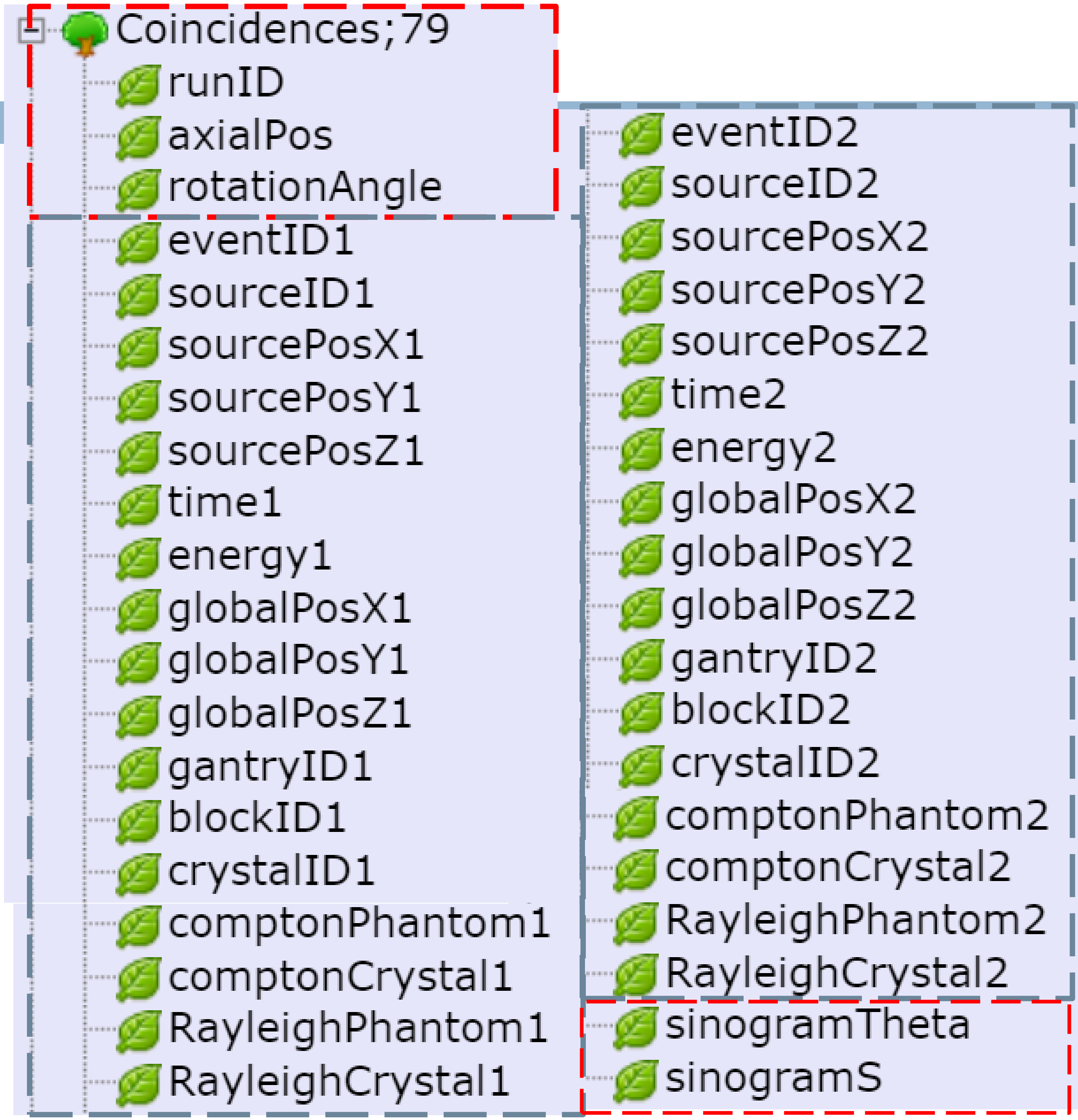
A readout scheme example.

The disk icons represent the data written to the GATE output files

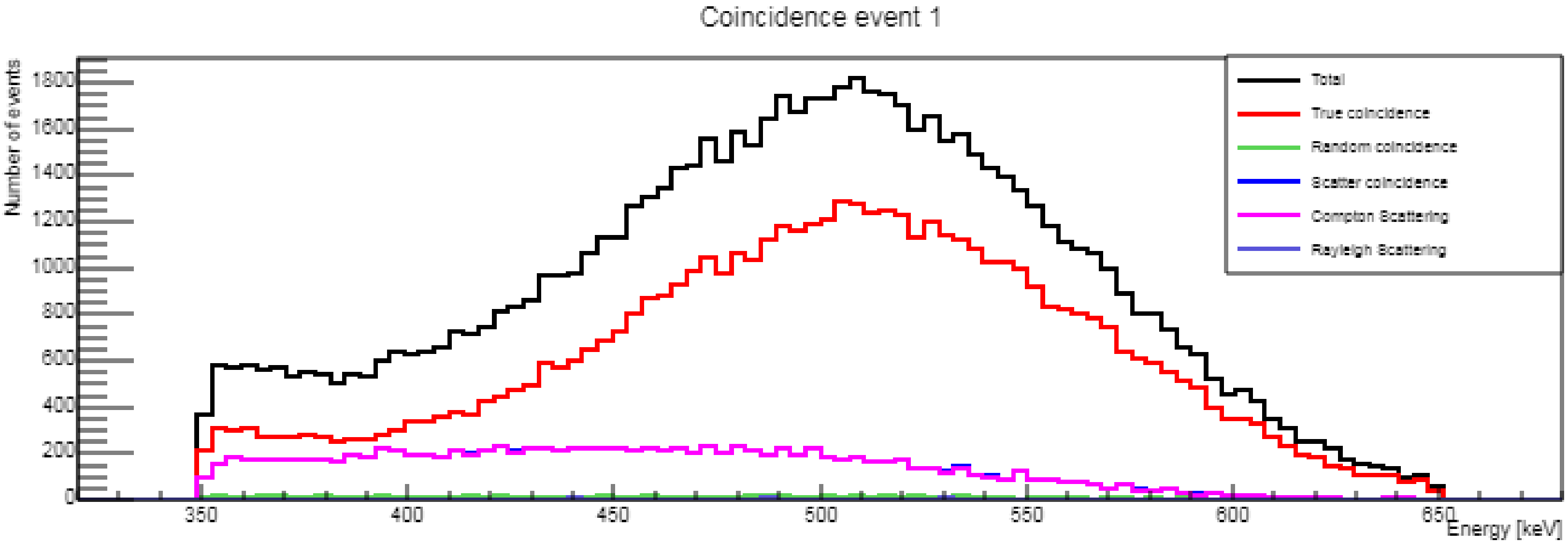
Root file – Data analysis

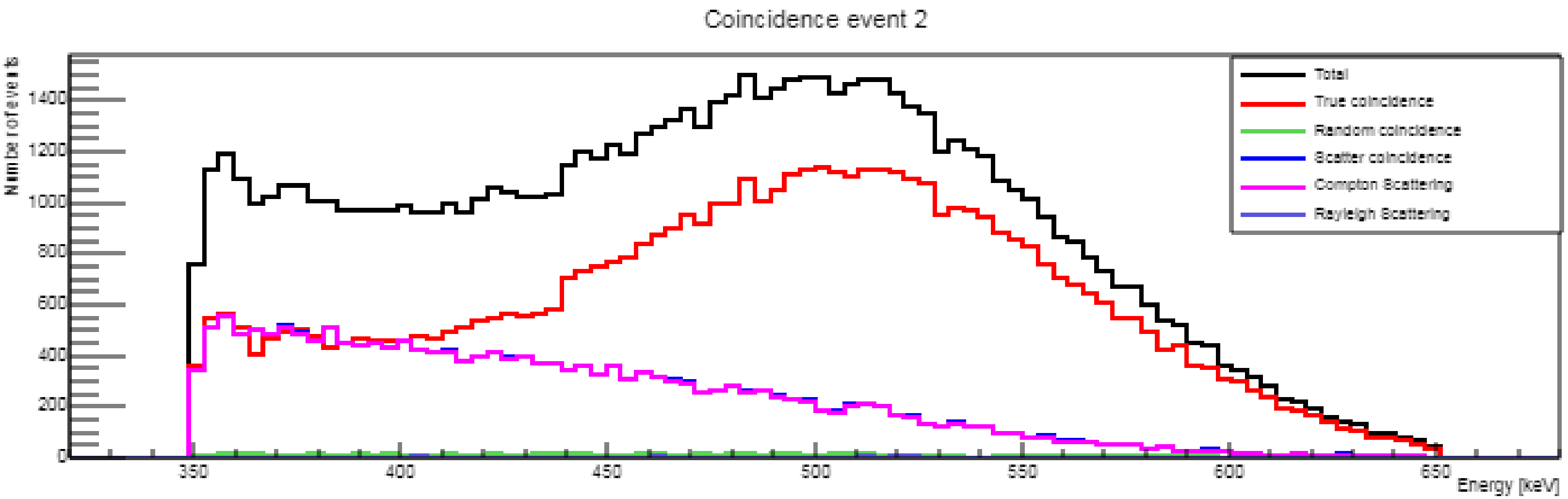
JSROOT: https://root.cern.ch/js/latest/





Data analysis - Energy spectra

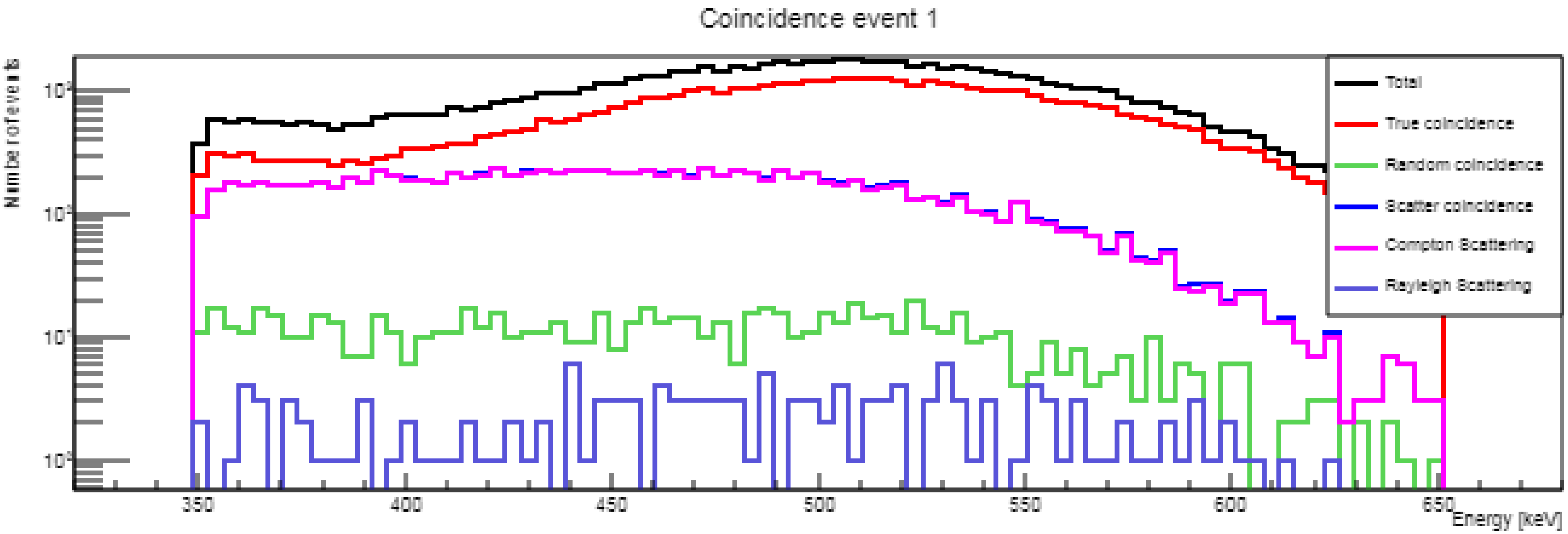


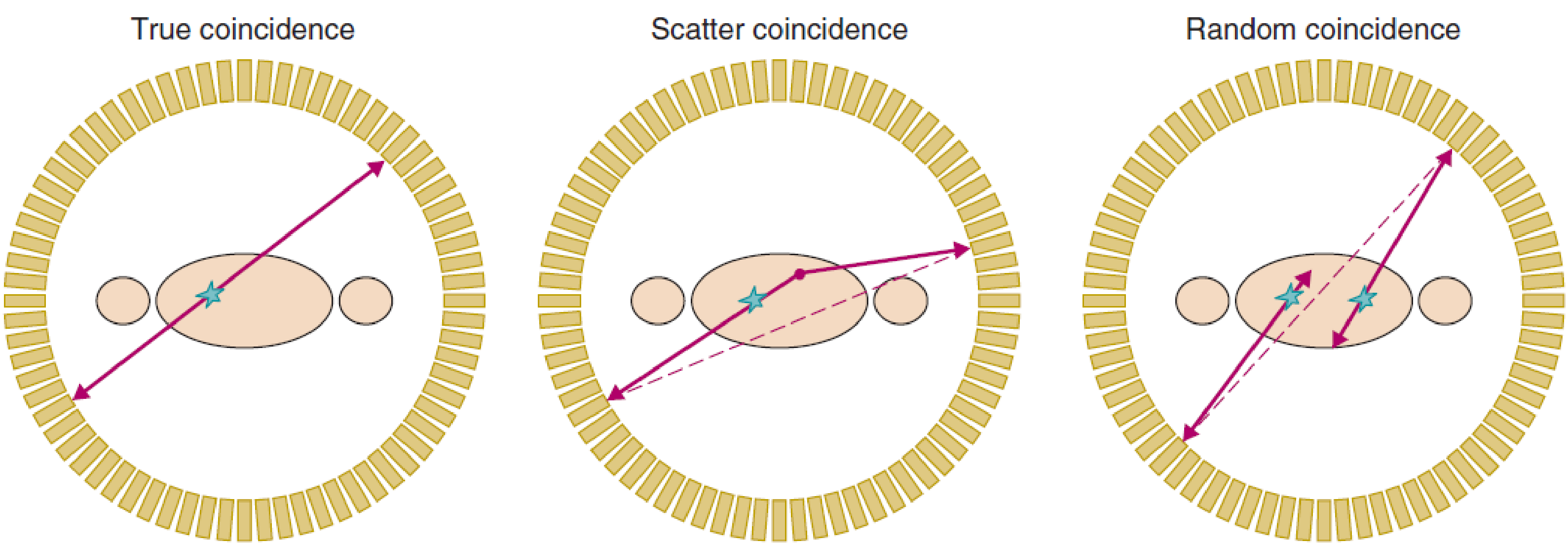


Energy spectra of Coincidences events
Total events (black), True events (red), Compton events (pink)

Coincidence sorter

Data analysis - Energy spectra





Coincidences events: True coincidence (left), Scatters (middle), Randoms (right)

Not all photons travel along straight lines: scatter, absorption, random coincidence

More complex PET systems …

Scanner type	Studies
ECAT EXACT HR+, CPS [Jan et al. 2005]	Spatial resolution Sensitivity Count rates Scatter fraction
ECAT HRRT, Siemens [Bataille et al. 2004]	Spatial resolution Scatter fraction Scattered coinc profiles Count rates
Hi-Rez, Siemens [Michel et al. 2006]	Scatter fraction Count rates NEC curves
Allegro, Philips [Lamare et al. 2006]	Count rate Scatter fraction
GE Advance, GEMS [Schmidtlein et al. 2006]	Energy spectra Scatter fraction
MicroPET P4, Concorde [Jan et al. 2003]	Spatial resolution Sensitivity Miniature Derenzo phantom

Scanner type	Studies
MicroPET Focus 220, Siemens [Jan et al. 2005]	Spatial resolution Sensitivity Count rates for mouse phantom
Mosaic, Philips [Merheb et al. 2006]	Scatter fraction Count rates
Inveon PET/SPECT/CT, Siemens [Lee et al. 2013]	PET scatter fraction, count rates and sensitivity SPECT scatter fraction, energy resolution, and sensitivity CT dose rate
Vereos, Philips [Salvadori et al., 2020]	Count rates Scatter fraction Energy resolution Timing resolution Sensitivity Intrinsic spatial resolution

Gate - GATE-modelled systems

Remarks and Conclusions

- Gate/Geant4 – A Monte Carlo simulation toolkit for PET imaging:
  - helps to design, optimize and predict the performance of imaging systems;
  - provides data for developing and optimize image reconstruction algorithms;
  - helps to evaluate the effects of scatters and noises in image quality.
  - is able to describe most imaging scenarios and phenomena, from transport of optical photons to particle-therapy mornitoring.
- Simulation is a powerful demonstration toolkit for training in medical physics, especially nuclear medicine.
- Disadvantages of Monte Carlo simulation:
  - Simulation does not describe the uptake and retention of radiopharmaceuticals by tissues and organs over time.
  - Simulating complex systems with high accuracy consumes long computation time.

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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