IMAGING EXPERIENCE WITH MONTE CARLO SIMULATION OF RADIATION DETECTORS

3RD INT'L WORKSHOP ON EXPERIMENTAL PARTICLE PHYSICS: DETECTORS & APPLIED ELECTRONICS (IPM - NOV 24, 2021)

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OUTLINE

- Monte Carlo method
- General vs Event-by-Event output data
- Computed Tomography (CT)
- Positron Emission Tomography (PET)
- ThErmal Neutron Imaging System (TENIS)

MONTE CARLO METHOD: INTRODUCTION

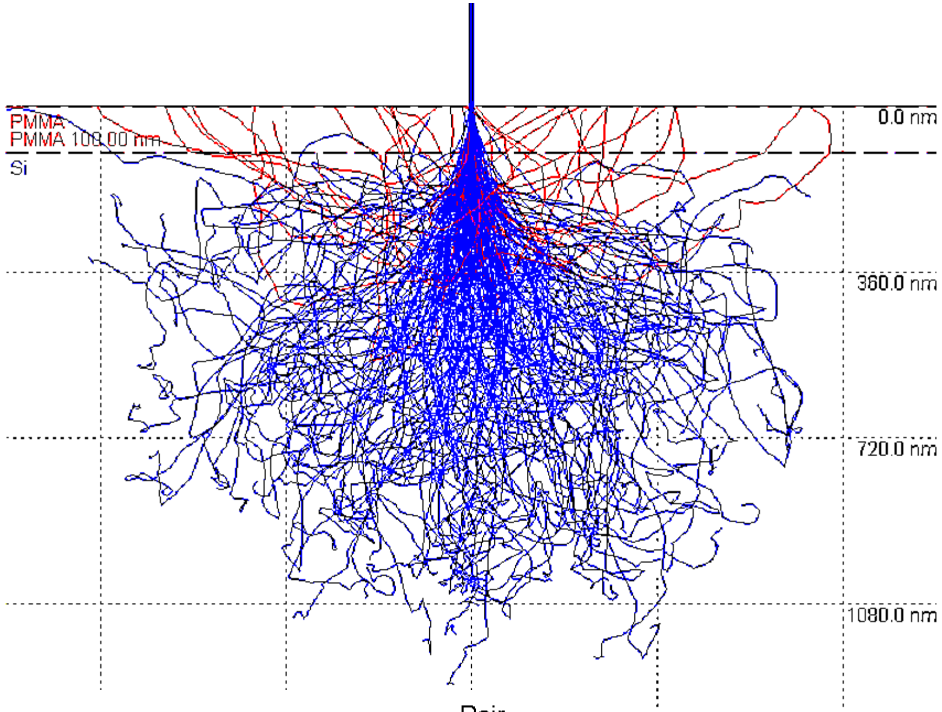
- **Monte Carlo Method**

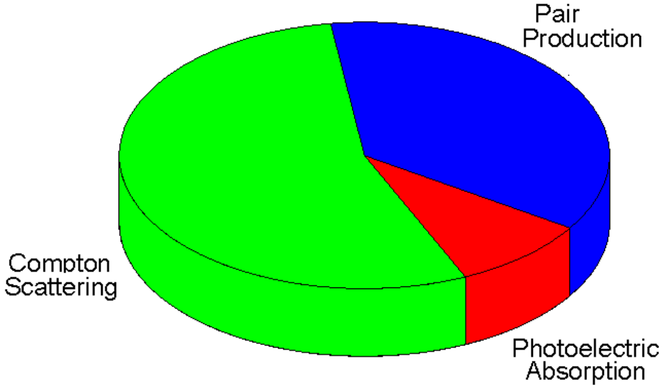
  "The use of random numbers in order to model a phenomenon, instrument and so on, which may be of probabilistic nature (e. g., **photon interactions with matter**) or may not (e. g., **integration**)"

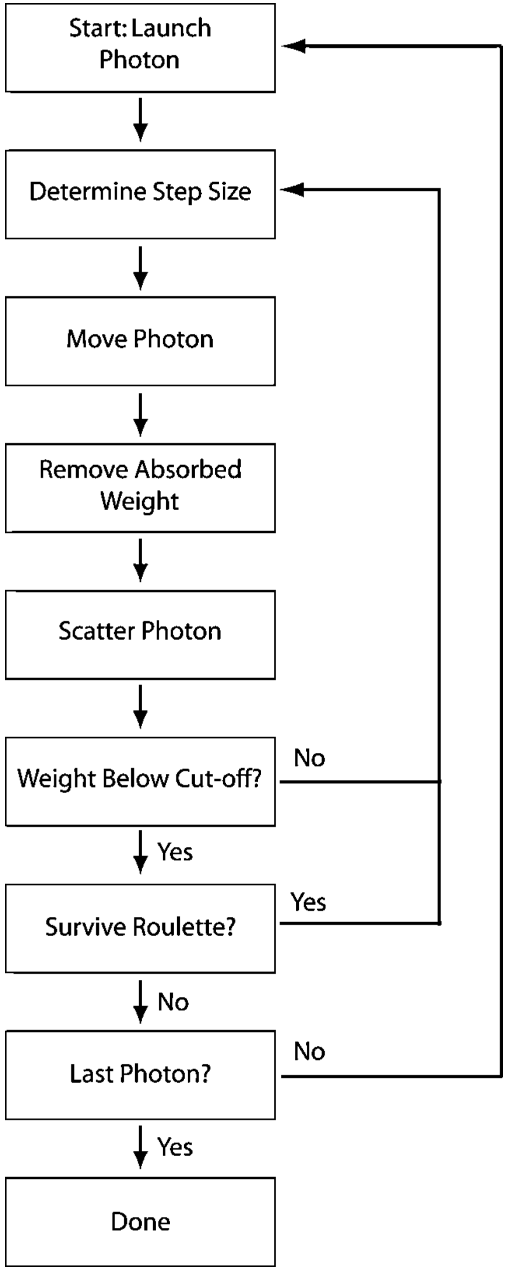
PHOTON INTERACTIONS WITH MATTER

A beam of 10 keV photons incident on PMMA and Silicon.

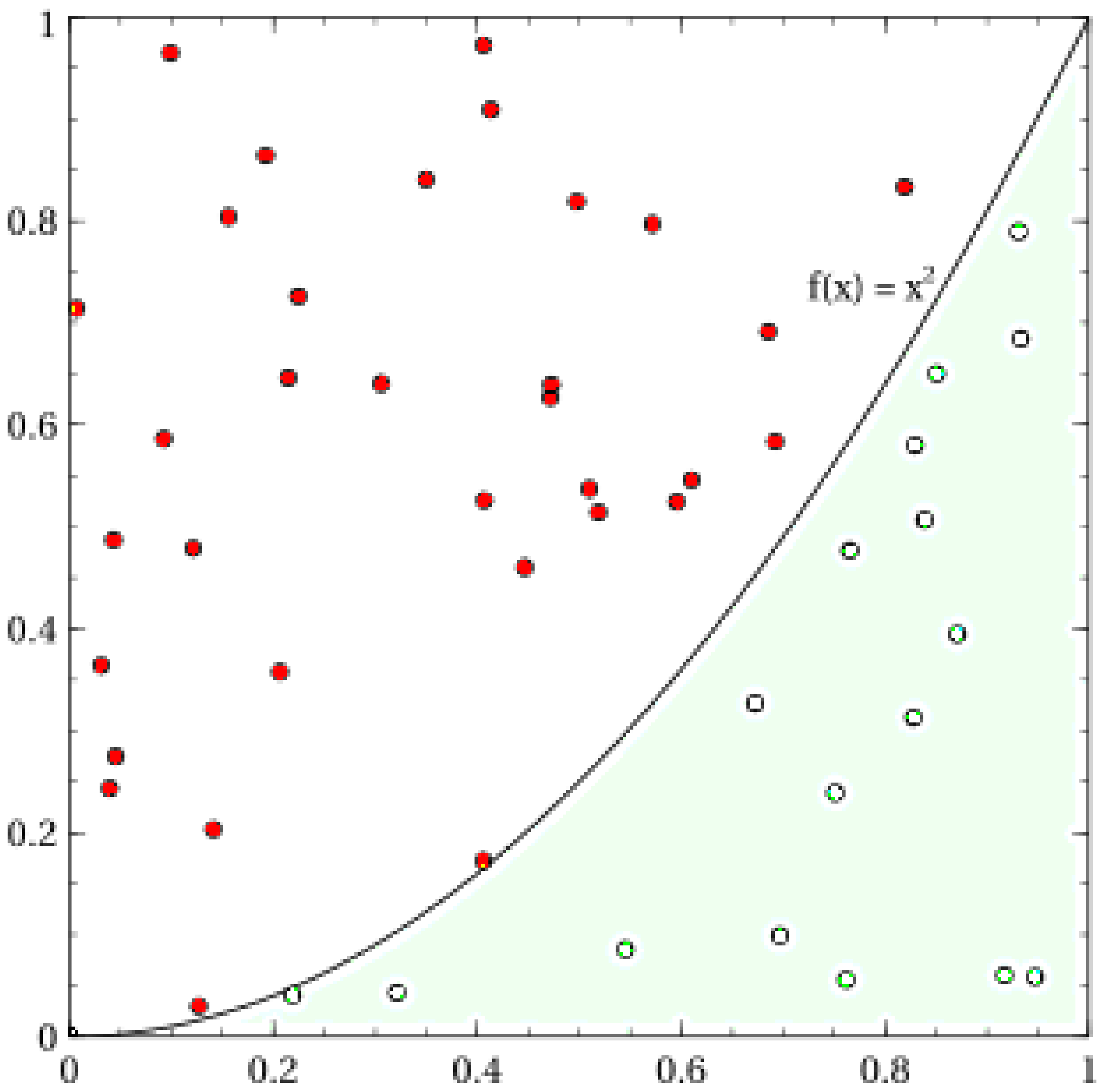
Russian Roulette







INTEGRATION



DEDICATED VS GENERAL-PURPOSE CODES

- **Dedicated Codes**
  - ETRAN: Electron TRANsport code
  - URANOS: Ultra Rapid Adaptable Neutron-Only Simulation

- **General-Purpose Codes**
  - MCNP: Monte Carlo N-Particle
  - FLUKA: FLUktuierende Kaskade
  - GEANT: GEometry ANd Tracking

MY SIMULATIONS WITH MCNP AND FLUKA

- **Detector response**
  - Scintillators (Organics and Inorganics)
  - BF_3, Boron-Lined Proportional Counters
  - HPGe, etc.
- **Radiation applications**
  - Soil moisture measurement
  - Well-logging
  - Dosimetry
  - BNCT
  - Neutron source and nuclear fuel, etc.

OUTPUT DATA OF MC CODES

	MCNP	FLUKA
• **Integral Tallies (For general users)**	**MCNP**	**FLUKA**
○ Current	F1	USERBDX
○ Surface and volume fluxes	F2, F4	USERBDX, USERTRACK
○ Deposition energy in volume of interest	F6	USERBIN

- **Event-by-event Tallies (For advanced users)**
  - PTRAC (MCNP)
  - USERDUMP (FLUKA)

MODELING IMAGING SYSTEMS

- **Requirements**
  - Radiation source definition (particle type, angular distribution and energy spectrum)
  - Taking into account all interactions
  - Modeling the detector response
  - Image Reconstruction (IR)

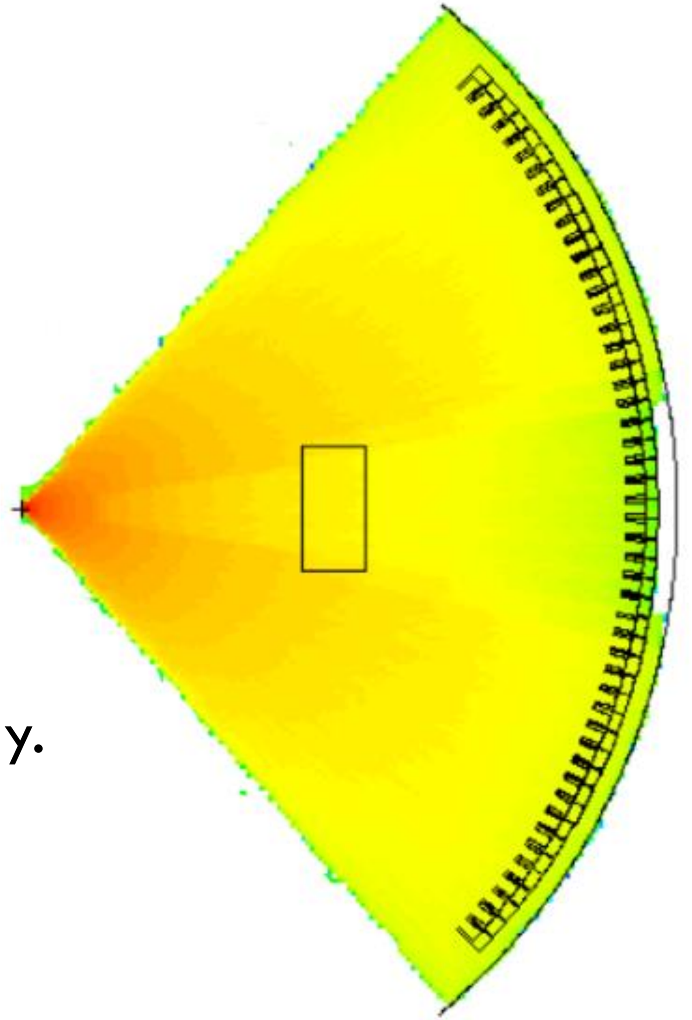
SELECTED IMAGING SYSTEMS

- Computed Tomography **(CT)**
- Positron Emission Tomography **(PET)**
- ThErmal Neutron Imaging System **(TENIS)**

MODELING A SIMPLE CT-SCANNER WITH FLUKA

- An array of **49** rectangular 2×3×3 cm^3 GOS* crystals
- Thin lead collimators
- Fan beam of 150 kVp X-ray photons using FLUKA's *source.f*
- A rectangular CH_2 phantom as an object

- In simulation, the phantom is rotated instead of detector array.



* GOS=Gd_2O_2S:Pr scintillator @ 7.34 g/cm^3

X-RAY ENERGY SPECTRUM

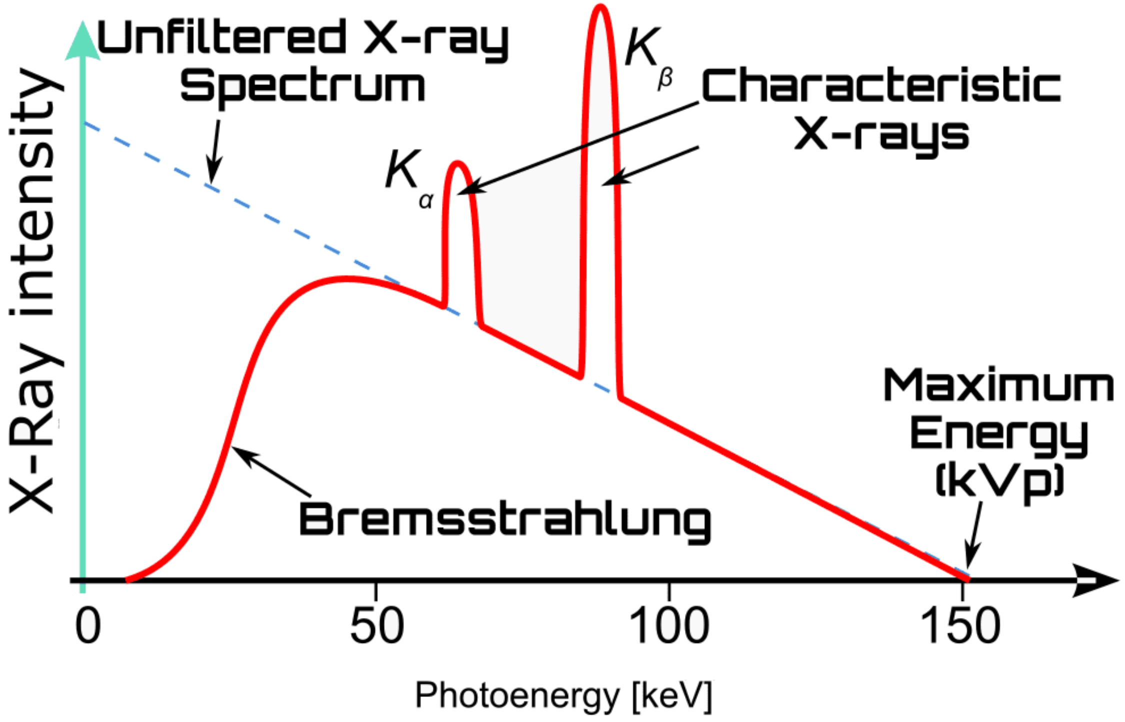
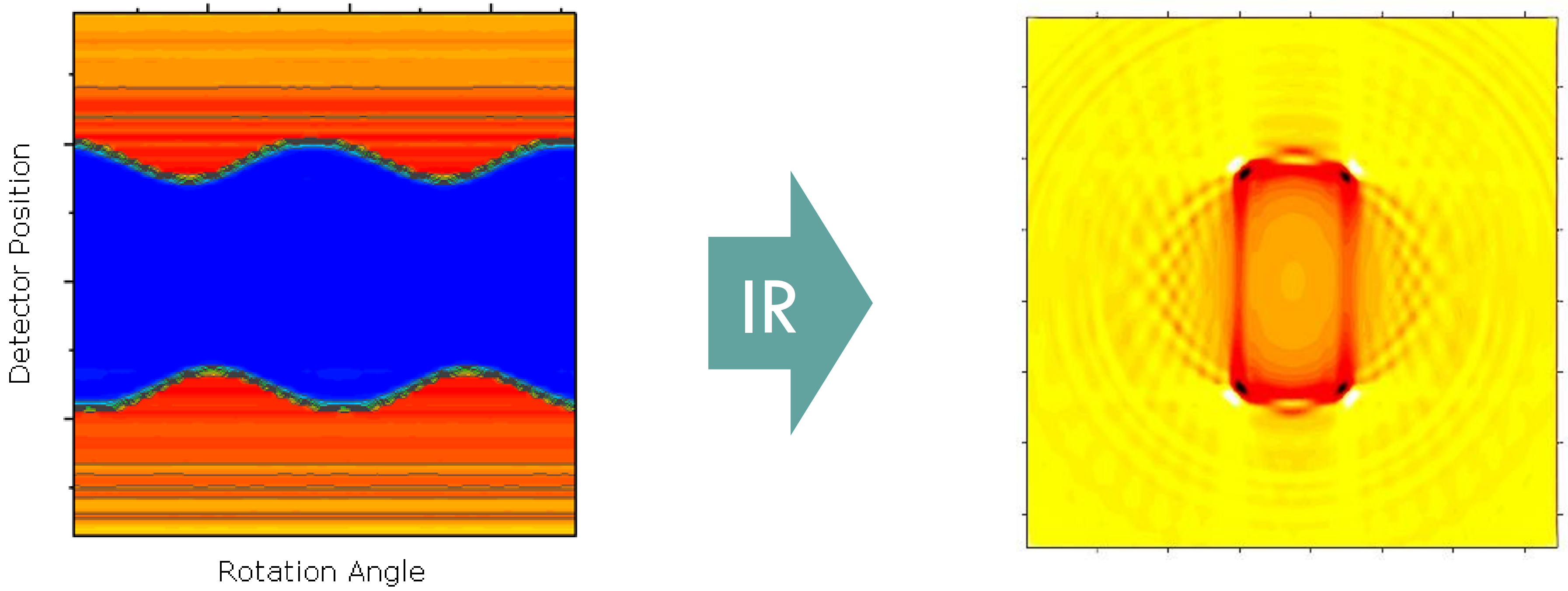


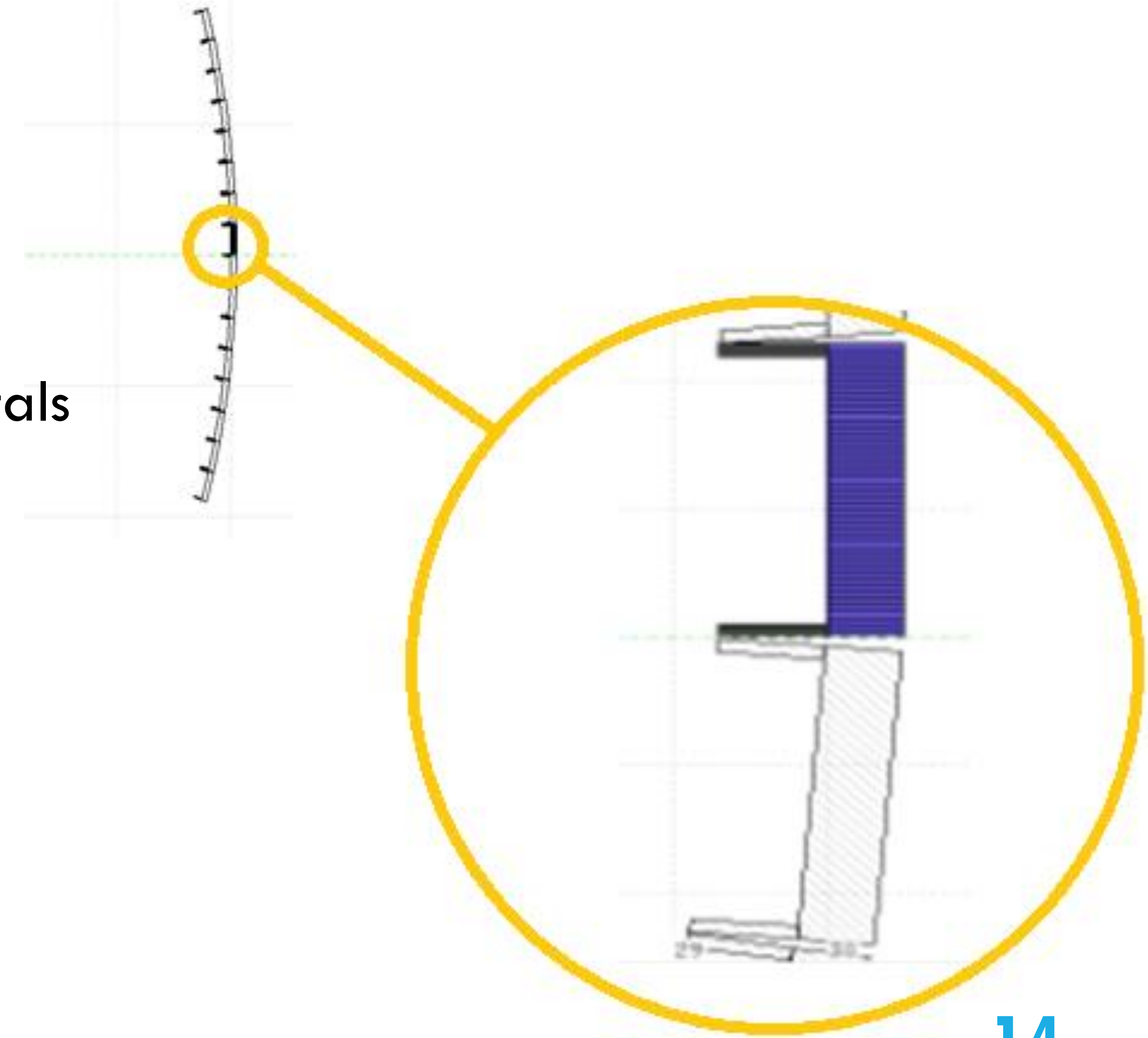
IMAGE-RECONSTRUCTION WITH MATLAB

- Construction of sinogram: A data matrix (rotation angle × detector number)
- Image Reconstruction (IR): Sinogram to 2D-image (using *ifanbeam* command)



REALISTIC CT-SCANNER

- Siemens Somatom Emotion
- An array of **736** rectangular $1.5 \times 1.5 \times 1.5\ cm^3$ Siemens UFC* crystals in the form of 16 modules
- Thin lead collimators



* Ultra Fast Ceramics scintillator @ $7.3\ g/cm^3$

PROBLEM WITH LARGE NUMBER OF CRYSTALS!

- ASTRA Toolbox (www.astra-toolbox.com)
- ASTRA is a MATLAB-Python toolbox for high-performance GPU image-reconstruction using CUDA*-capable NVIDIA graphics card.

* CUDA (Compute Unified Device Architecture): A parallel computing platform and application programming interface (API) that allows software to use certain types GPUs.

SNYDER HEAD PHANTOM

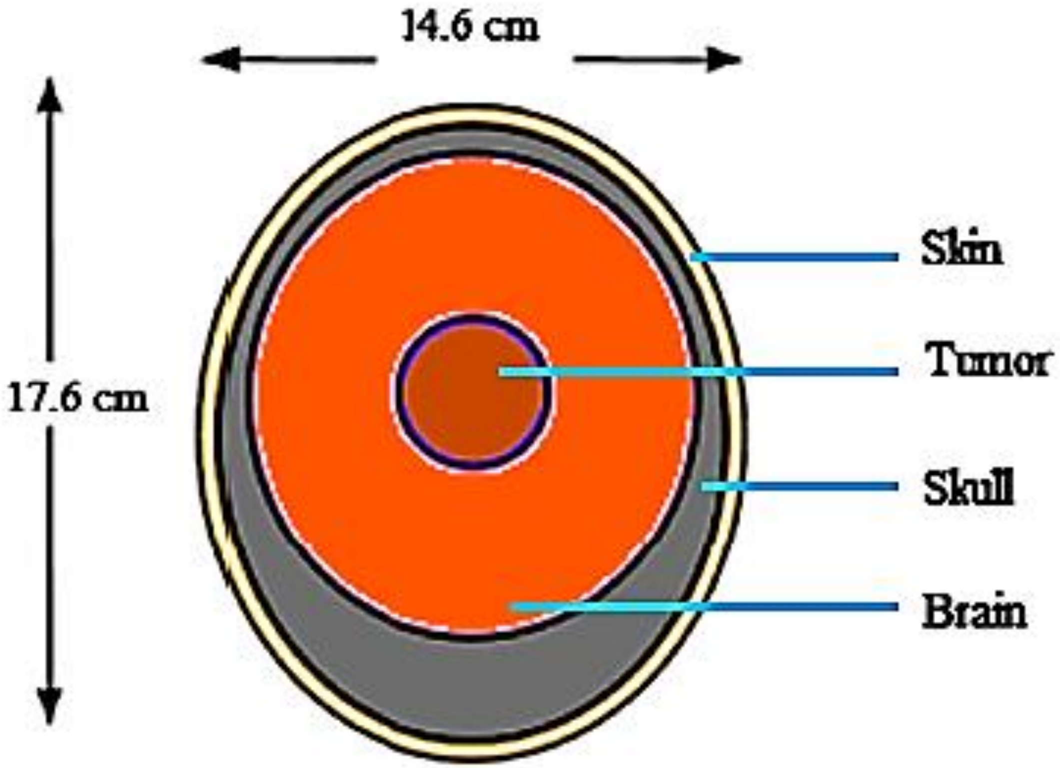
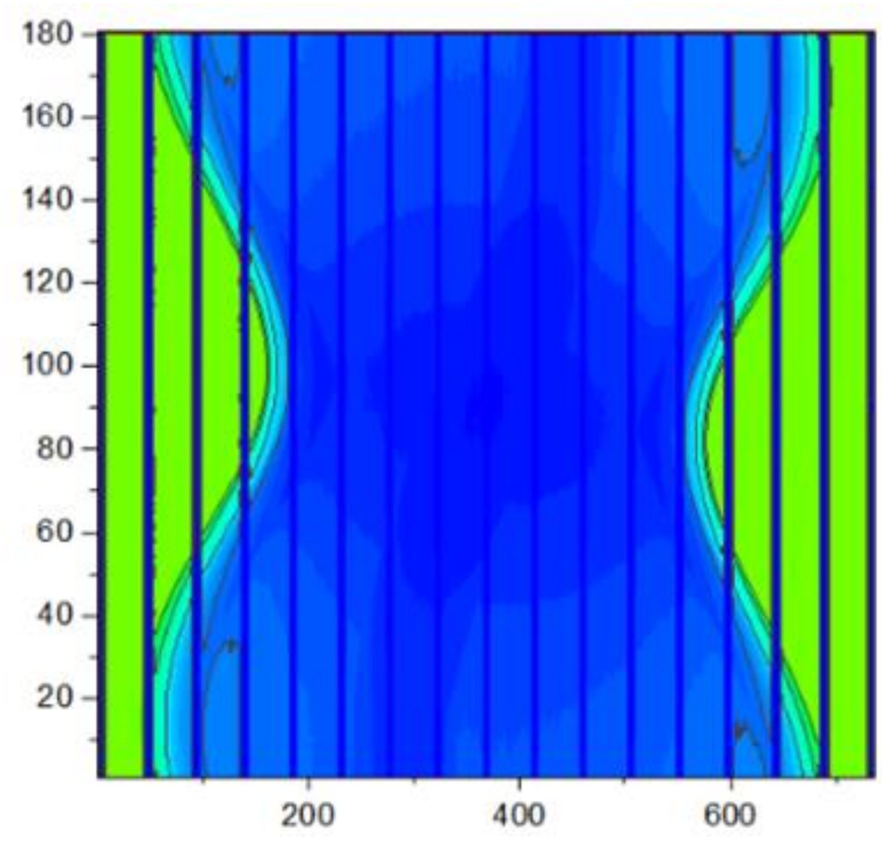
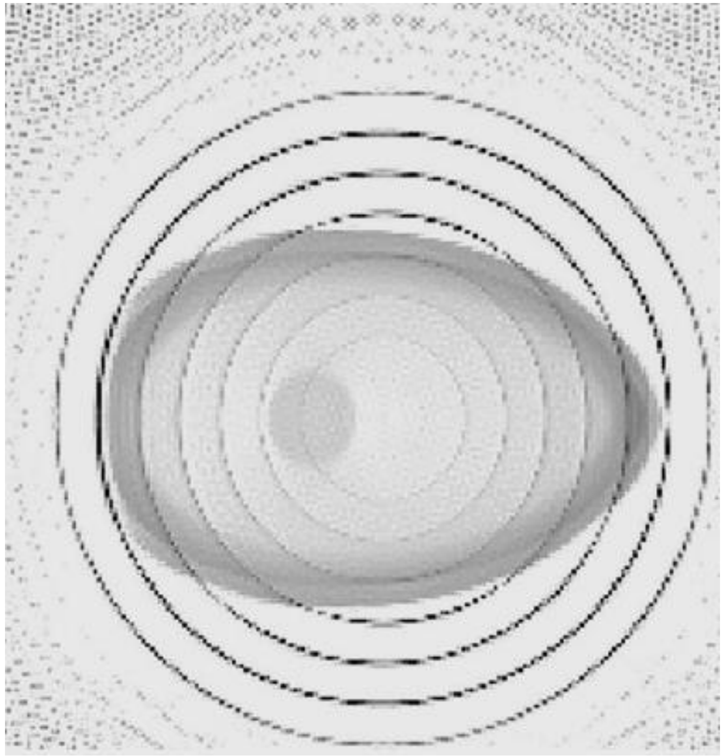


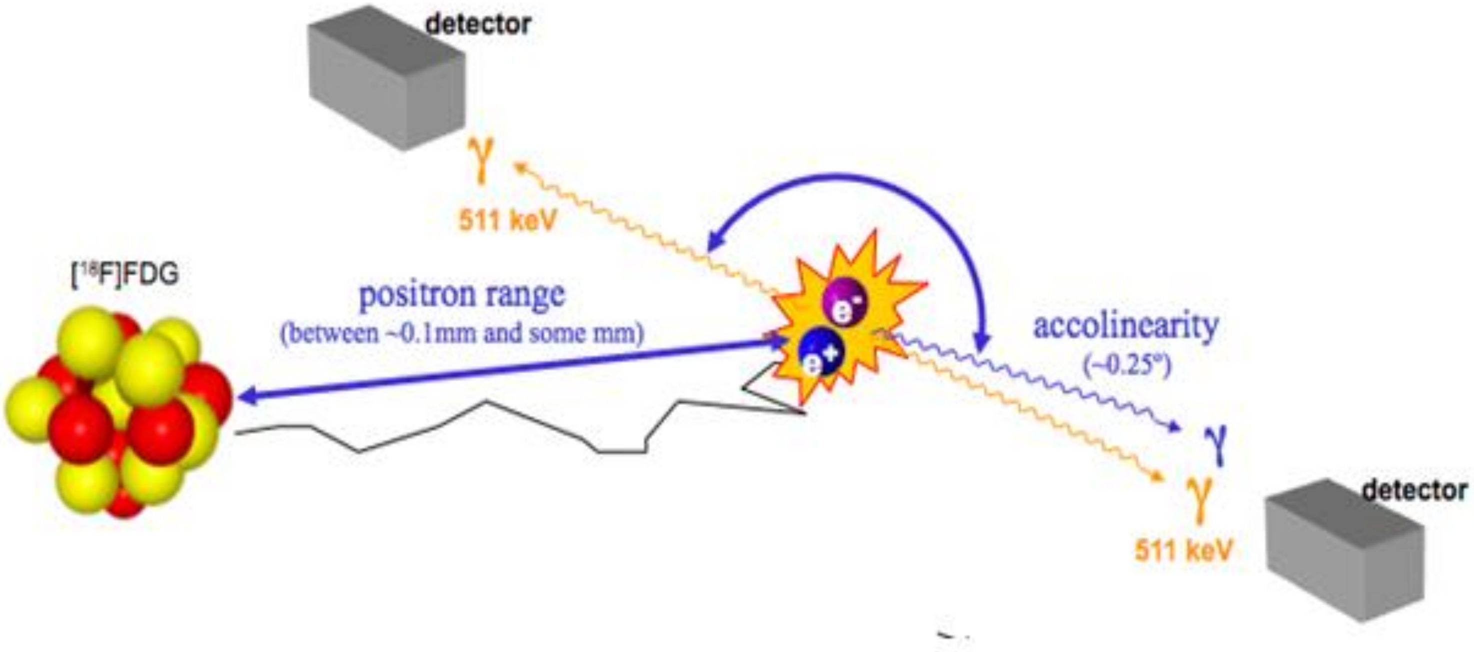
IMAGE-RECONSTRUCTION WITH MATLAB



IR



BASICS OF PET IMAGING



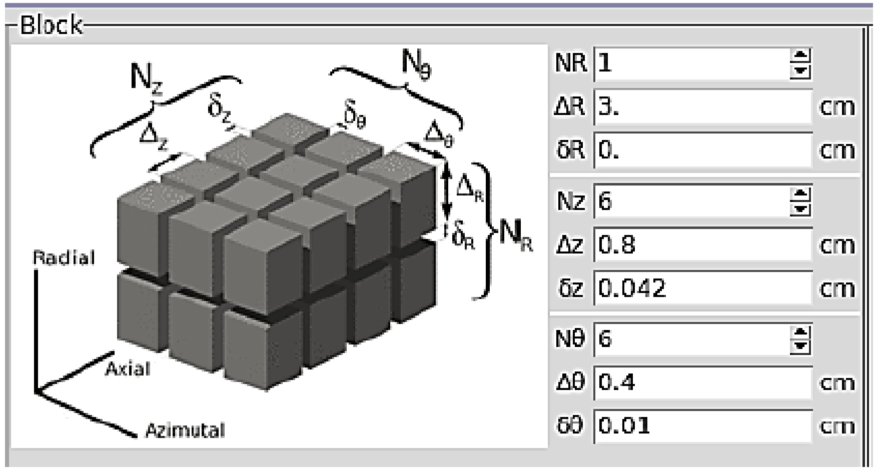
MODELING GE ADVANCE PET-SCANNER

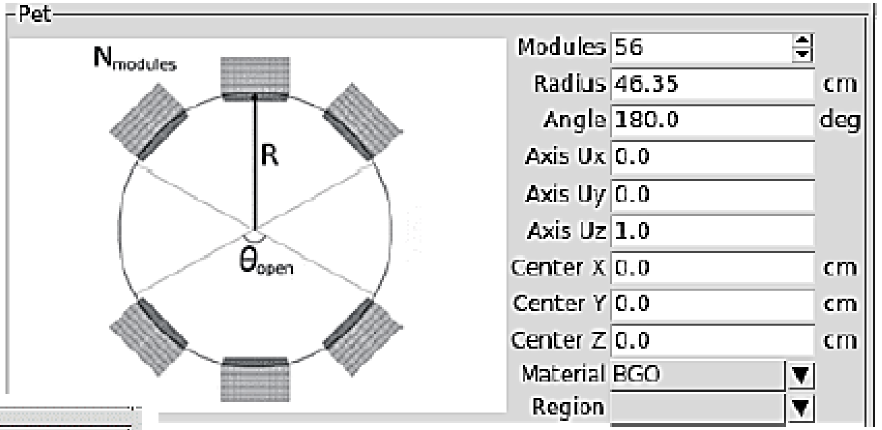
- General Electric Advance PET Scanner (GEMS*)
- 12096 BGO** crystals in the form of 56 modules

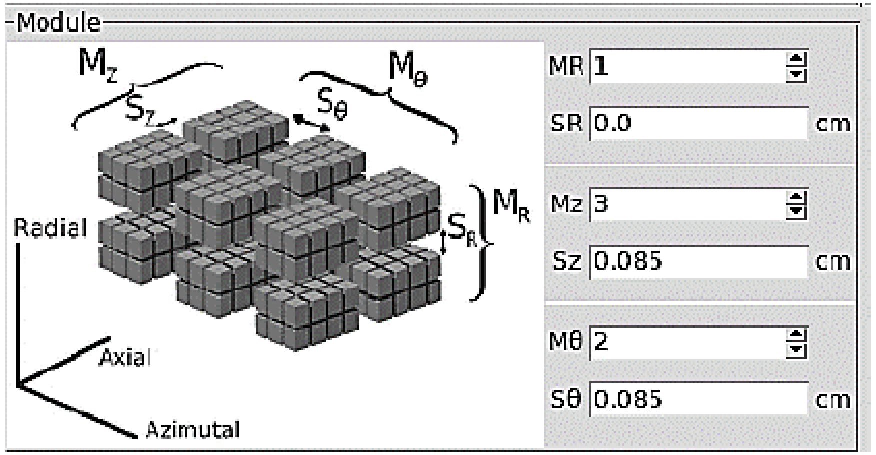
* General Electric Medical Systems

** $Bi_4Ge_3O_{12}$ @ 7.13 g/cm^3

PET GEOMETRY IN FLUKA (PET TOOLS)







EVENT-BY-EVENT OUTPUT

- Collimators of CT scanners are replaced with coincidence circuits in PET.
- The exact time of any interaction must be recorded (It is not the case in CT).
- USERDUMP card of FLUKA is used to extract the collision file.
- Deposition energy, interaction time and position are recorded.

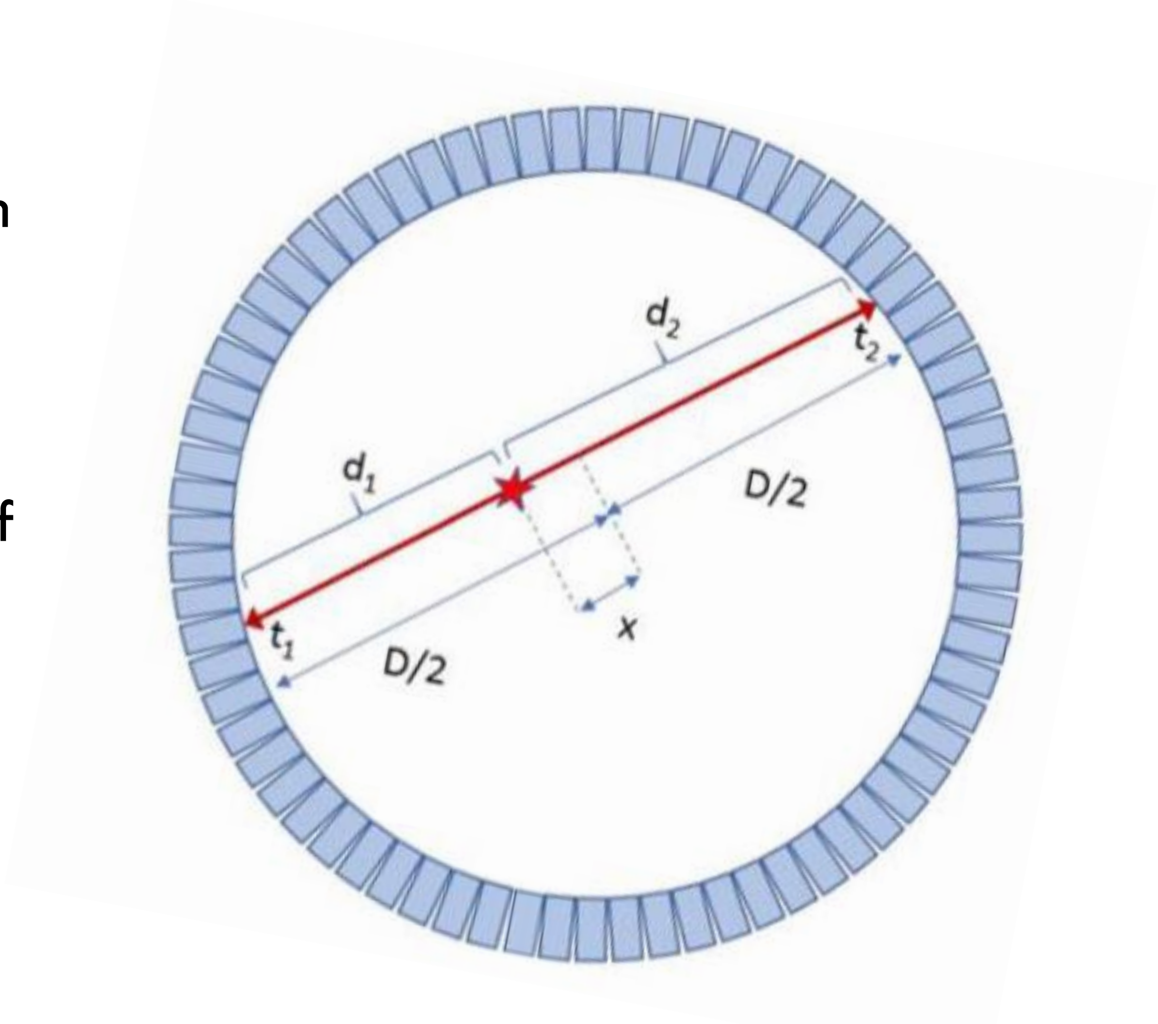
IMAGE-RECONSTRUCTION ALGORITHMS

Three IR algorithms were developed and implemented:

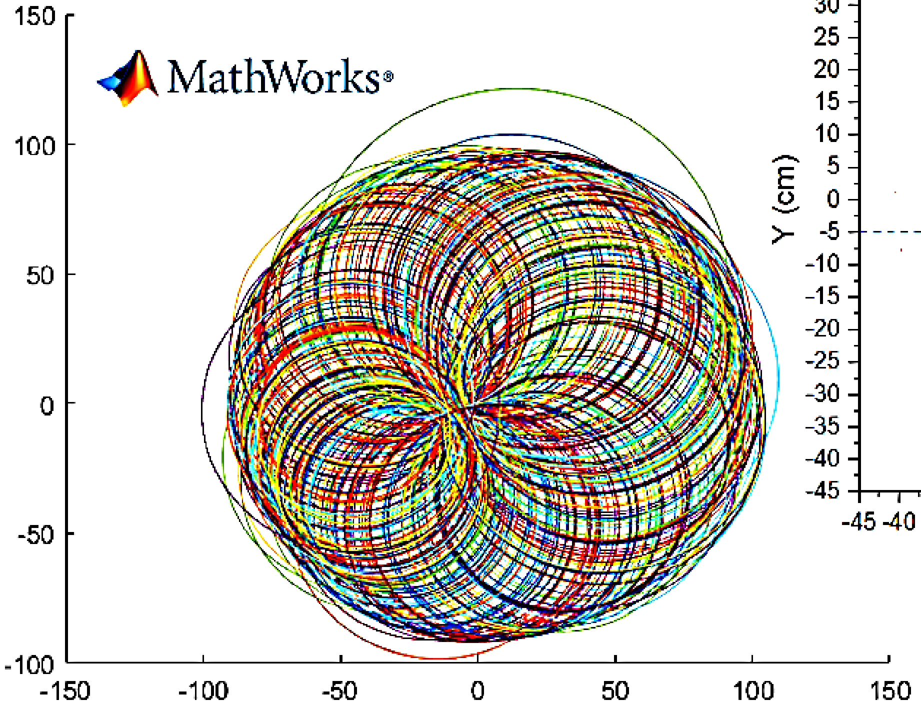
- **Circle**
- **LOR** (Line of Response)
- **TOF** (Time of Flight)

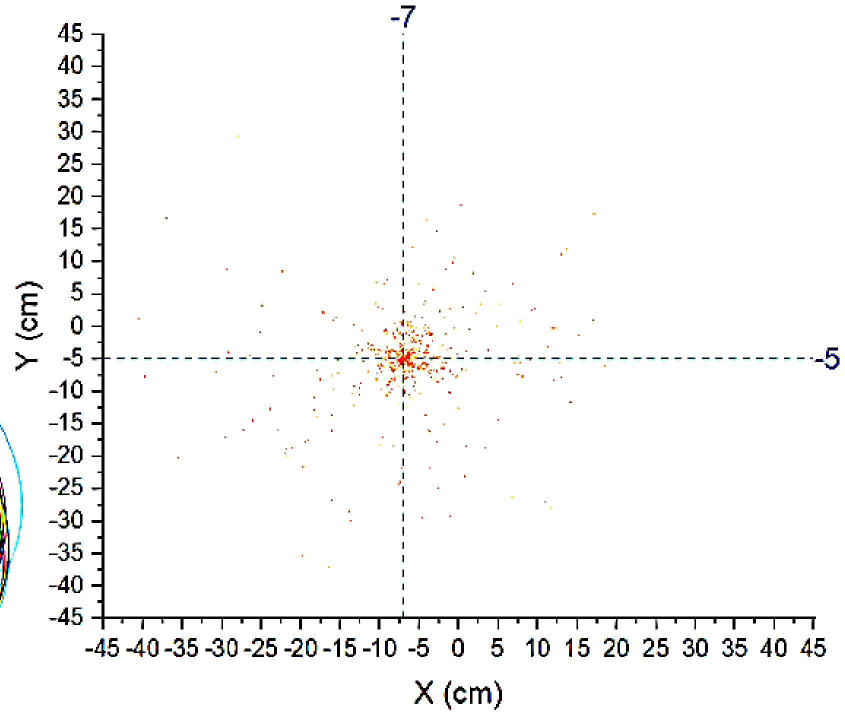
CIRCLE ALGORITHM

- Calibration data based on the deposition energy data.
- Location of an unknown positron source is determined by the intersection of a pair of circles centered at the front surfaces of opposite crystals with coincident signals whose radii are obtained using the calibration .



CIRCLE ALGORITHM (CNT'D)

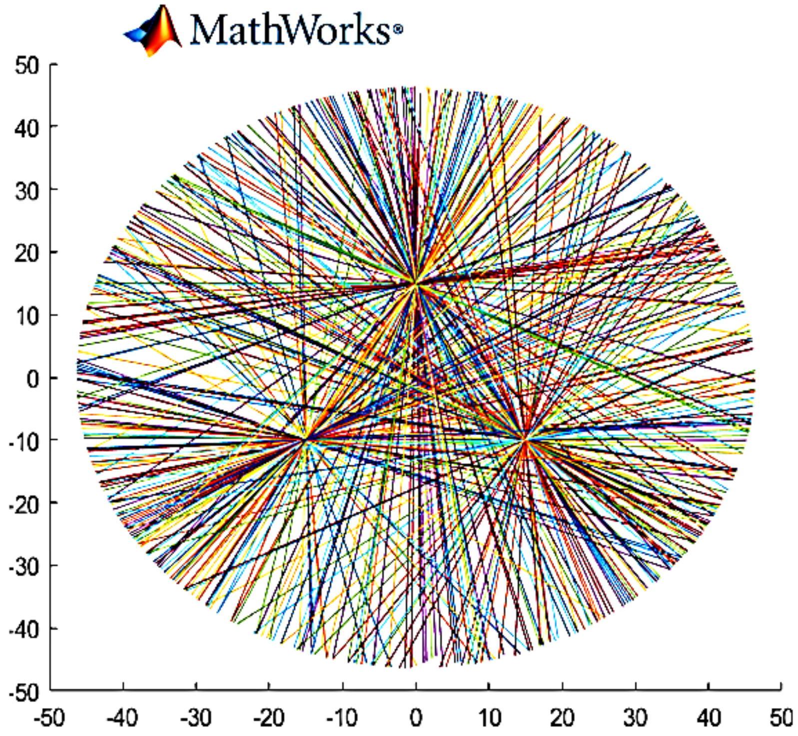


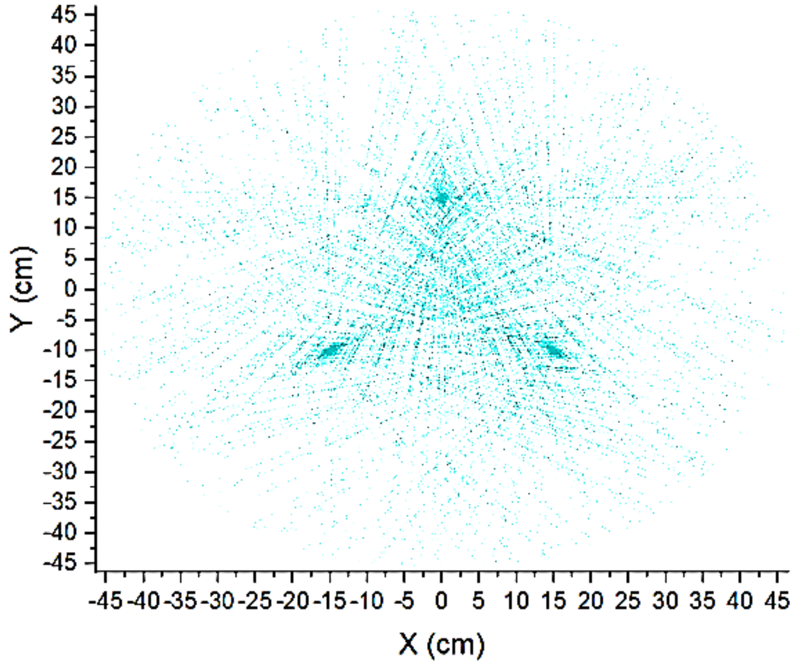


LOR ALGORITHM

- Line of response (LOR) for all coincident crystals are drawn to find the positron source location.
- The relationship between the number of lines and the run time of MATLAB confirms that it takes almost one year of computation run time with an Intel Core i9-7900 CPU @ 3.30 GHz, 32 GB RAM desktop computer for 25000 lines.
- Having considered 258000 lines for the image reconstruction, the GPU+CPU computation time remains surprisingly less than one minute.

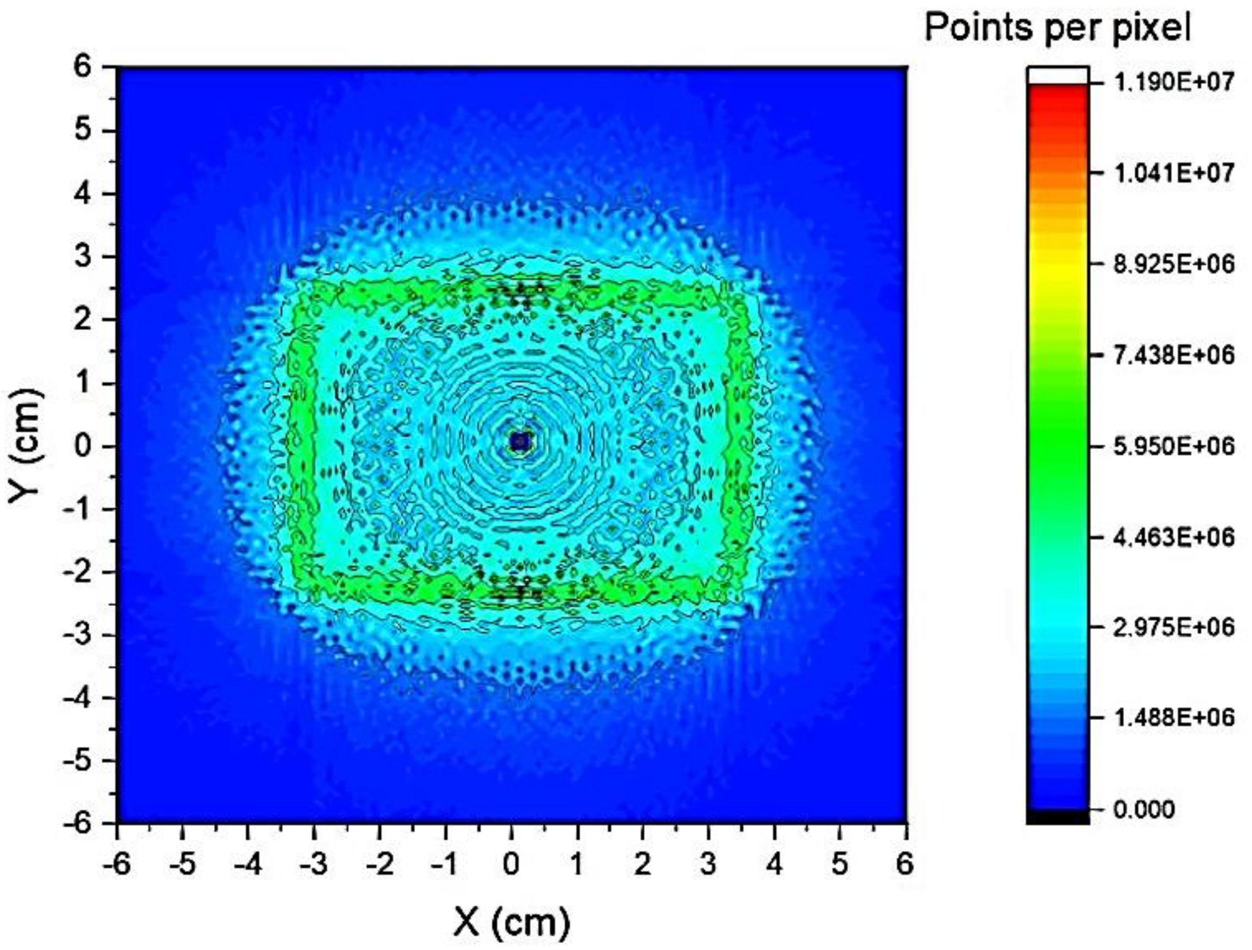
LOR ALGORITHM (CONT'D)





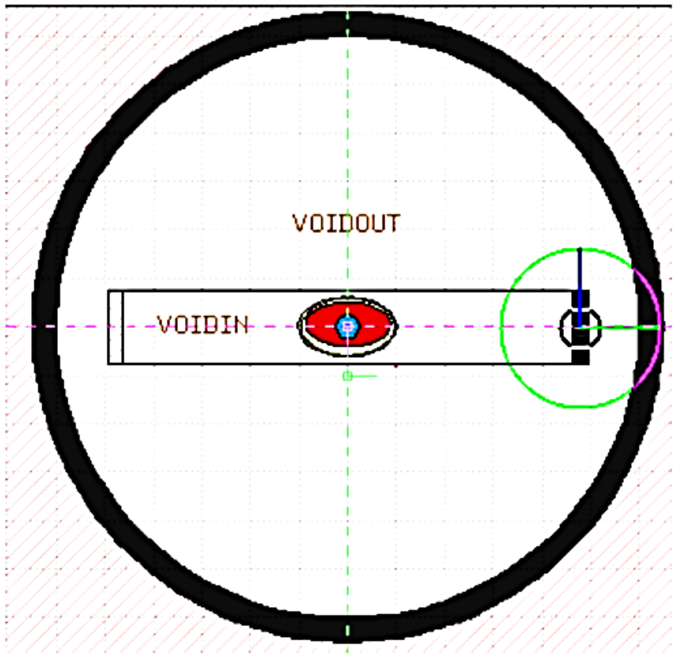
LOR ALGORITHM (CONT'D)

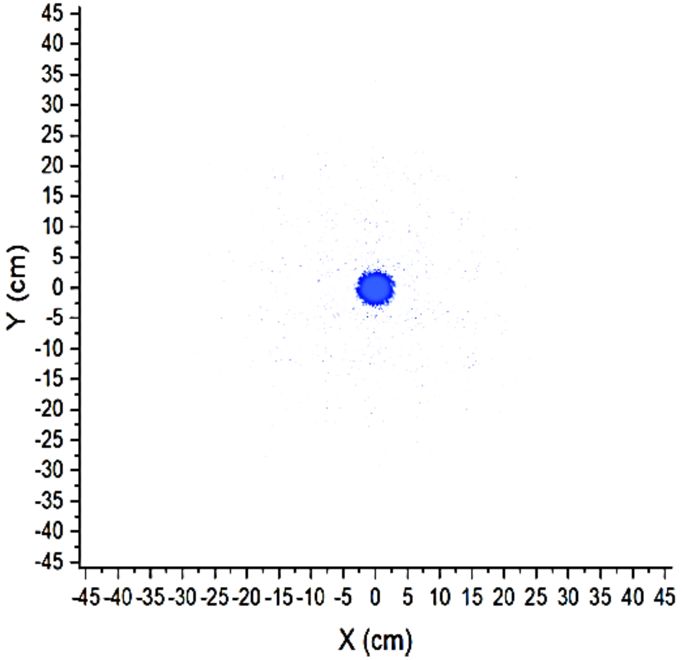
Density distribution of intersection points in LOR algorithm for rectangular frame-shaped positron sources with small thickness (7 cm × 5 cm × 0.25 cm)



TOF ALGORITHM

In TOF-PET, the location of the annihilation event is obtained by measuring the difference of the arrival time of the two photons at the detectors along the LOR.



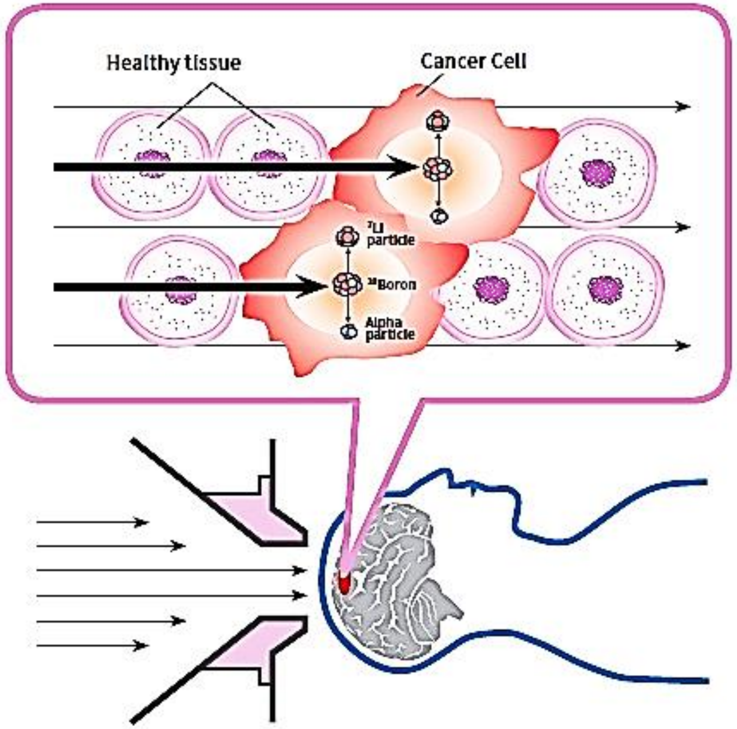


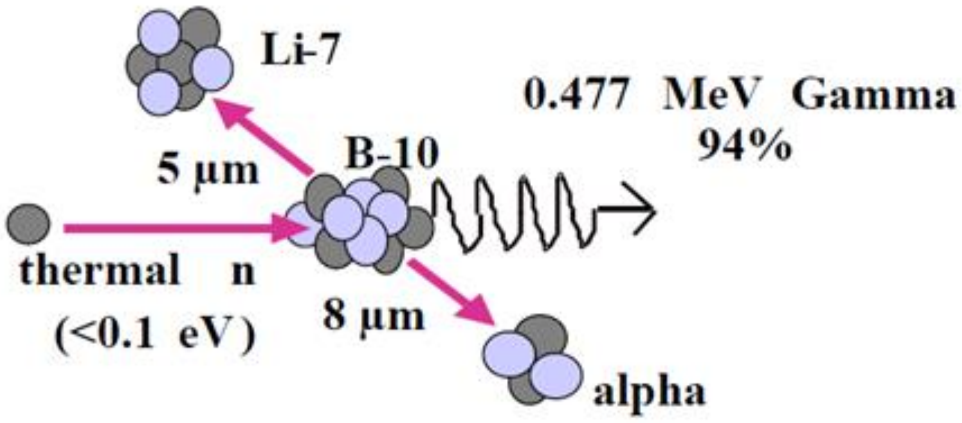
COMPARISON OF THREE ALGORITHMS

- The circle algorithm is most suitable for point positron sources.
- The comparison on the reconstructed images of LOR and TOF confirms that the use of the TOF algorithm gives better results.
- In all three image-reconstruction algorithms, the image quality is deteriorated with decreasing the size of positron sources.

THERMAL NEUTRON IMAGING SYSTEM (TENIS)

Boron Neutron Capture Therapy (BNCT)



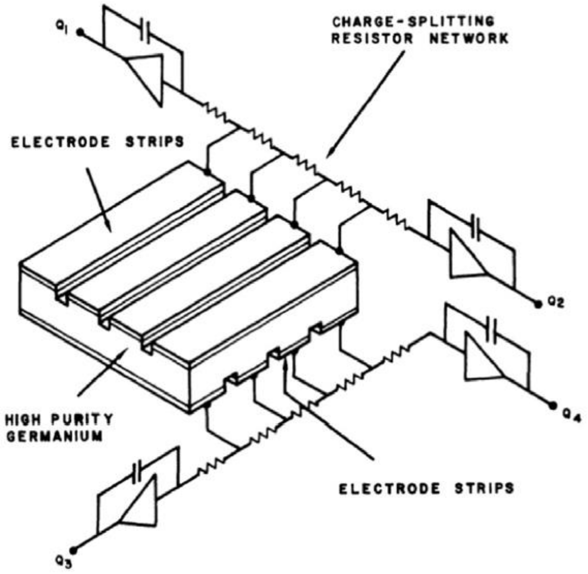


THERMAL NEUTRON MEASUREMENT

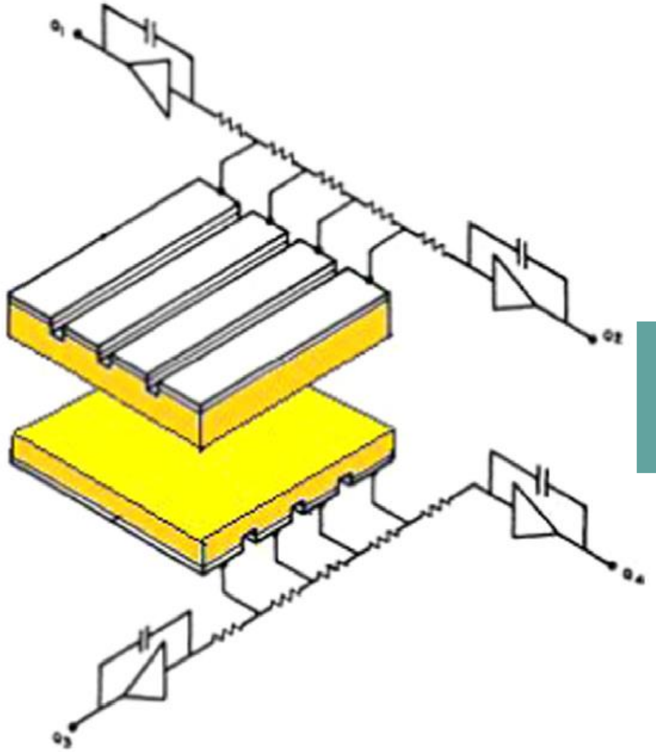
- **Direct Methods**
  - TLDs,
  - Fission chambers,
  - BF3 or 3He proportional counters, etc.

- **Indirect Methods**
  - Prompt gamma-ray spectroscopy with semiconductor detectors, scintillators, etc.

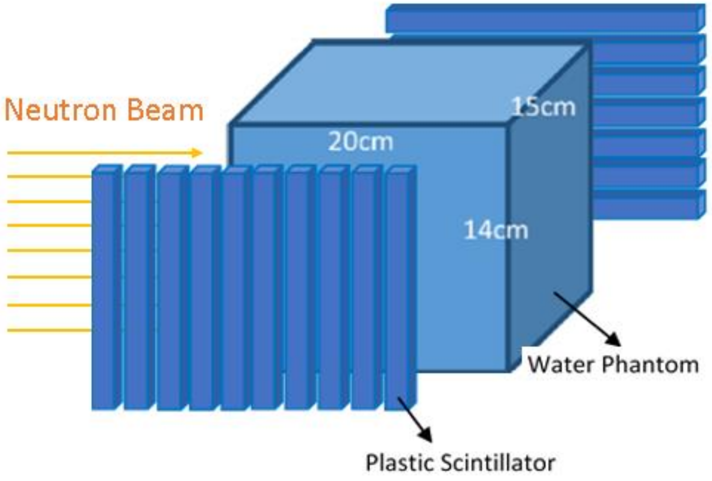
IDEA OF REAL-TIME 2D MAPPING



The orthogonal-strip position-sensitive detector

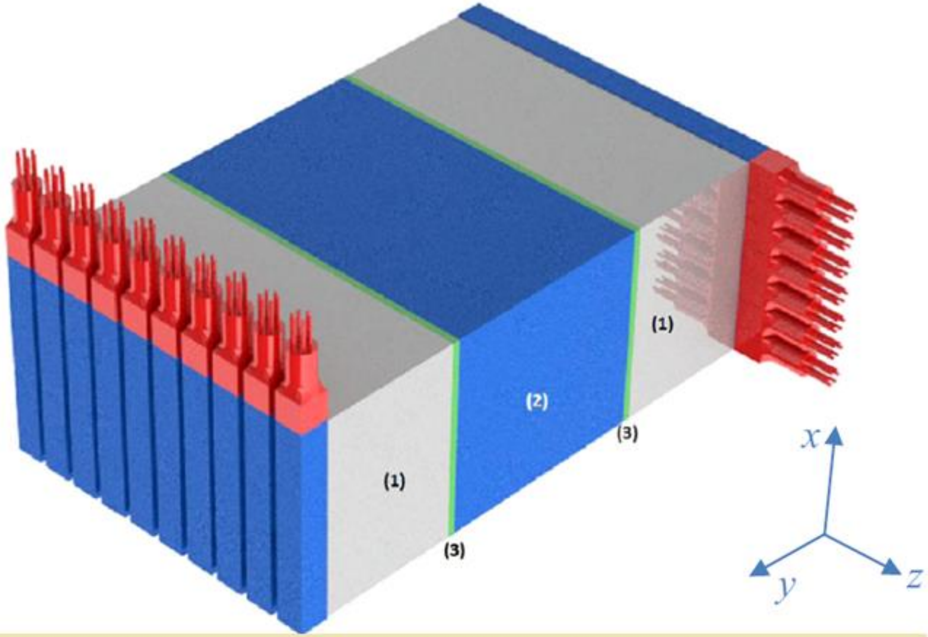


Modified orthogonal-strip position-sensitive detector.

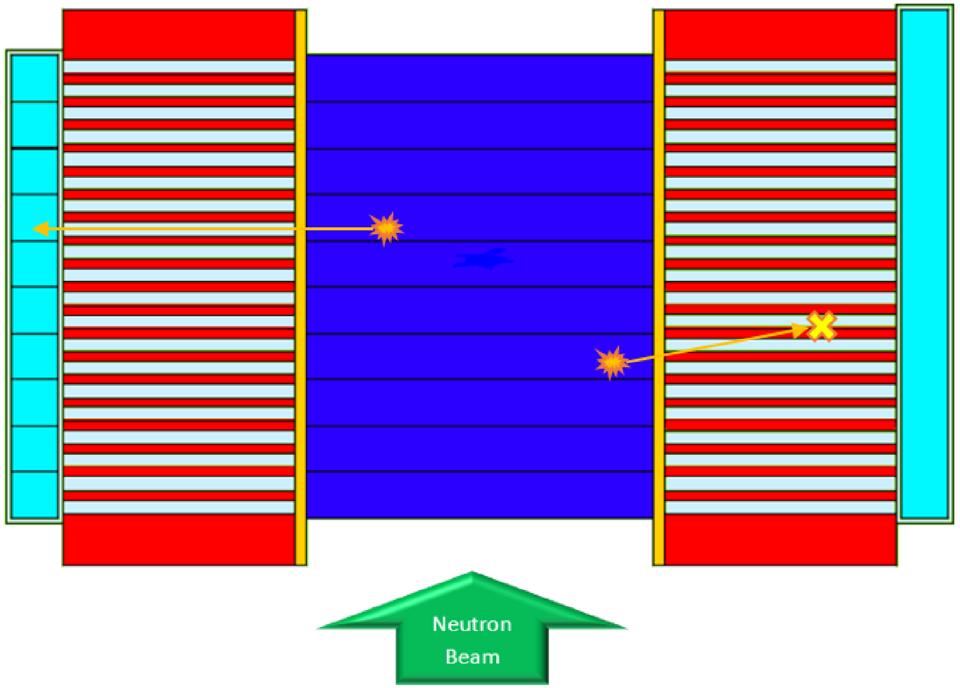


PROPOSED SYSTEM

H(n$_{th}$, γ)D (Eγ= 2.22 MeV)

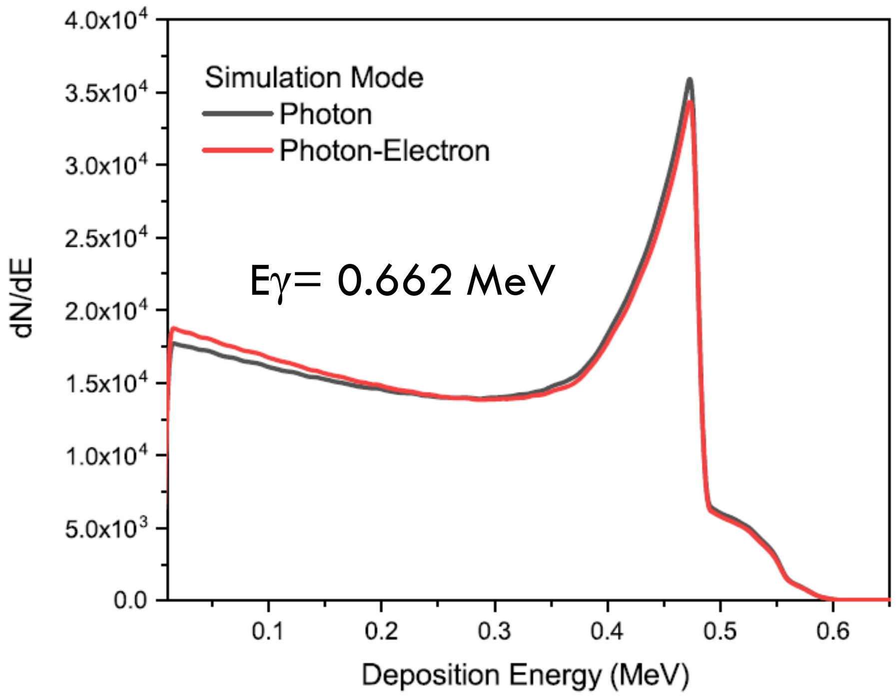


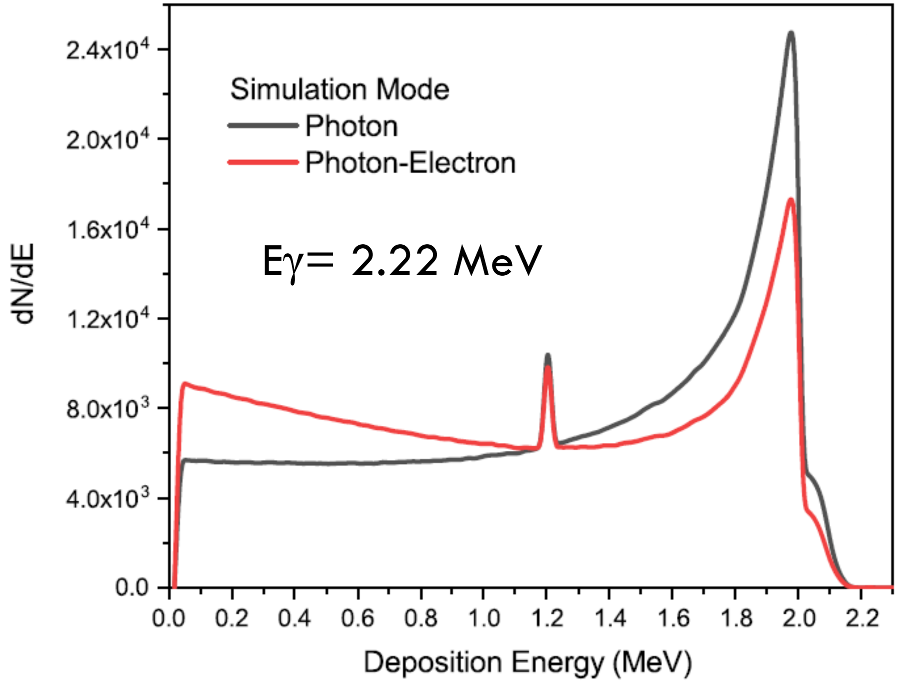
(a) Two sets of orthogonal plastic scintillators to be placed around the water phantom. (b) The detection system consists of horizontal and vertical scintillators, thick lead collimator blocks (1), rectangular water phantom (2), thin cadmium sheets (3) and 17 PMTs.



MODELING PLASTIC SCINTILLATORS

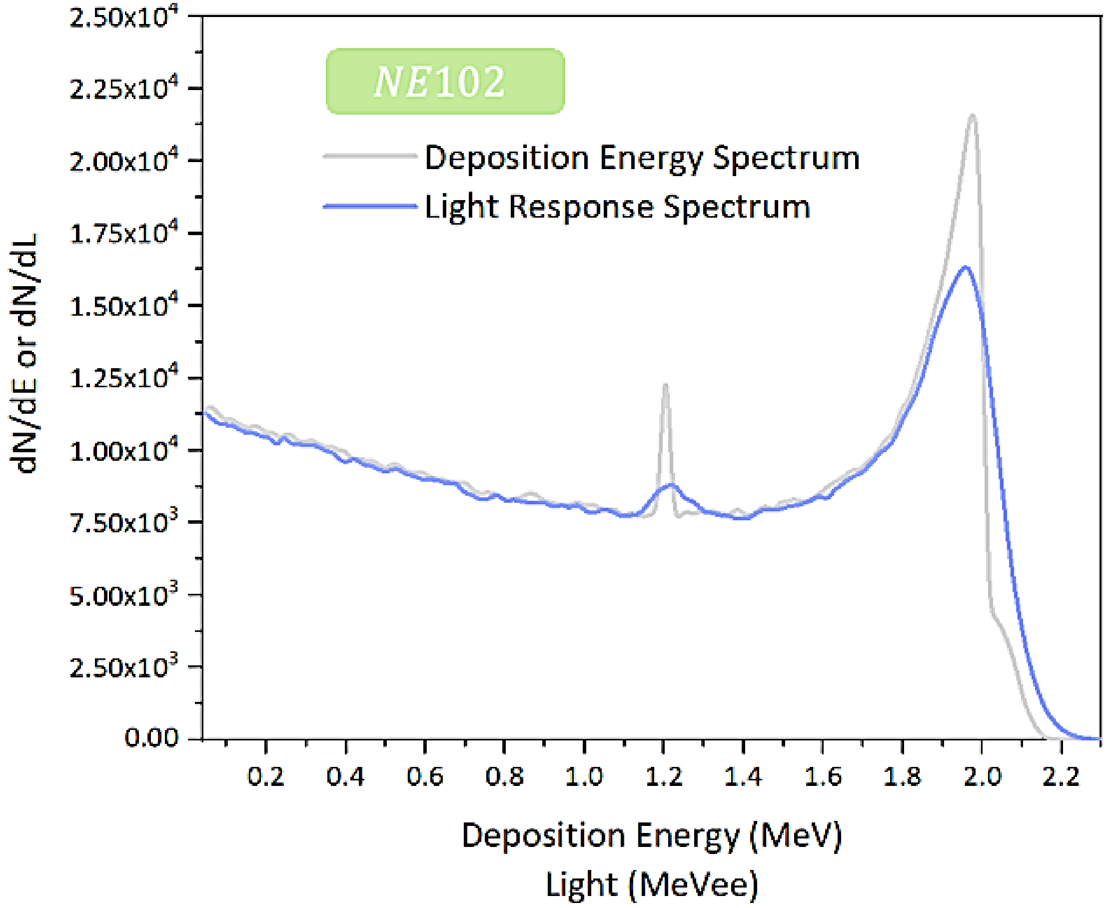
Deposition energy response (PTRAC size): photon mode **(~900MB)** vs. photon-electron mode **(~4GB)**

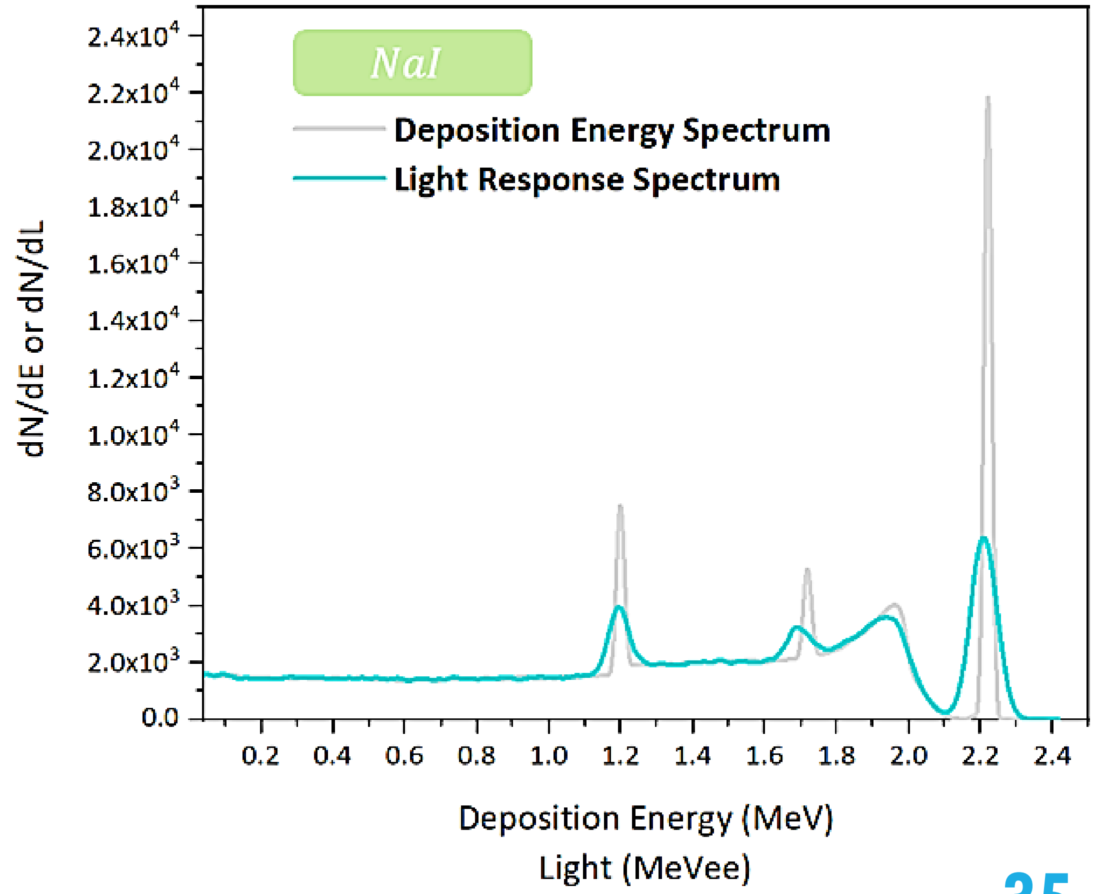




LIGHT TRANSPORT INCORPORATION

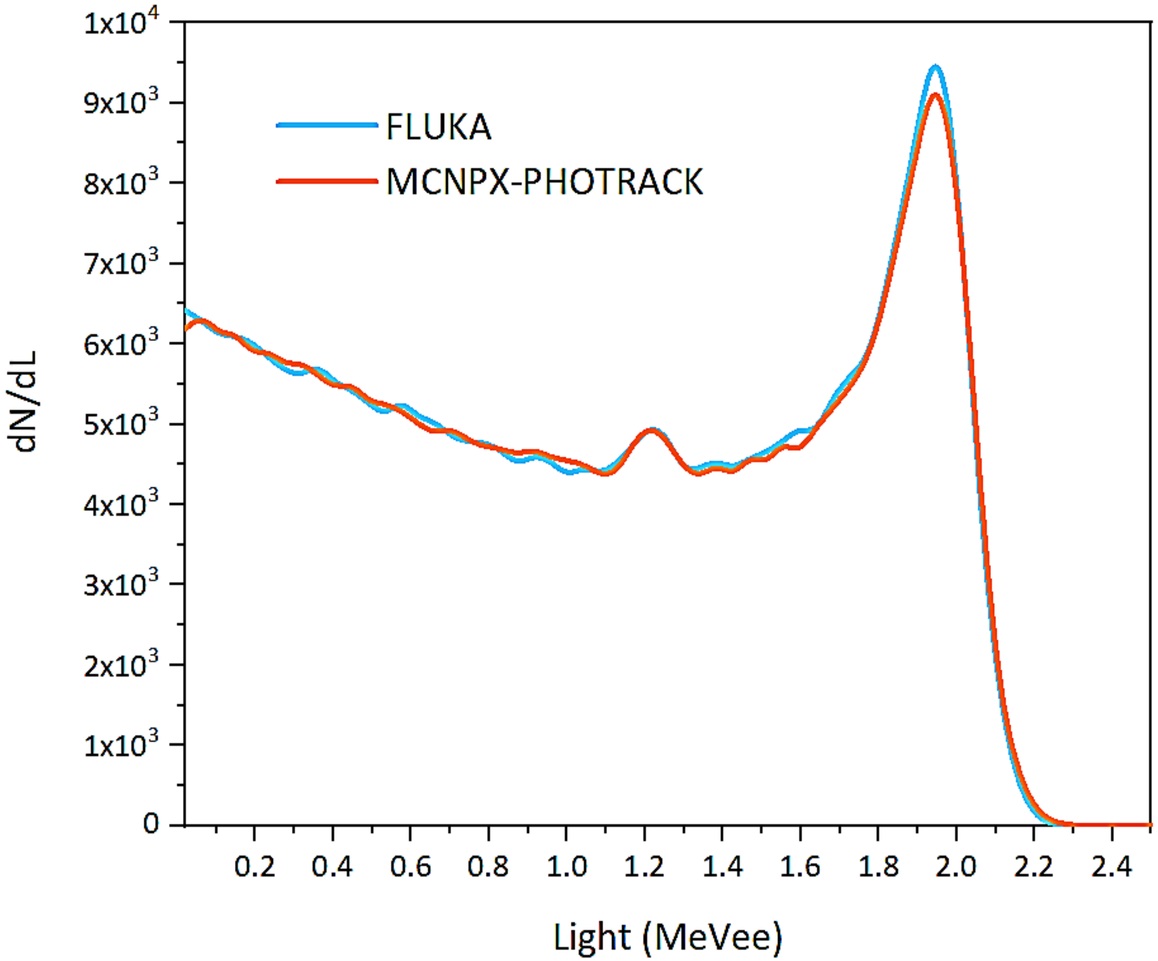
$2 \times 2 \times 20\ \text{cm}^3$ NE102 & NaI scintillators
2.22 MeV photon beam





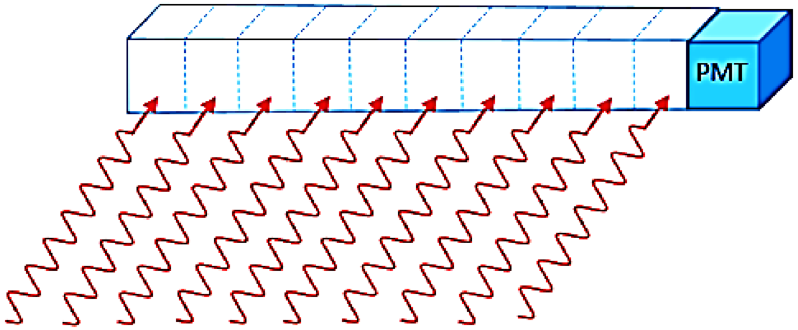
FLUKA VS. MCNP-PHOTRACK

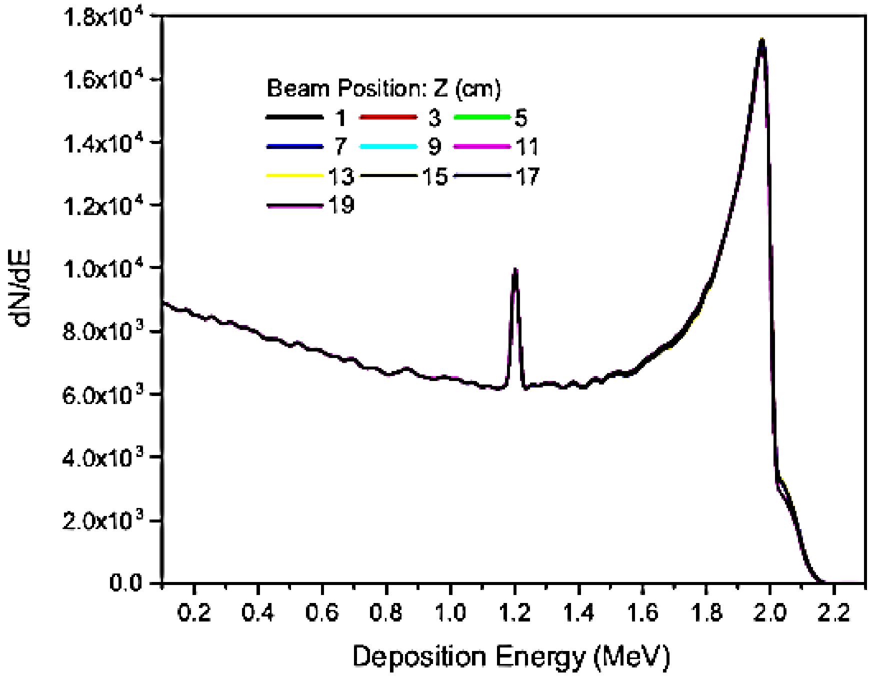
- 2.22 MeV gamma-rays
- 2×2×20 cm^3 plastic scintillator

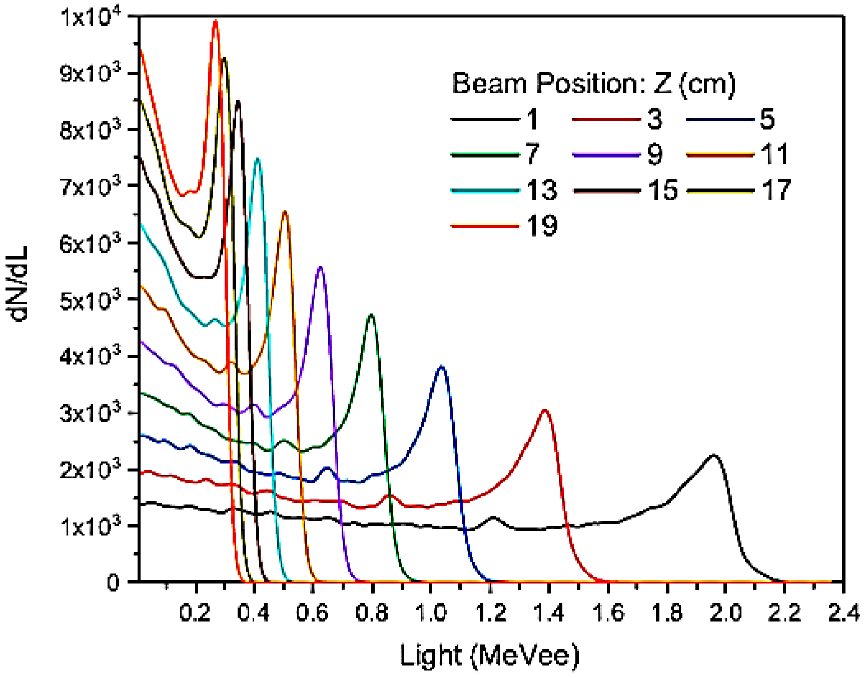


LONGITUDINAL RESPONSE

- Fully-painted surface

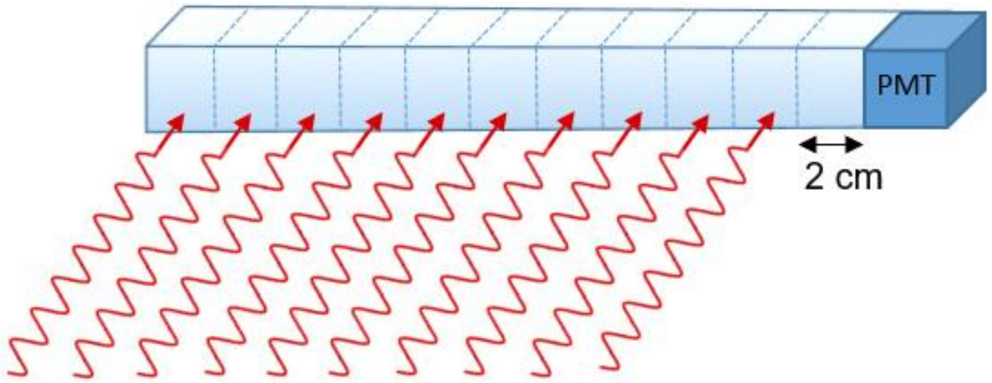


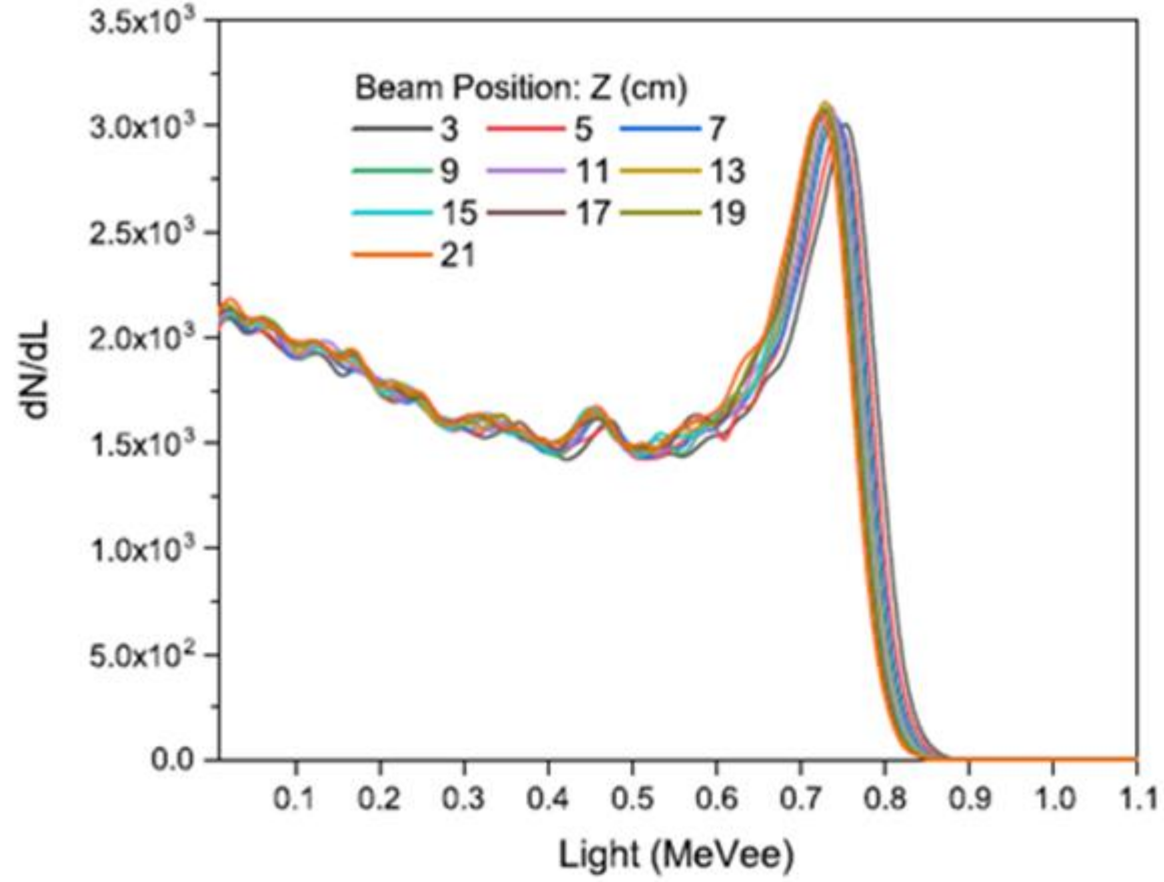




RESPONSE UNIFORMITY

- Fully-polished surface
- 2×2×22 cm^3 plastic scintillator





THERMAL NEUTRON IMAGE

- MCNP (or FLUKA) simulation
- 1 keV neutron beam, incident on the left side of the water phantom
- **Can we get the thermal neutron image by multiplying the responses of vertical scintillators by horizontal ones?**

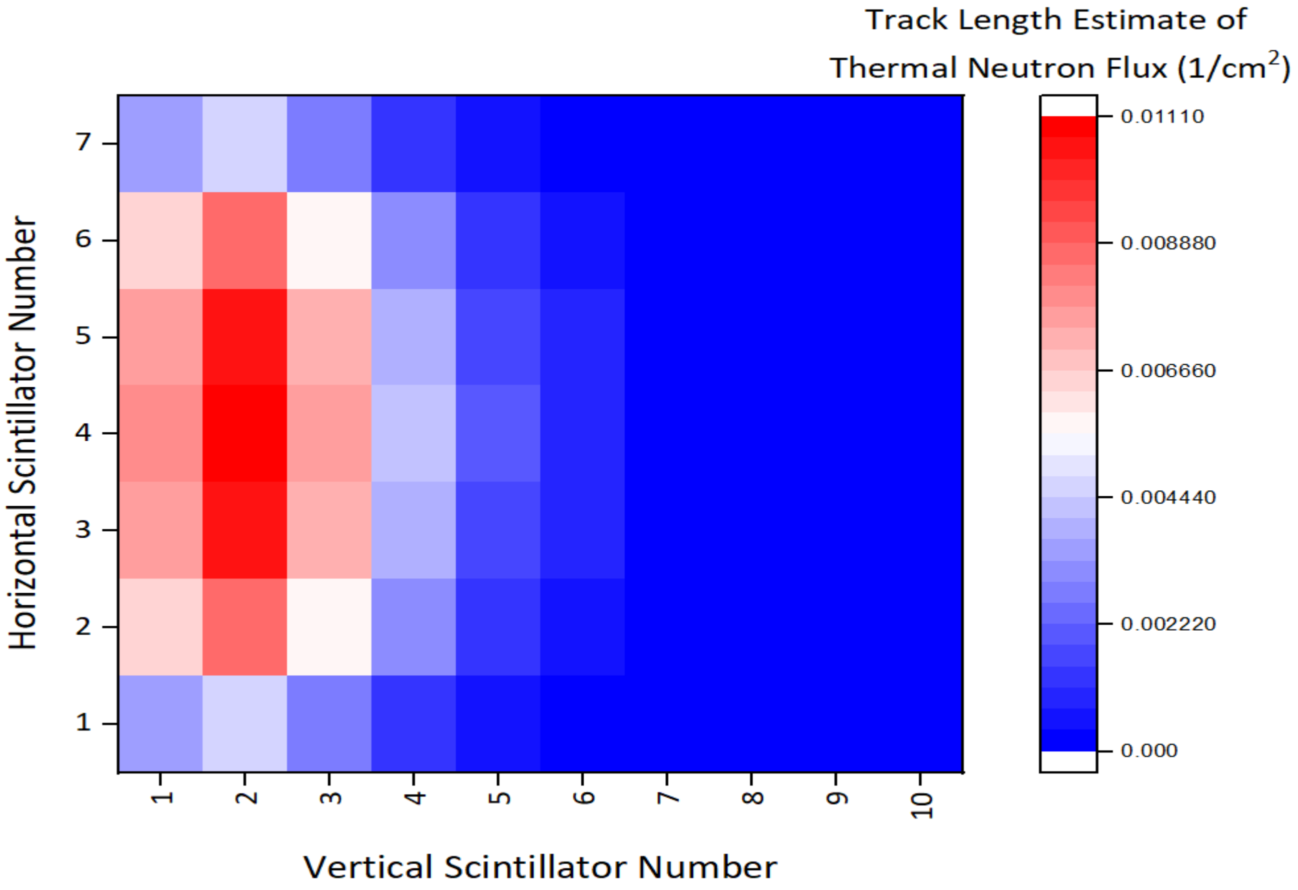
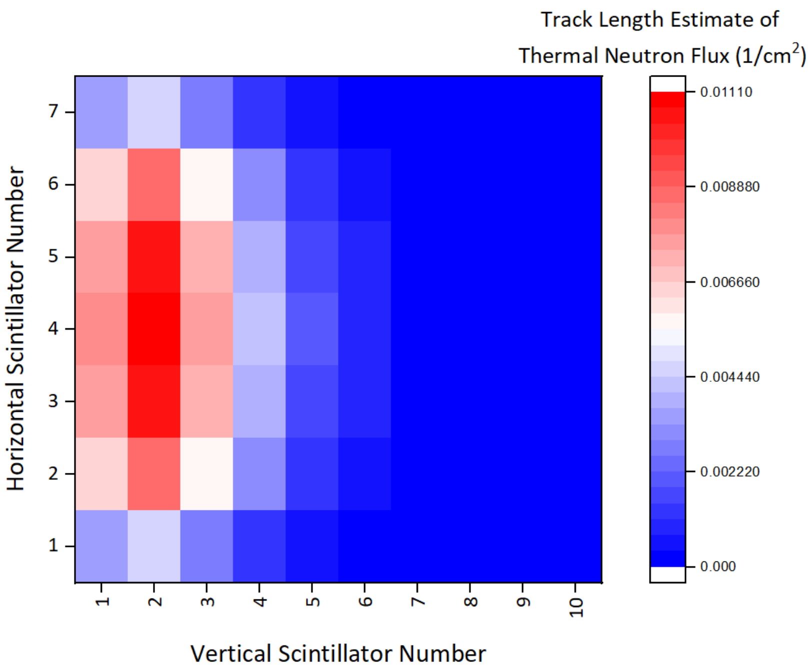


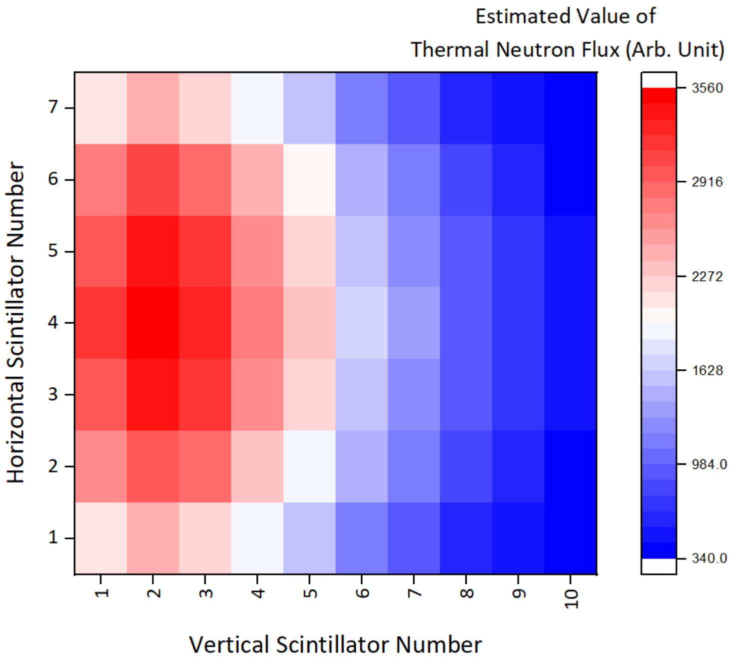
IMAGE RECONSTRUCTION OF TENIS

Multiplication algorithm

$$Flux_{Est}(i,\ j) = R_{Hrs}(i) \times R_{Vrt}(j)$$



Real Image



Reconstructed Image

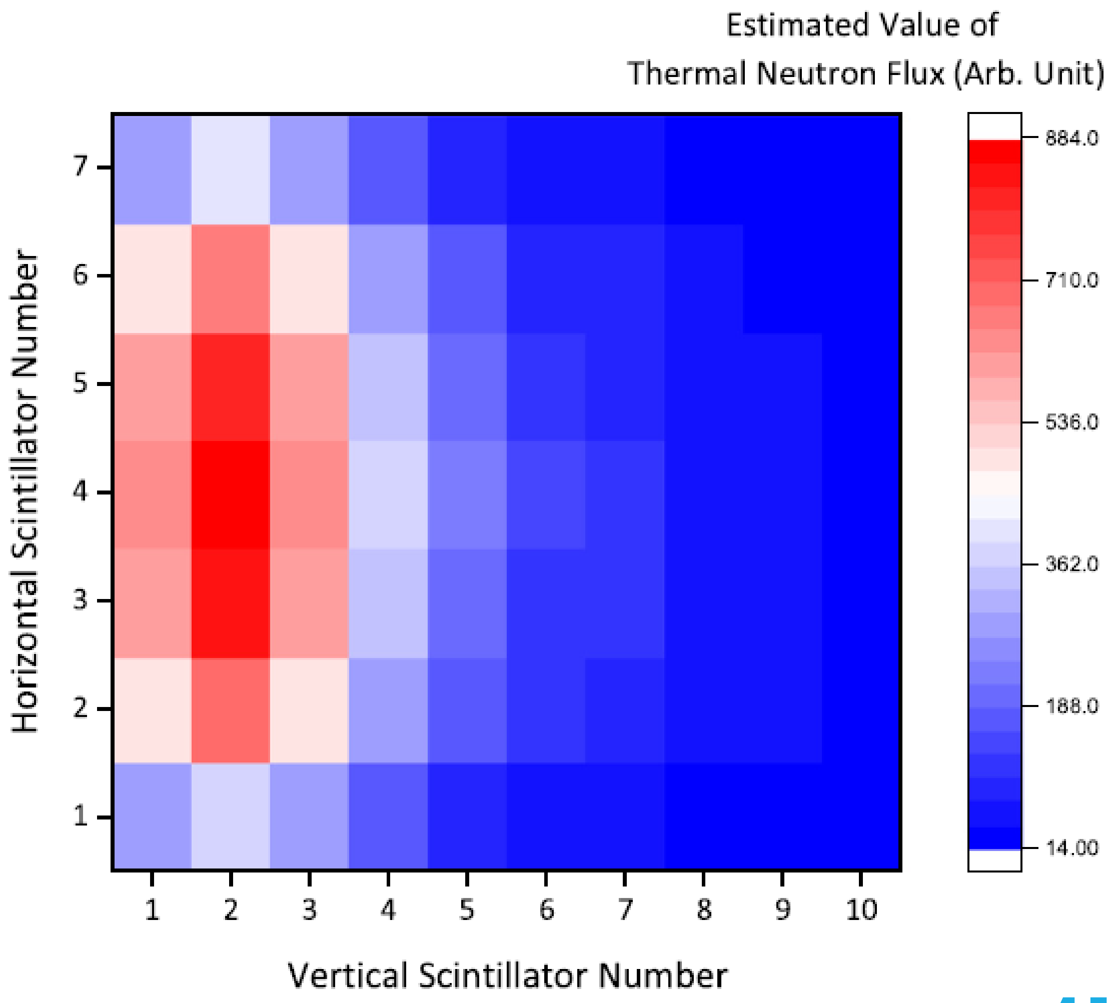
IMAGE RECONSTRUCTION OF TENIS (CNT'D)

Modified multiplication algorithm

$$Flux_{est}\ (i,j) = \left(-a + b\sqrt{\frac{R_{Vrt}(j)}{R_{Vrt}\,(Max)}}\right)^2 \times R_{Hrz}(i)$$

a = 0.23 and b = 1.23

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{M}\left(Flux_{Est}\left(R_{Hrz}\,(i)\,,R_{Vrt}\,(j)\right) - Flux(i,j)\right)^2$$



WHAT'S NEXT WITH TENIS?

- Polyenergetic neutron source (AmBe, etc.)
- 3D image reconstruction
- Neutron spectroscopy
- Measurement studies

THANK YOU FOR YOUR ATTENTION

Thanks to my graduate students:

- Yasaman Nasirzadeh (PhD)
- Behrouz Amini Sourani (MSc)
- Hamideh Yazdandoost (PhD)

- Feel free to contact me by sending e-mail to: ghal-eh@um.ac.ir