National Physical Laboratory

Monte Carlo Simulation

Dr Andrew Robinson

Optimisation in Imaging - HSST
March 2019

- What is Monte Carlo simulation?
- Why use it for medical imaging?
- Examples (demos)
- Validation of simulations
- Tools you can use

What is Monte Carlo simulation?

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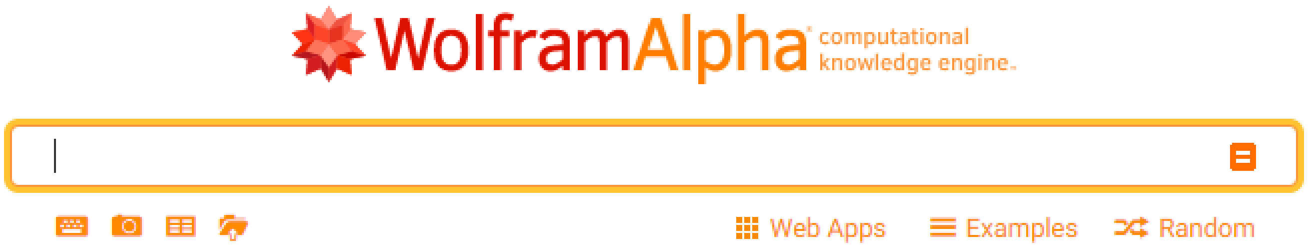
What is Monte Carlo simulation?

Based on the Monte Carlo method

What is Monte Carlo simulation?



What is Monte Carlo simulation?

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WolframAlpha computational knowledge engine.

what is the monte carlo method

Web Apps Examples Random

Input interpretation:

Monte Carlo method

Open code

Definition:

Any method which solves a problem by generating suitable random numbers and observing that fraction of the numbers obeying some property or properties. The method is useful for obtaining numerical solutions to problems which are too complicated to solve analytically. It was named by S. Ulam, who in 1946 became the first mathematician to dignify this approach with a name, in honor of a relative having a propensity to gamble. Nicolas Metropolis also made important contributions to the development of such methods.

The most common application of the Monte Carlo method is Monte Carlo integration.

More information »

Related topics:

Monte Carlo integration | quasi-Monte Carlo method | stochastic geometry | uniform distribution theory

What is Monte Carlo simulation?

WolframAlpha computational knowledge engine.

simulation

Web Apps Examples Random

Input interpretation:

simulation (English word)

Open code

Definitions:

1	noun	the act of imitating the behavior of some situation or some process by means of something suitably analogous (especially for the purpose of study or personnel training)
2	noun	(computer science) the technique of representing the real world by a computer program
3	noun	representation of something (sometimes on a smaller scale)
4	noun	the act of giving a false appearance

American pronunciation:

s,imyuhl'eyshuhn (IPA: sˌɪmjəlˈeɪʃən)

Hyphenation:

sim-u-la-tion (10 letters | 4 syllables)

What is Monte Carlo simulation?

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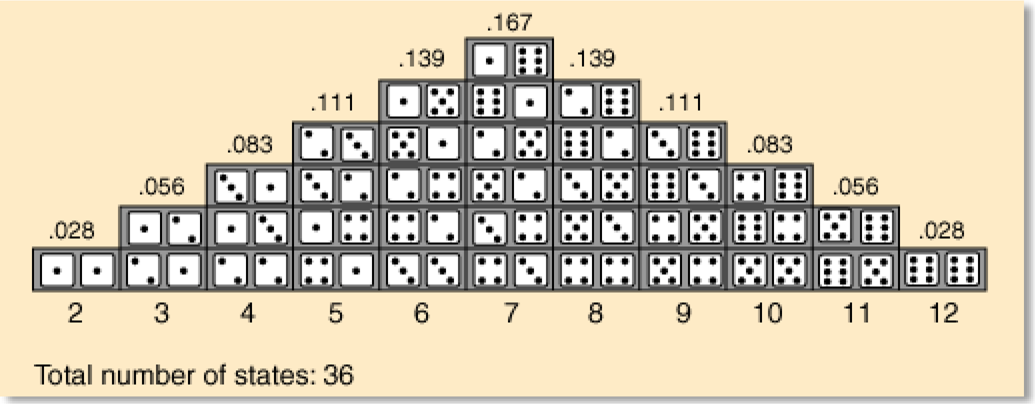
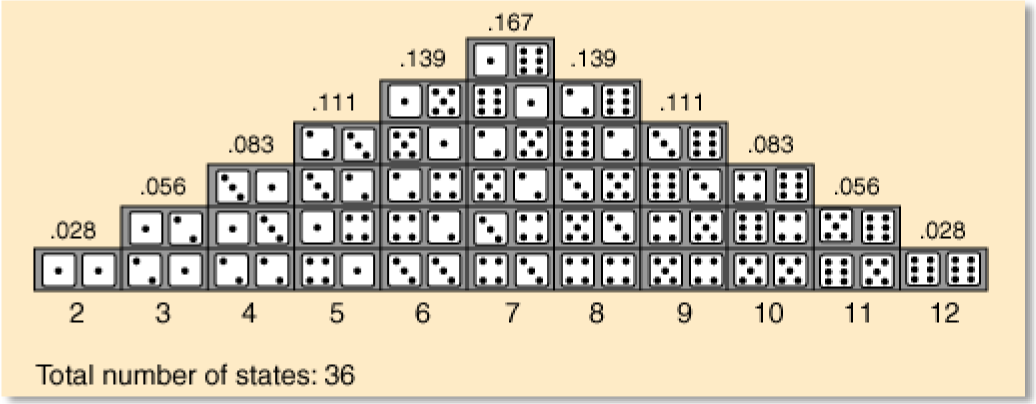
"A method which solves a problem by generating suitable random numbers and observing that fraction of the numbers obeying some property or properties. The method is useful for obtaining numerical solutions to problems which are **too complicated to solve analytically**."

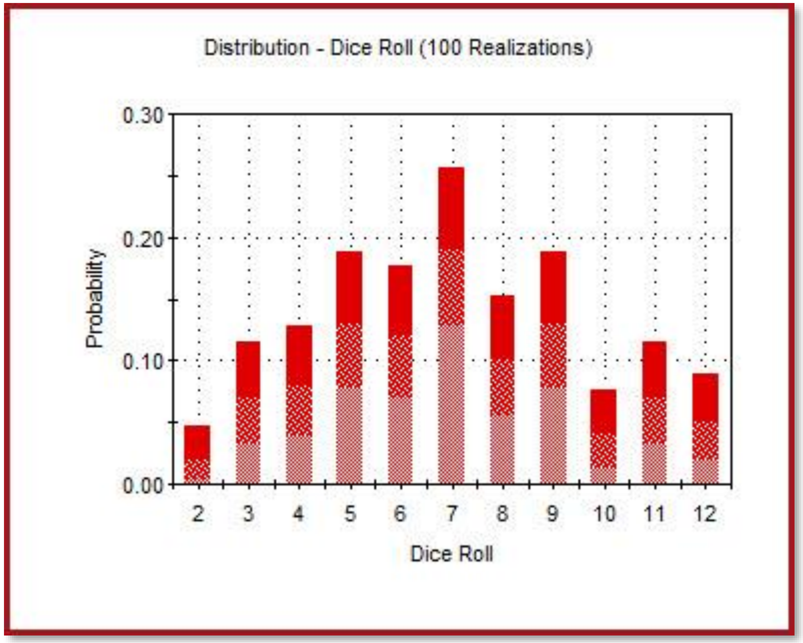
"A technique of **representing the real world by a computer program**."

Simple Example

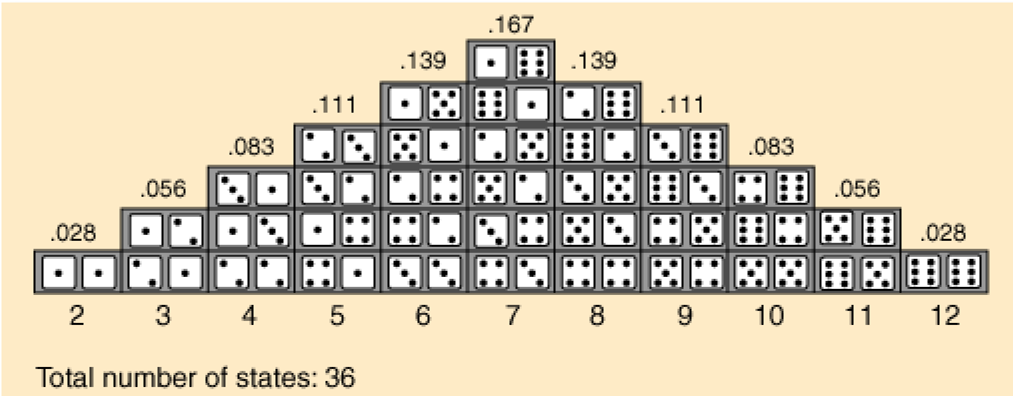


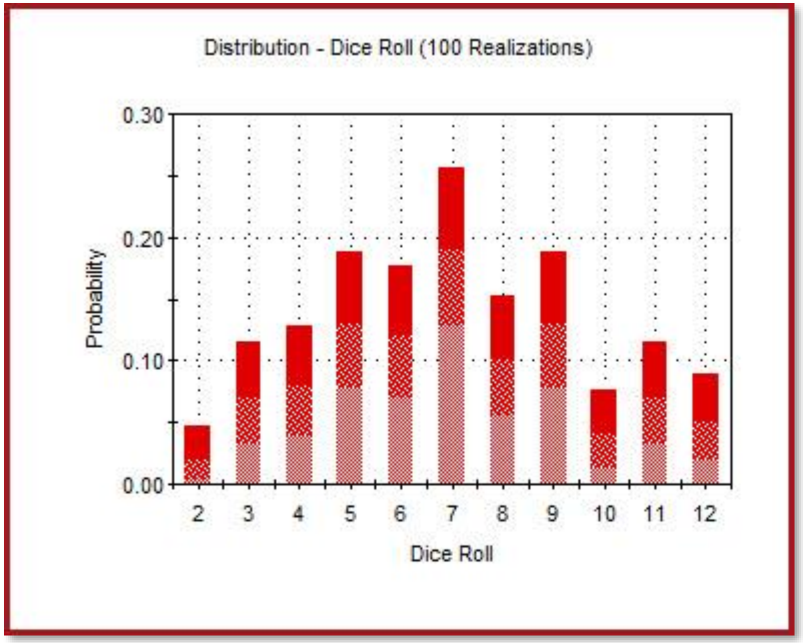
Simple Example

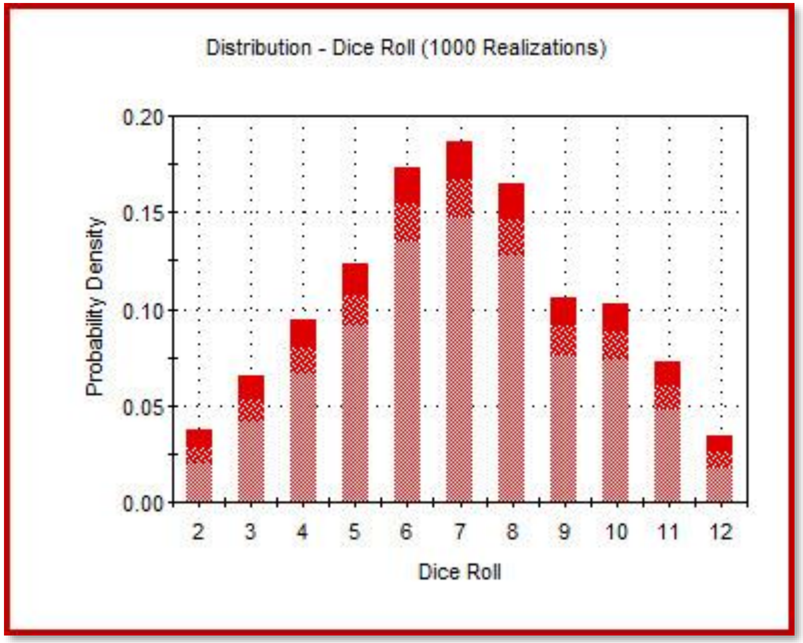




Simple Example







- What is Monte Carlo simulation?
- **Why use it for medical imaging?**
- Examples (demos)
- Validation of simulations
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Why use it for medical imaging?

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Doesn't require patients

No camera time

Extra information (physically non-observable)

Easily modify the system

Can provide a "ground truth"

No radiation dose (patient or operator)

Infinitely repeatable

Optimise imaging protocols

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Blue	= Positive Charge
Green	= Neutral Charge
Red	= Negative Charge

Optimisation of imaging windows using Monte Carlo Simulation

Optimisation of imaging windows using Monte Carlo Simulation

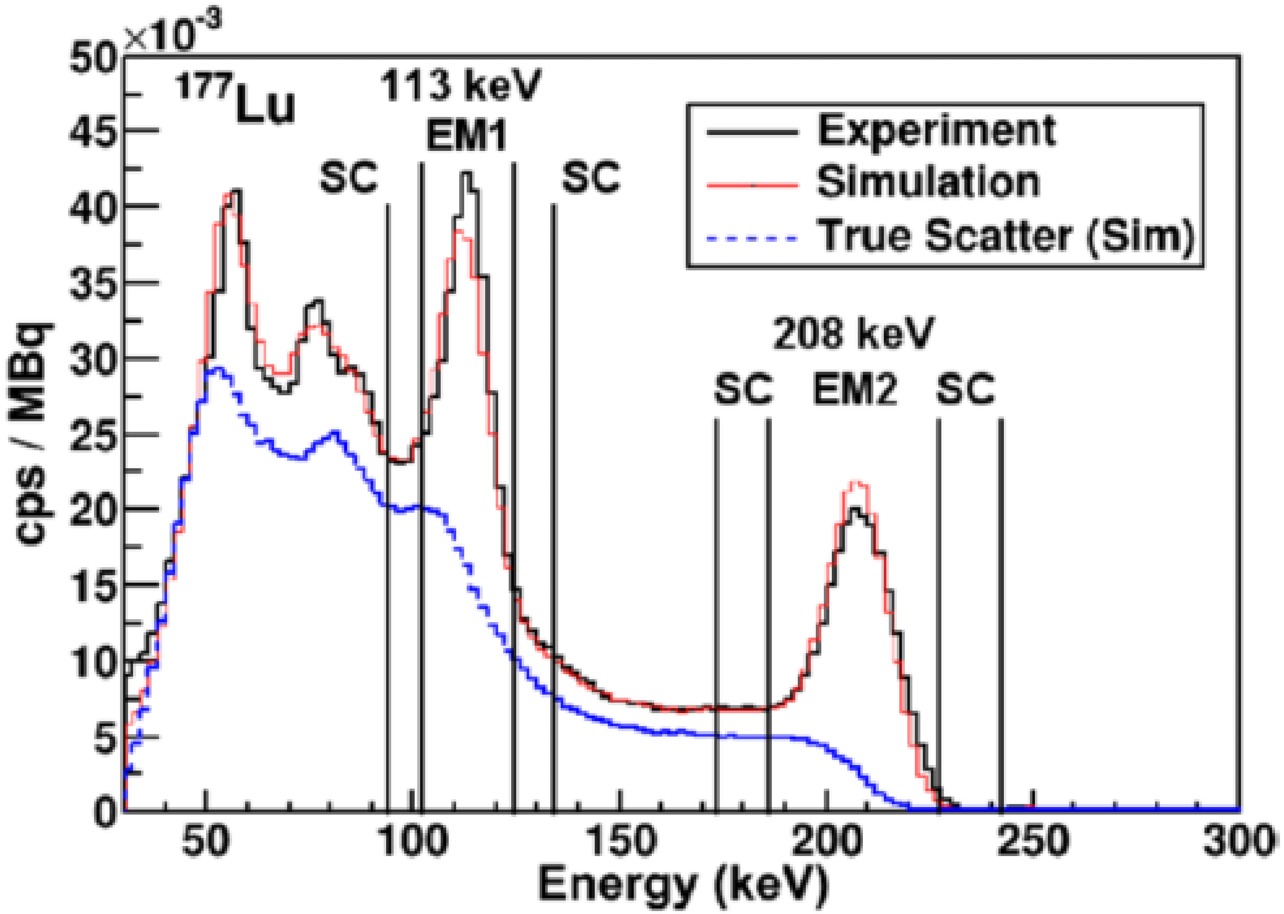

Figure 5. Emission spectrum for a water filled phantom measured

Optimisation of imaging windows using Monte Carlo Simulation

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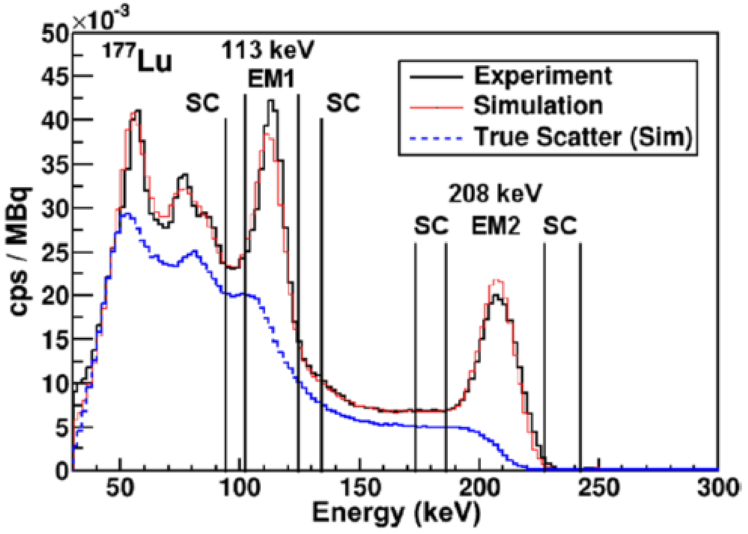
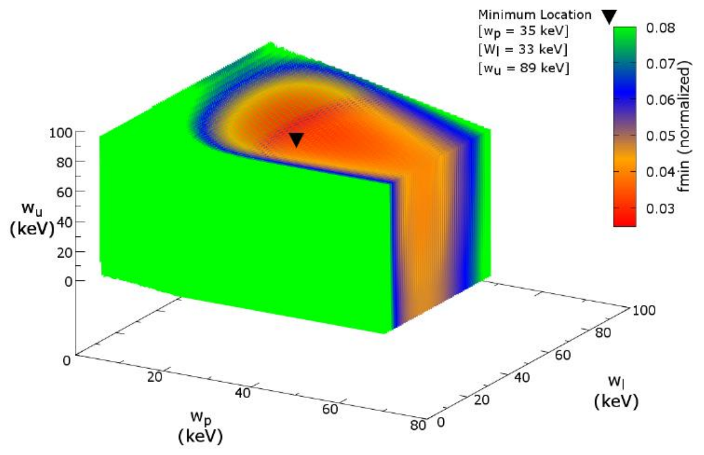


Figure 5. Emission spectrum for a water filled phantom measured



$$C_{TEW} = \left(\frac{C_l}{w_l} + \frac{C_u}{w_u}\right) \times \frac{w_p}{2}$$

$$f_{min} = \left|1 - \frac{C_{TEW}}{TS}\right| = \left|1 - \frac{\left(\frac{C_l}{w_l} + \frac{C_u}{w_u}\right) \times \frac{w_p}{2}}{TS}\right|$$

$$\{w_l \in \mathbb{N}^0\}\ \{w_u \in \mathbb{N}^0\}\ \{w_p \in \mathbb{N}^1\}$$

$$E_l + \frac{w_l}{2} > E_{min}$$
$$E_u + \frac{w_u}{2} < E_{max}.$$

Sensitive range Camera.

$$E_l + \frac{w_l}{2} \le E_p - \frac{w_p}{2}$$
$$E_u - \frac{w_u}{2} \ge E_p + \frac{w_p}{2}.$$

Over-lapping windows.

Tb$_{65}$ (Theranostic Isotope Quartet)

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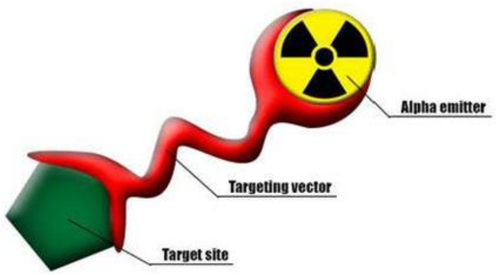
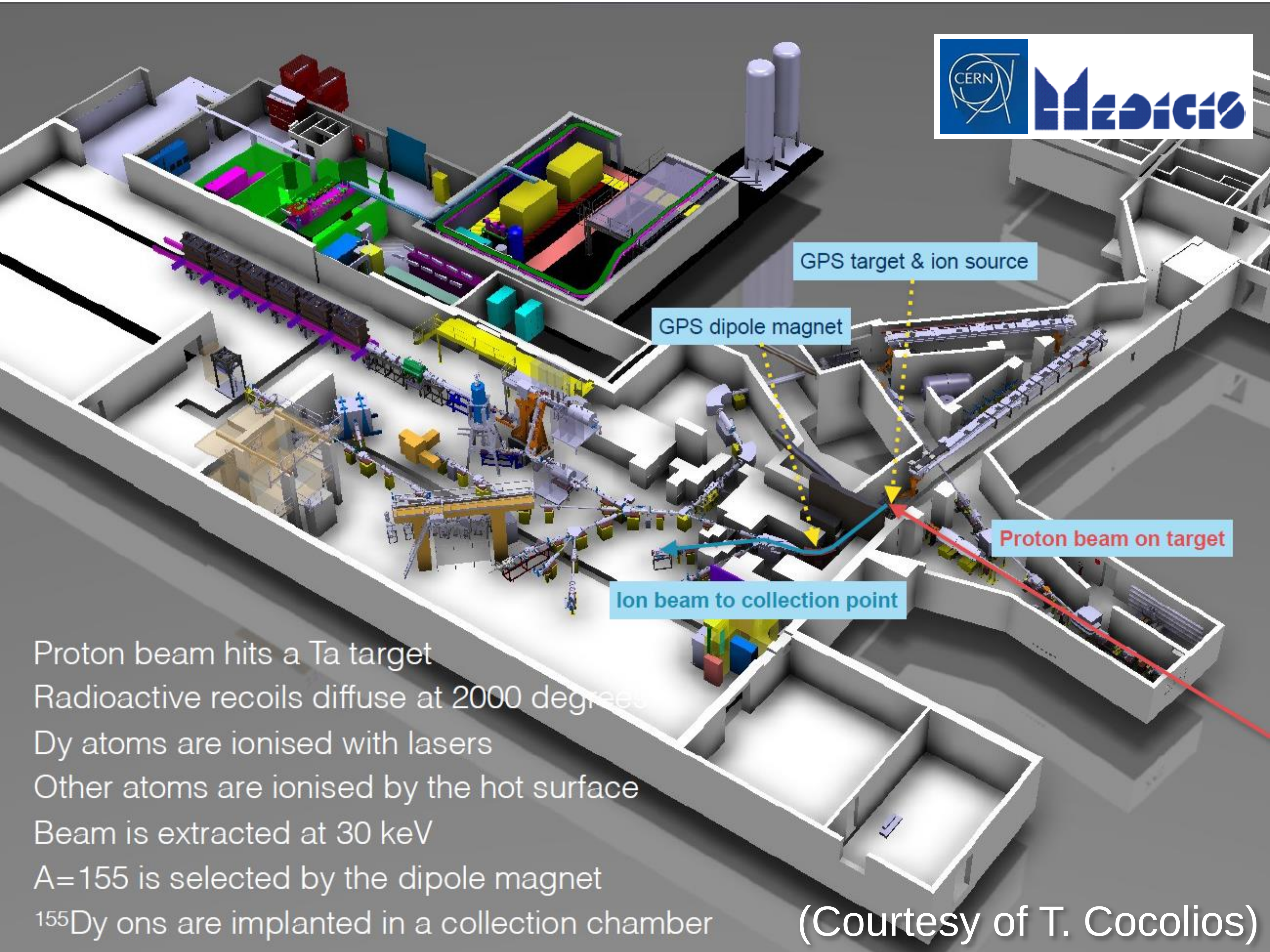


	Decay Mode	Half-life	MRT Application
^{149}Tb	α, β+ (17%, 7%)	4.12 hours	Therapy (α)
^{152}Tb	β+ (17%)	17.5 hours	PET Imaging
^{155}Tb	EC (100%)	5.32 days	SPECT Imaging
^{161}Tb	β- (100%)	6.89 days	Therapy (β-)



Proton beam hits a Ta target
Radioactive recoils diffuse at 2000 degrees
Dy atoms are ionised with lasers
Other atoms are ionised by the hot surface
Beam is extracted at 30 keV
A=155 is selected by the dipole magnet
^{155}Dy ons are implanted in a collection chamber

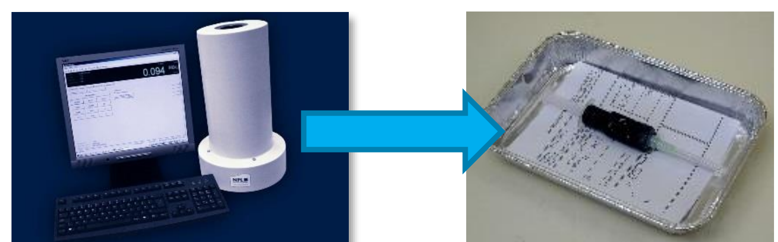
Medical physics questions for ^{155}Tb

How to image it?

- Which gamma-rays to look at?
- What energy gate to set?
- Which collimators to use?

How to measure activity?

- Is there a primary standard?
- What dial factors to use on a hospital calibrator?



^{155}Tb (SPECT Imaging)

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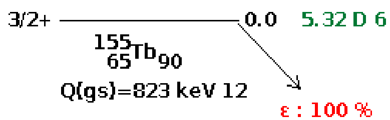
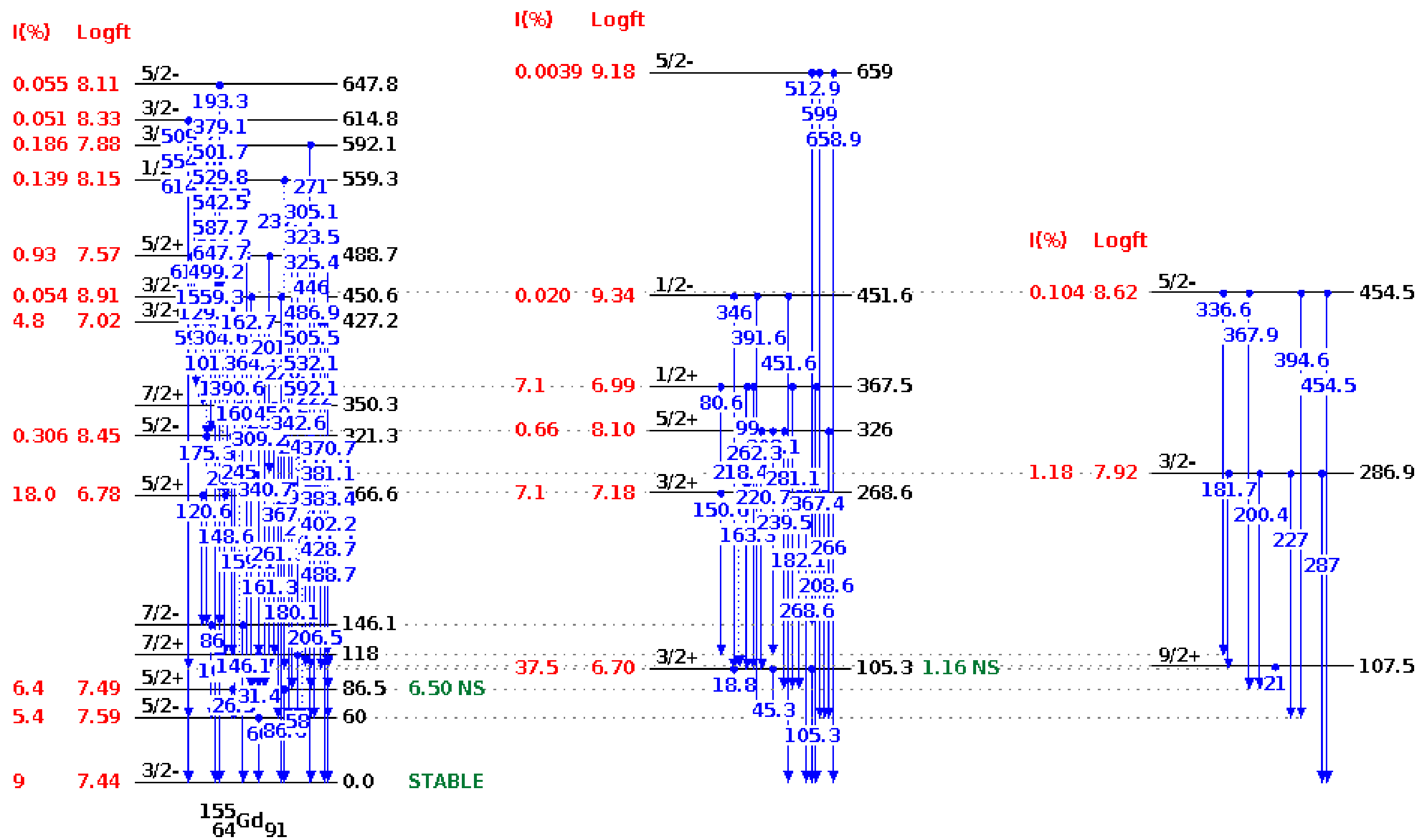


Eg (keV)	Ig (%)
86.545 3	32.0 6
105.305 3	25
180.103 1	7.45 15
262.322 2	5.29 5
163.311 1	4.44 5
161.334 1	2.76 3
148.650 1	2.648 23
45.2972 13	1.604 20
367.225 2	1.48 18
340.690 1	1.182 23
60.0086 10	1.11 4
160.589 2	0.781 15
367.638 2	0.78 13
268.625 2	0.71 5
220.778 2	0.508 5
181.694 1	0.422 5
26.533 6	0.394 13
286.999 4	0.317 6
281.087 2	0.302 4
208.089 2	0.231 13



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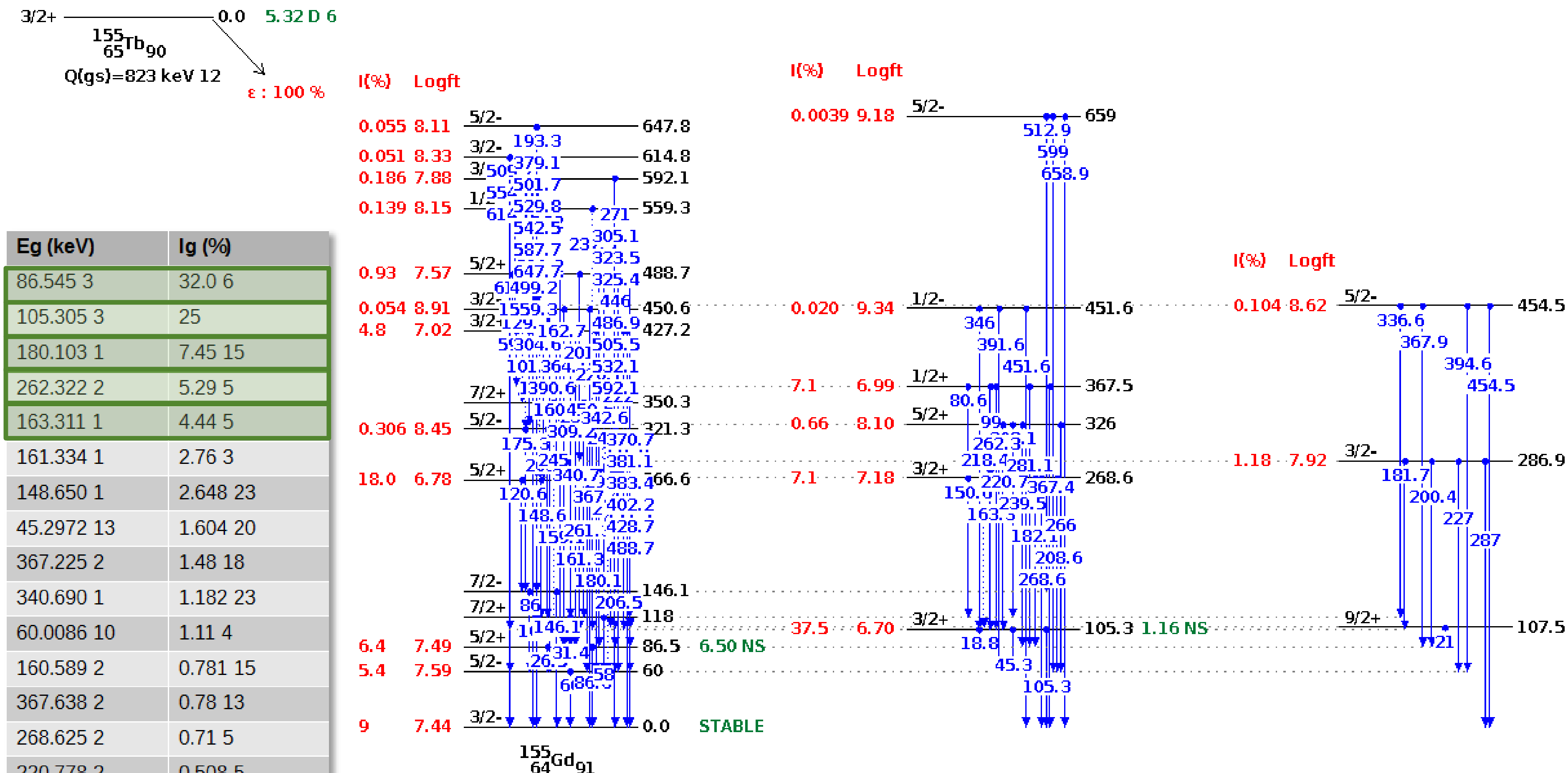

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  - ✓ Geometry
  - ✓ Detector modelling
  - ✓ Physics models (dependent on energy range)

<u>Comparison with experimental data</u>

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Physics in Medicine & Biology

Phys. Med. Biol. 61 (2016) 5107–5127

doi:10.1088/0031-9155/61/14/5107

The influence of triple energy window scatter correction on activity quantification for ^{177}Lu molecular radiotherapy

Andrew P Robinson[1], Jill Tipping[2], David M Cullen[1] and David Hamilton[2]

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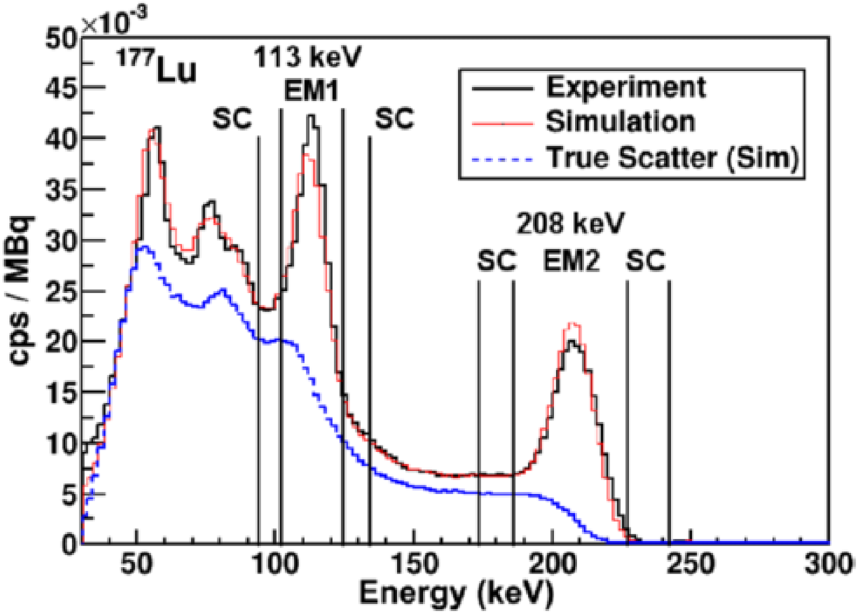

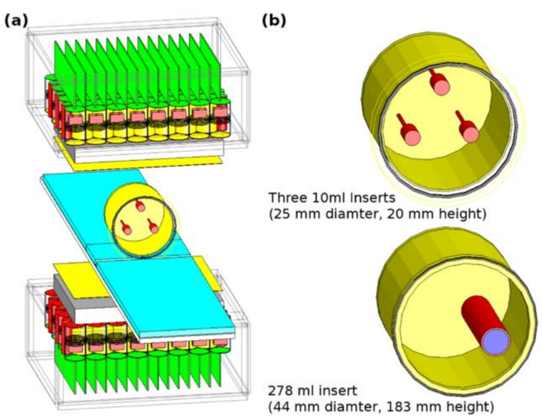

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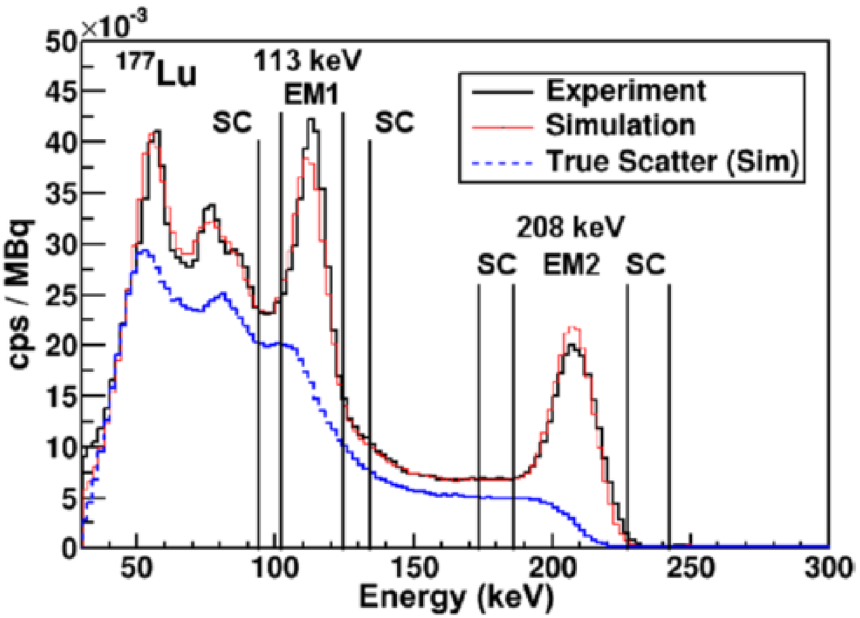

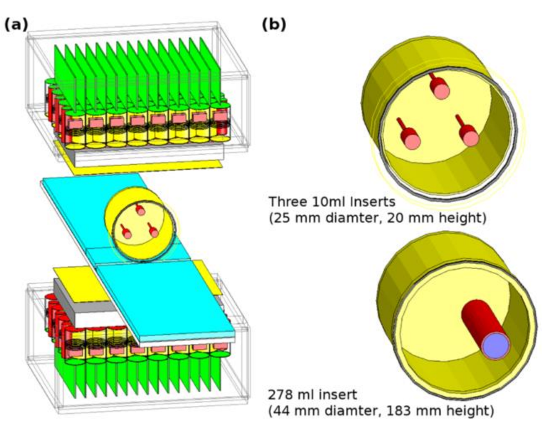

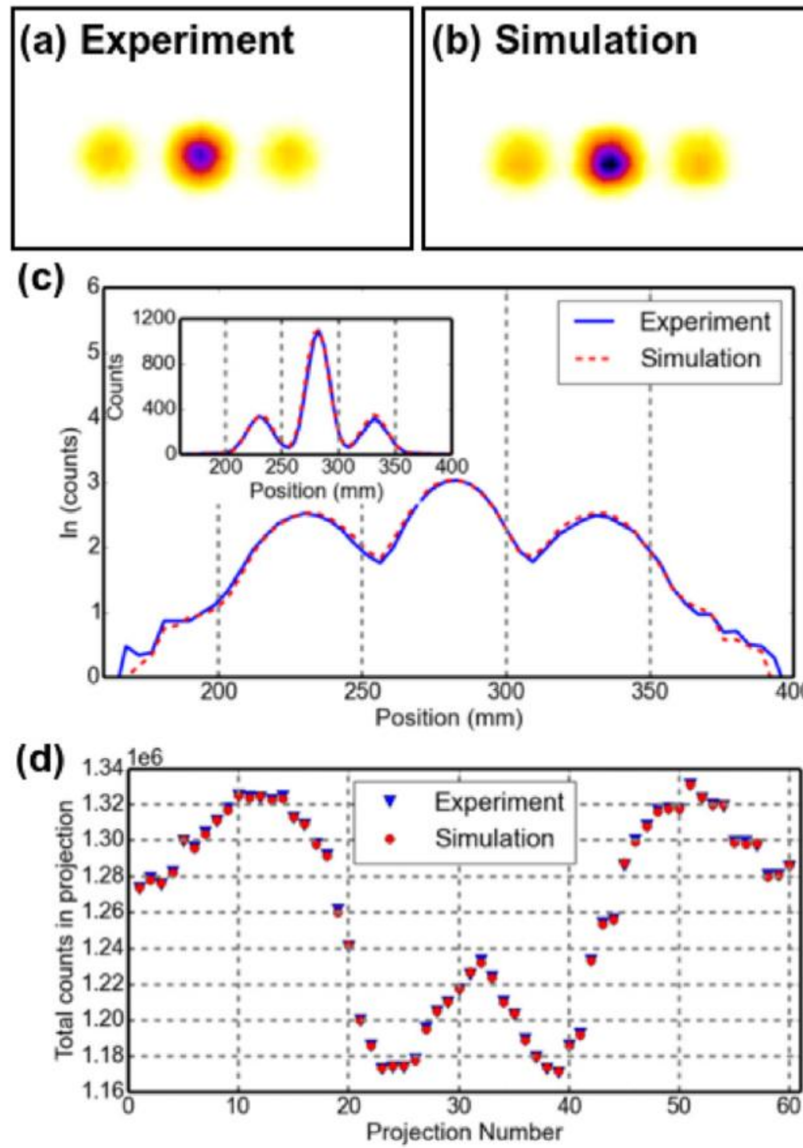

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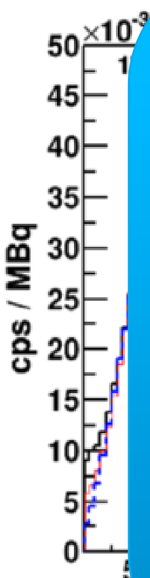
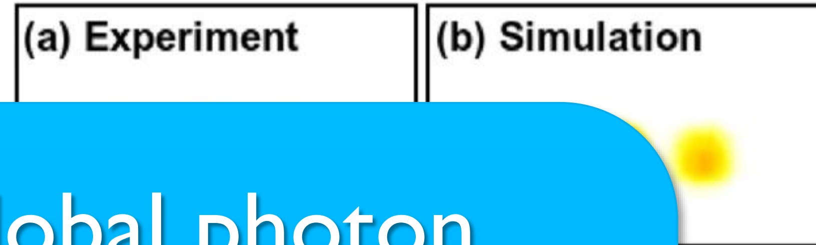
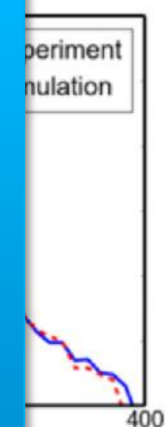
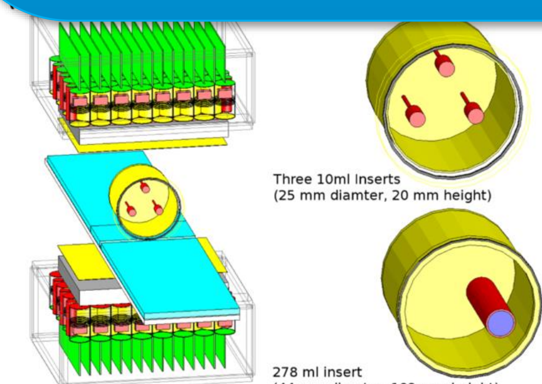
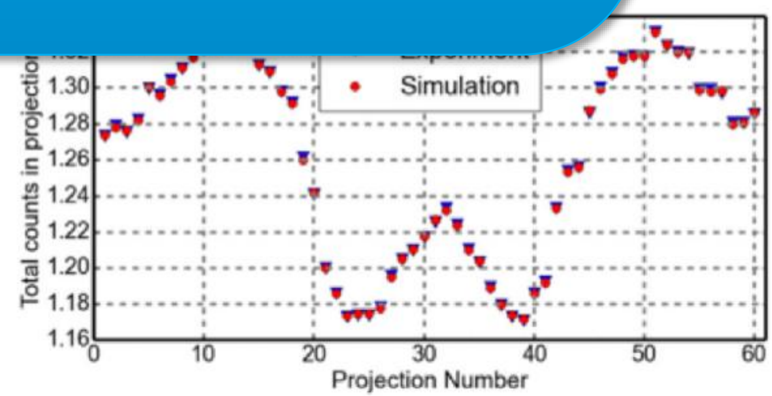




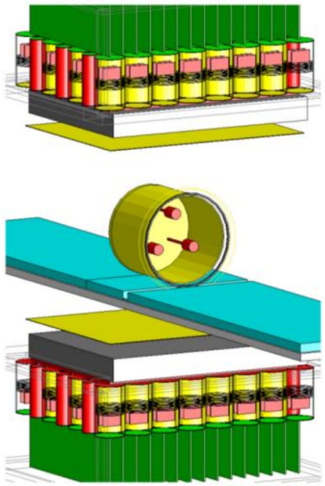
“Validates the global photon transport, geometry and material composition of the model for the full range of <u>direct observables</u> from a commercial SPECT camera.”

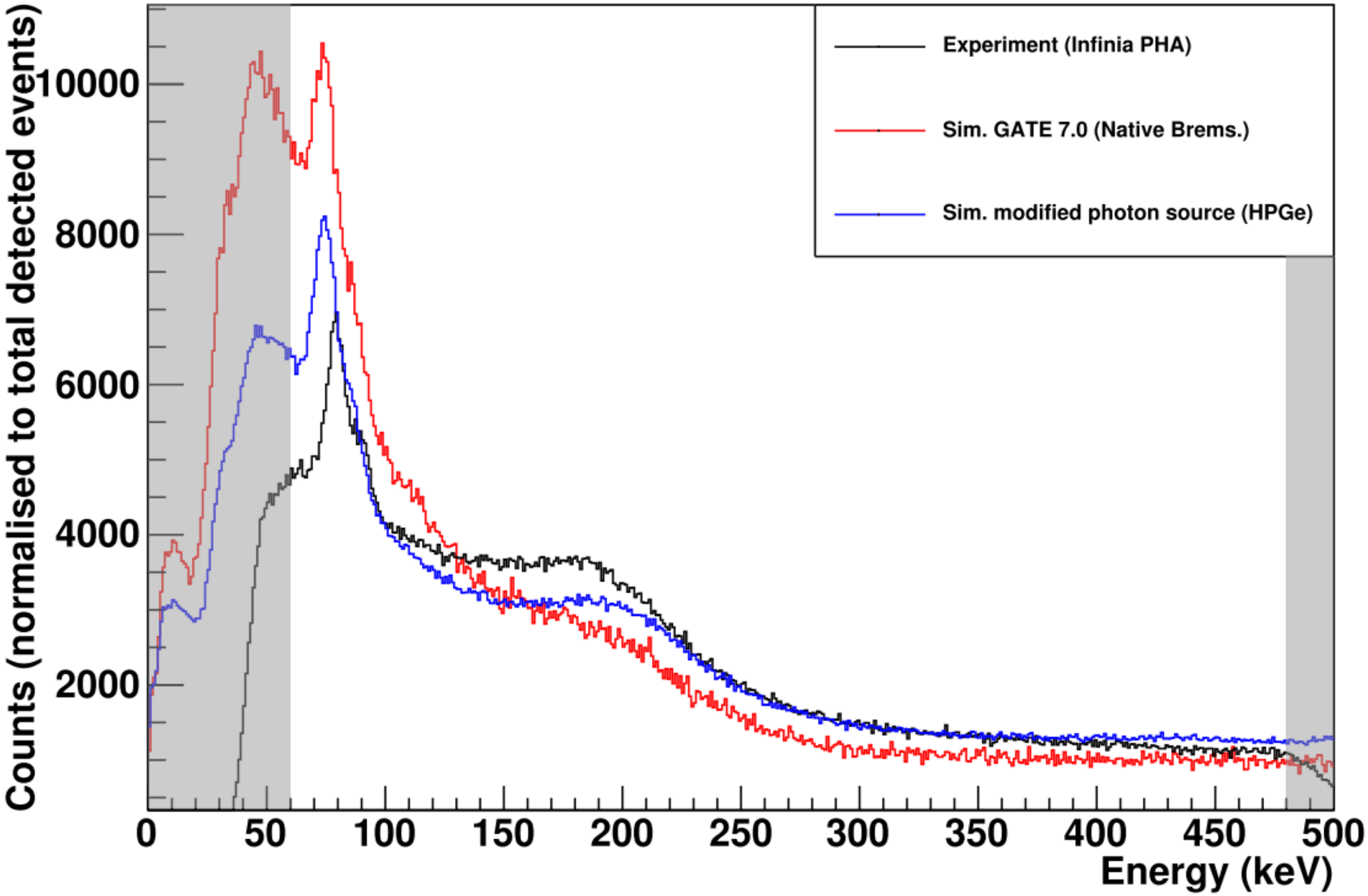






^{90}Y Bremsstrahlung Imaging





C. Oldfield, PhD Thesis, Uni. Of Manchester (2017)

^{90}Y Bremsstrahlung Imaging

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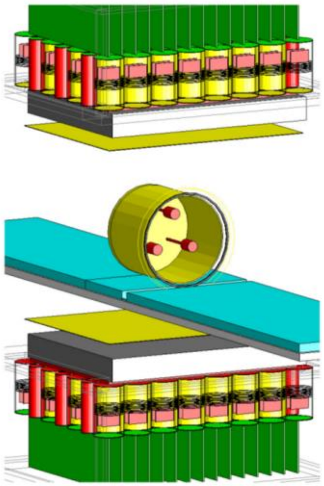

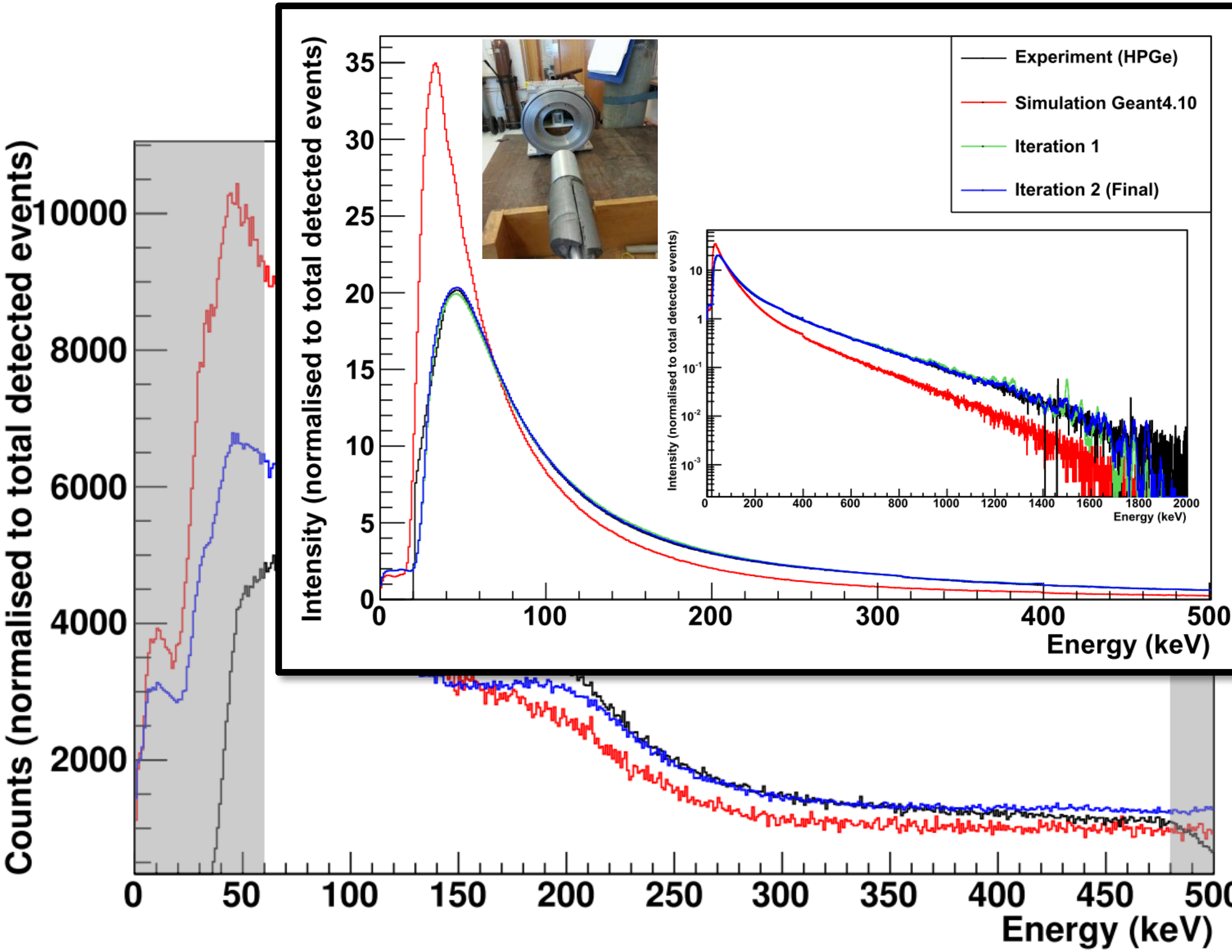

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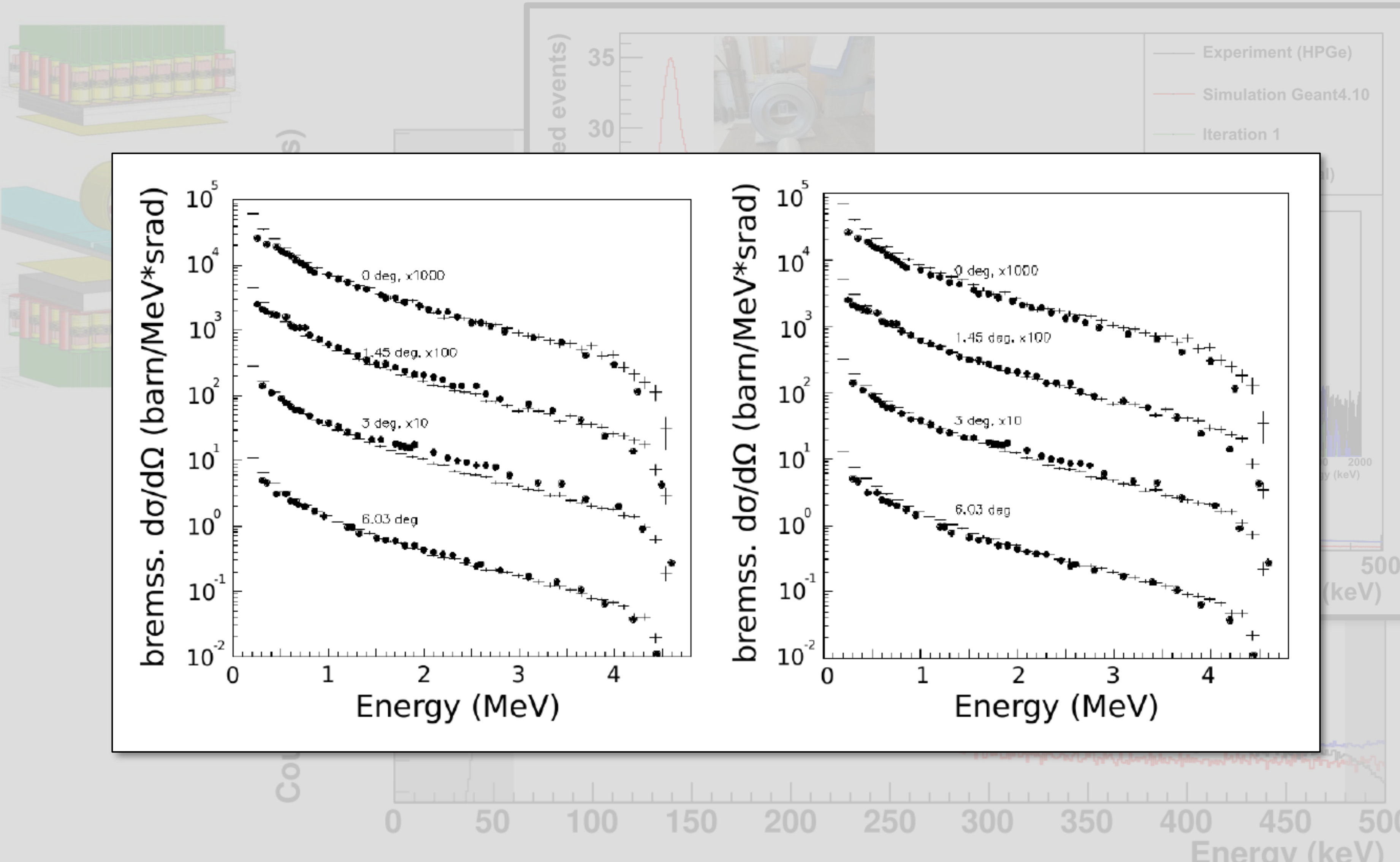

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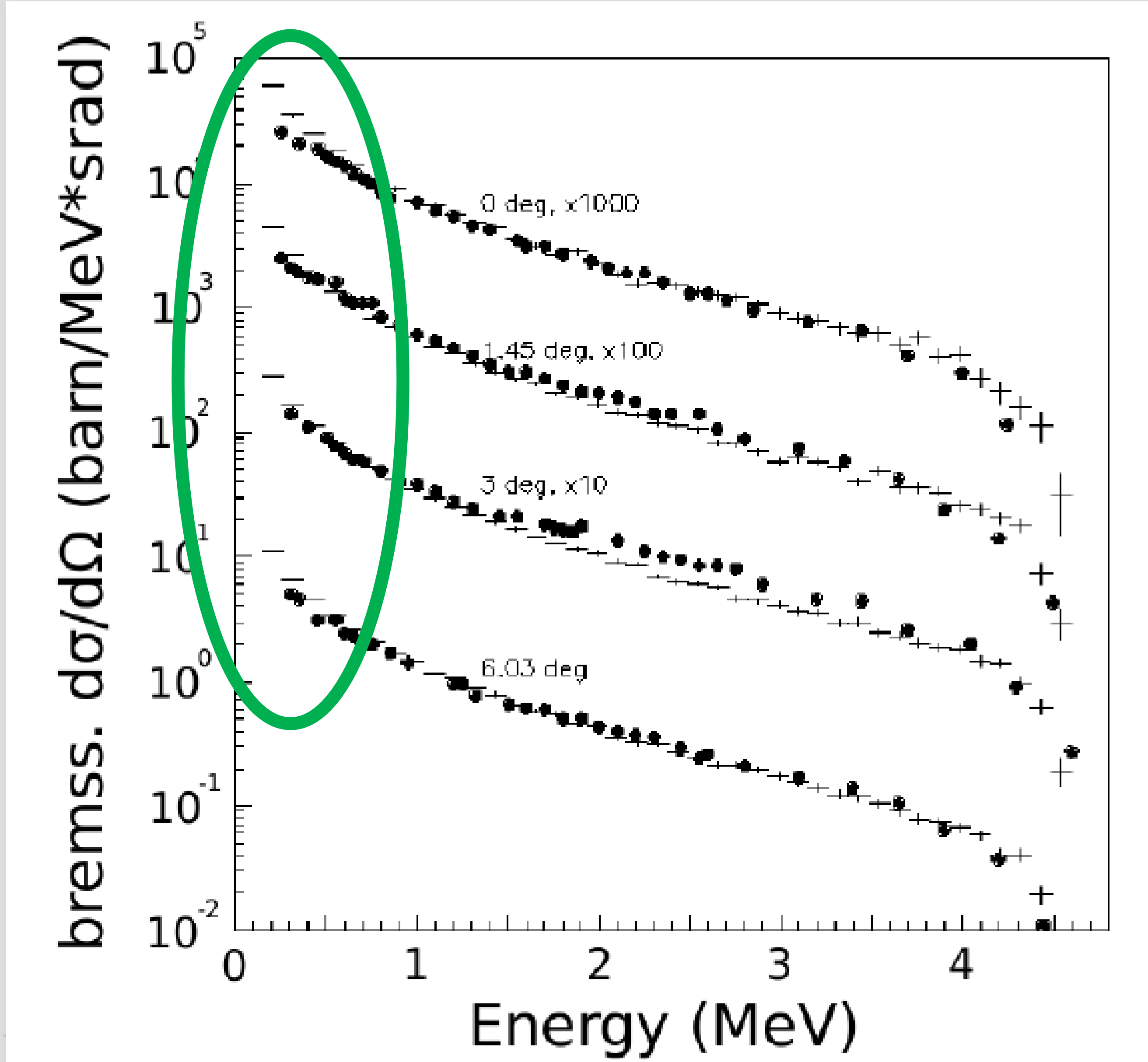

C. Oldfield, PhD

^{90}Y Bremsstrahlung Imaging

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MetroBeta
Radionuclide beta spectra metrology

Home | Project overview | Impact | Stakeholder registration | Partners & Collaborators

About this project

Objectives:

The project addresses the following scientific and technical objectives:

1. To improve modern measurement techniques for silicon detectors (Si(Li)), solid scintillator crystals ($LaBr_3$/$CeBr_3$) and magnetic spectrometers for measurements of beta spectra. (WP3)
2. To optimise beta spectrometers, based on Metallic Magnetic Calorimeters (MMCs), and measure new high resolution beta spectra for low (< 100 keV) and intermediate (< 1 MeV) end-point energy pure beta emitters Sm-151, C-14, Tc-99 and Cl-36. (WP2), D5, D6
3. To improve theoretical computation methods and compare the measured and calculated beta spectra. (WP1 and WP4)
4. To investigate the effect of improved beta spectra on absolute activity measurements and measure Bremsstrahlung cross-sections to quantify their effect. (WP4)
5. To facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers) and end users (the nuclear medicine community and the nuclear power industry). (WP5)

^{90}Y Bremsstrahlung Imaging

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- MC codes **do not reproduce correctly** the bremsstrahlung production
  - Study presented at the last ICRM LS WG **(simulation of dose calibrator)**
  - Med. Phys. 37 (2010) 2943, NIM B 350 (2015) 41-48

- There is a need **to measure the cross-section** for bremsstrahlung production in order to improve the accuracy of the **simulation**
  - Use to calculate the correction for energy loss through the escape of bremsstrahlung photons in LSC and in MMCs for beta spectra measurement

- News experiments are proposed using:
  - an **electron gun** (up to 2 MeV)
  - A set-up for **gamma measurement**

5. To facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers) and end users (the nuclear medicine community and the nuclear power industry). (WP5)

OpenDose: a collaborative effort to produce reference dosimetric data with Monte Carlo simulations

Aims to provide a free and public resource of robust reference data to enable dosimetry calculations in nuclear medicine, using a variety of Monte Carlo codes through an international collaboration

OpenDose

Challenges

- 2 ICRP 110 reference adult phantoms
  (male and female)
- 140 organs (19600 target/source combinations!)
- ICRP 107: ~1200 radionuclides
- MIRD RADTABS source of decay data: ~300 radionuclides

Too big for a single institution!!!

Proposal

- Collaborative work, everyone is welcome!
- Create a free database
- Create an easily accessible website
- Make data available with associated uncertainties
- First meeting took place at the EANM 2016, Barcelona.

Courtesy of Dr A. Denis-Bacelar

OpenDose

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14 research teams (18 institutes)

5 Monte Carlo codes:

Geant4/GATE - FLUKA - PENELOPE - MCNP/MCNPX - EGSnrc/EGS++

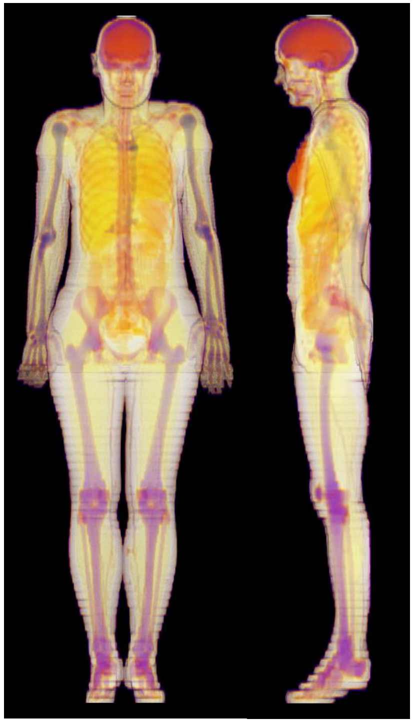
Courtesy of Dr A. Denis-Bacelar

OpenDose: initial comparisons

- Compute mono-energetic specific absorbed fractions (SAF, ϕ/m)

$$S(r_t \leftarrow r_s) = \sum_i \frac{\Delta_i \Phi_i (r_t \leftarrow r_s)}{m_t}$$

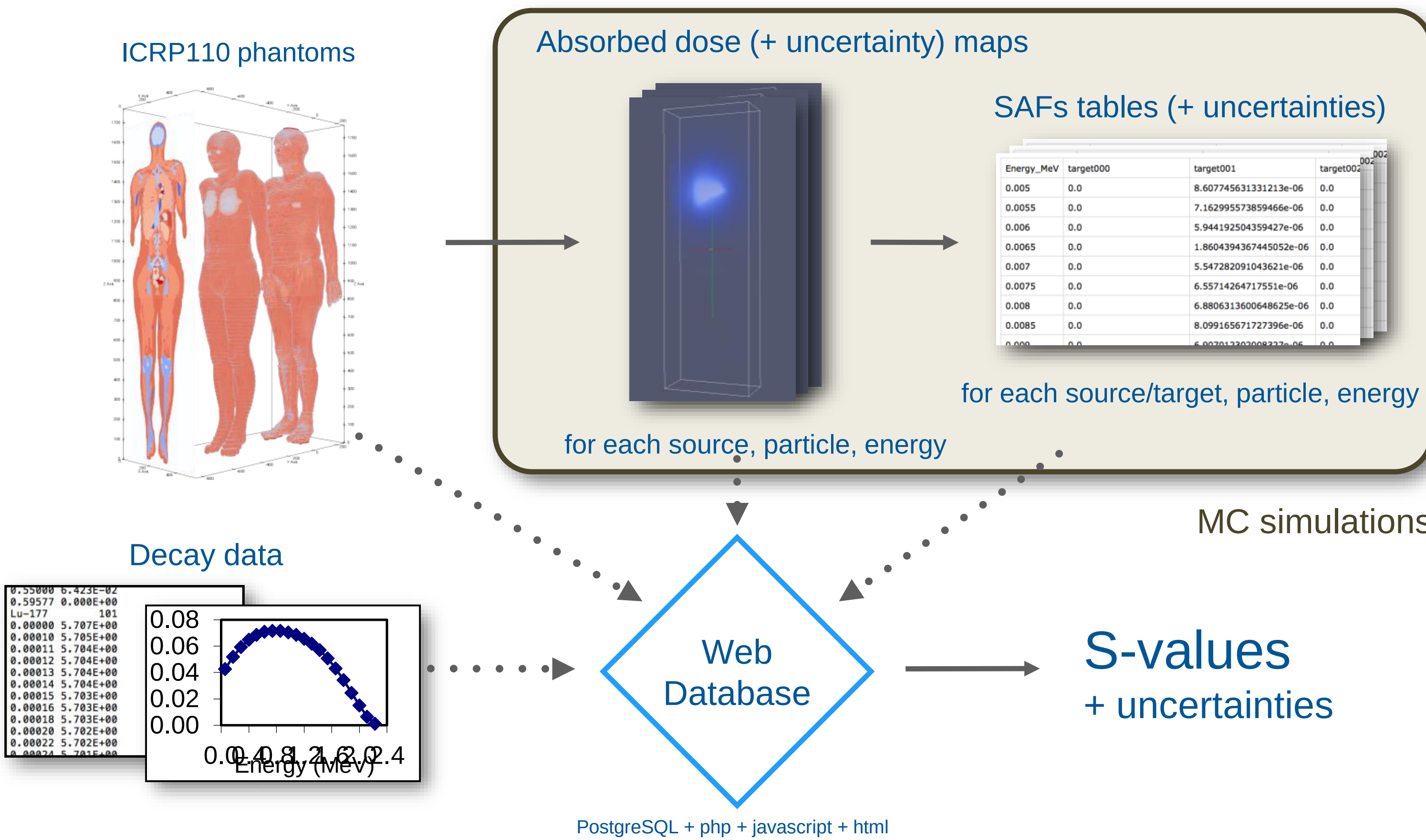
- *Generate S-values by integrating over the decay spectra*
- Check-point simulations:
  - Adult female phantom
  - Sources: liver, blood (trunk)
  - Targets: 140
  - Seven energies: 0.05, 0.1, 0.2, 0.5, 1, 2 and 5 MeV
  - Electrons and photons
  - 10^8 histories, cut-off energies of 10 keV
  - 2 (sources) × 2 (e^-/g) × 7 (energies) = 28 simulations / ~1 week (1 core)



- But…2 (female/male models) × 140 (sources) × 2 (e^-/p) × 91 (energies) = 50960 !

Courtesy of Dr A. Denis-Bacelar

OpenDose: Framework



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Validation of simulations

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Tools you can use

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EGSnrc

(http://www.nrc-cnrc.gc.ca/eng/solutions/ advisory/egsnrc_index.html)

Tools you can use

National Physical Laboratory

MCNP (https://mcnp.lanl.gov/)

Los Alamos NATIONAL LABORATORY EST. 1943

A General Monte Carlo N-Particle (MCNP) Transport Code

mcnp

- MCNP5
- MCNP6
- MCNP FAQ
- MCNP Bugs
- Upcoming Classes
- Related Efforts
- Monte Carlo Team Personnel
- User Manual
- Reference Collection
- Forum For Users
- How to get MCNP

CONTACTS

MCNP Team

MCNP Web Admin

Entrust

Monte Carlo Code Group

Los Alamos National Laboratory

ABSTRACT

MCNP is a general-purpose Monte Carlo N-Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. Specific areas of application include, but are not limited to, radiation protection and dosimetry, radiation shielding, radiography, medical physics, nuclear criticality safety, Detector Design and analysis, nuclear oil well logging, Accelerator target design, Fission and fusion reactor design, decontamination and decommissioning. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori.

Pointwise cross-section data typically are used, although group-wise data also are available. For neutrons, all reactions given in a particular cross-section evaluation (such as ENDF/B-VI) are accounted for. Thermal neutrons are described by both the free gas and S(alpha,beta) models. For photons, the code accounts for incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorbtion in pair production with local emission of annihilation radiation, and bremsstrahlung. A continuous-slowing-down model is used for electron transport that includes positrons, k x-rays, and bremsstrahlung but does not include external or self-induced fields.

Important standard features that make MCNP very versatile and easy to use include a powerful general source, criticality source, and surface source; both geometry and output tally plotters; a rich collection of variance reduction techniques; a flexible tally structure; and an extensive collection of cross-section data.

MCNP contains numerous flexible tallies: surface current & flux, volume flux (track length), point or ring detectors, particle heating, fission heating, pulse height taly for energy or charge deposition, mesh tallies, and radiography tallies.

MCNP Highlights

The MCNP6.2 release from RSICC is expected in Spring 2017.

The MCNP Reference Collection was updated on 2017-01-31.
There are new reference reports on fission neutron multiplicity and Whisper sensitivity-uncertainty methods.

The MCNP6.1.1 update (2014) is available from RSICC.

The MCNP6.1 production release (2013) is available from RSICC.

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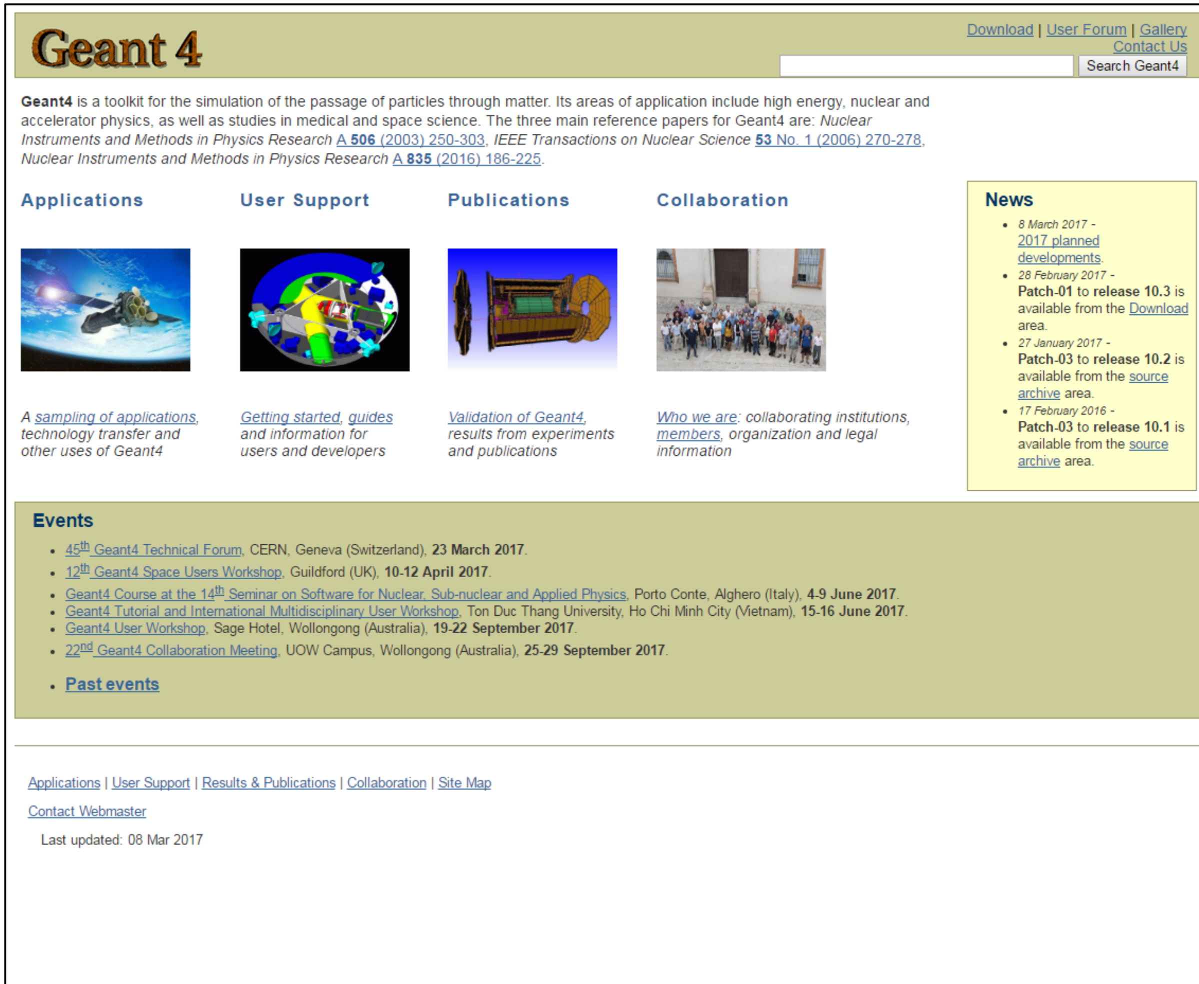
Tools you can use

NPL National Physical Laboratory

Geant4 (http://geant4.web.cern.ch/geant4/)

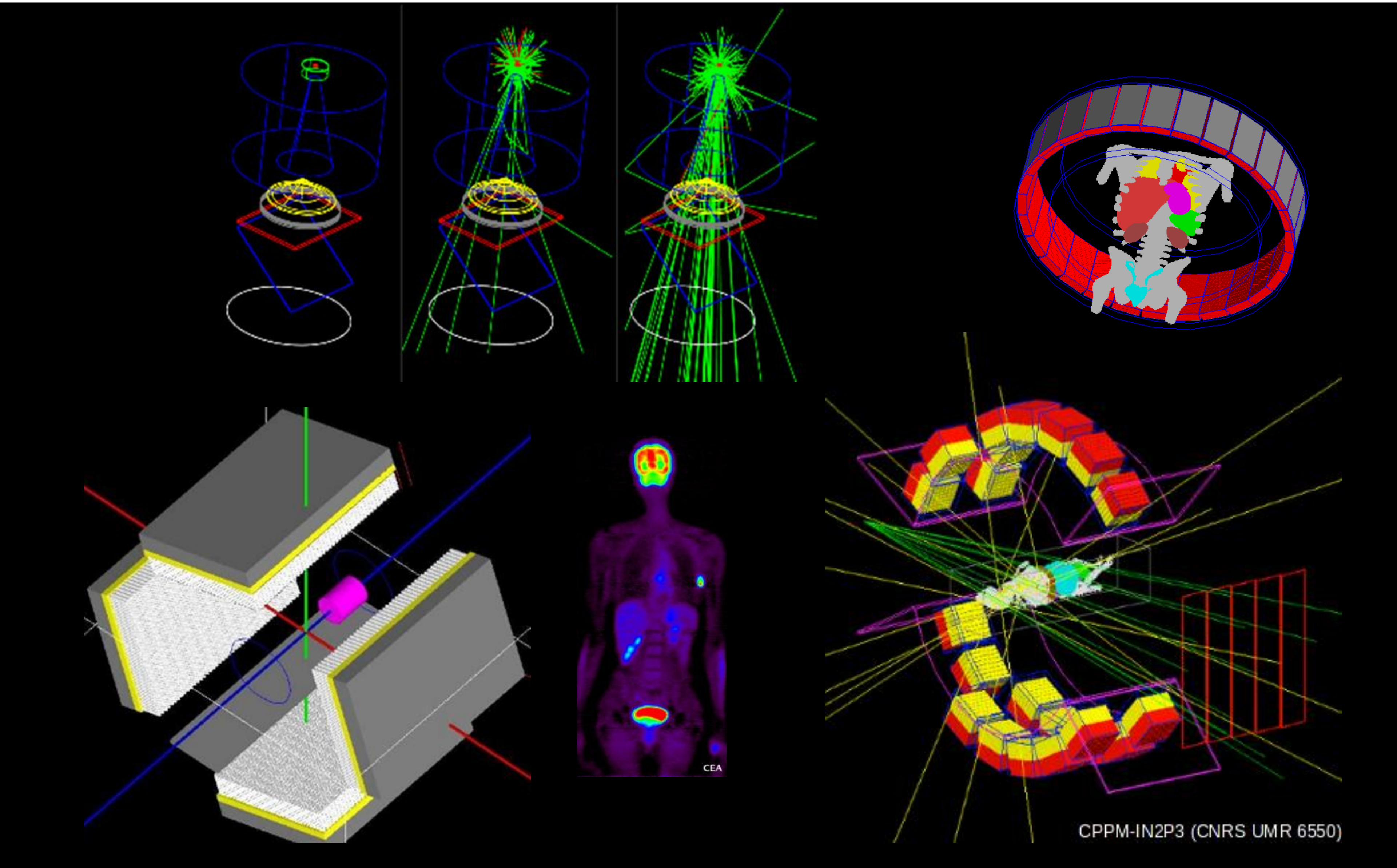


Tools you can use

GATE (http://www.opengatecollaboration.org/)

GATE

http://www.opengatecollaboration.org/



GATE

http://www.opengatecollaboration.org/

```
.
├── AddExternalData.sh
├── CMakeLists.txt
├── example_ARF
├── example_CT
├── example_DNA
├── example_doseactor
├── example_dosimetry/
│   ├── brachytherapy
│   ├── electron_radiotherapy
│   ├── external-beam-therapy-photon
│   ├── molecular-therapy-I131
│   └── protontherapy
├── example_fluorescence
├── example_OPTICAL
├── example_PET
├── example_PHANTOM_SOURCE
├── example_PhysicsLists
├── example_Radiotherapy
├── example_ROOT_Analyse
├── example_SPECT
├── example_SPECT_GPU
├── example_TimeActivityCurve
├── example_TrackerDetector
├── example_UserFluenceSource
├── example_UserSpectrum
├── example_vpgtle
└── gpumacros
```

- ✓ Wide variety of examples
- ✓ Multiple modalities
- ✓ Doesn't require C++
- ✓ Large user base
- ✓ Actively developed
- ✓ Increasingly well referenced

- χ Still requires validation
- χ Develop data analysis tools
- χ Undocumented bugs

Monte Carlo Training

- GATE workshop at https://ptcog58.org/ 10-15 June, 2019 Manchester.
- GATE training for beginners in Clermont-Ferrand (France), Fall 2019 (3 days).
- GATE Training sessions are available

  http://www.opengatecollaboration.org/TrainingSessions

- Geant4 additional HSST training course (sessions in May and September 2019)

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Summary

- Monte Carlo simulation can be a powerful tool for modelling imaging systems.
- There are a number of benefits to using MC:
  - Extra non-observable information
  - “Ground truth”
  - Optimisation of protocols
- Importance of <u>validation</u> – comparison to experimental data
- A number of packages available
  (GATE is a good starting point for many modalities).

Validation of simulations

- Can you trust the results from a simulation?

- Yes - **<u>if the simulation has been validated</u>**
  - ✓ Geometry
  - ✓ Detector modelling
  - ✓ Physics models (dependent on energy range)

<u>Comparison with experimental data</u>

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