

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?

What is Monte Carlo simulation?

Based on the Monte Carlo method

What is Monte Carlo simulation?



What is Monte Carlo simulation?



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?



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:
sɪmjuhl'eyshuhn (IPA: sɪmjuh'l̩ eɪʃən)

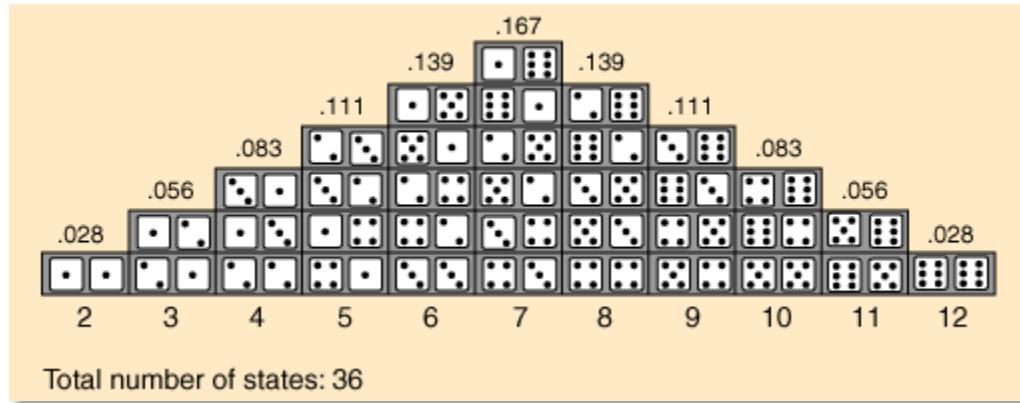
Hyphenation:
sim-u-la-tion (10 letters | 4 syllables)

What is Monte Carlo simulation?

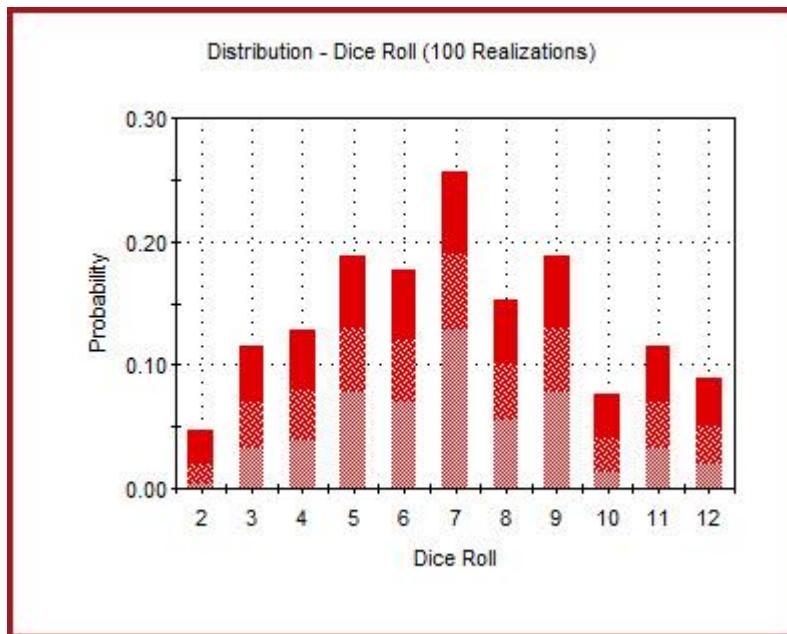
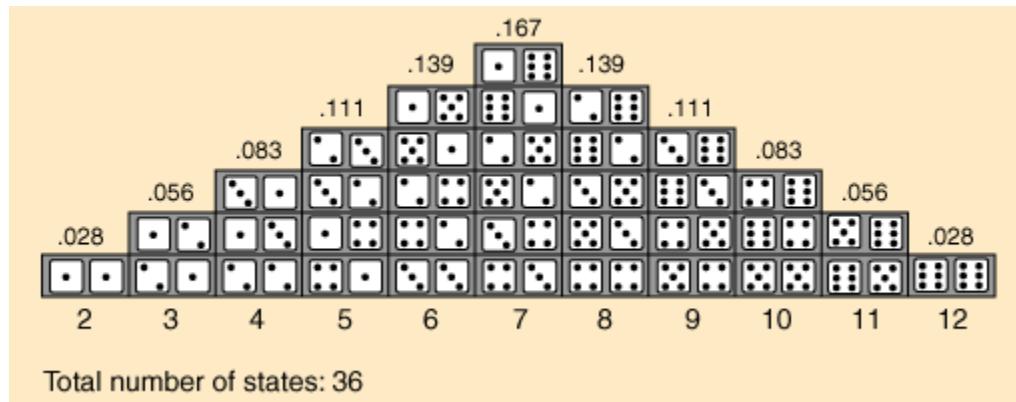
“A method which solves a problem by generating suitable random numbers and observing that fraction of the numbers obeying some property or properties. The method is useful for obtaining numerical solutions to problems which are **too complicated to solve analytically.**”

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

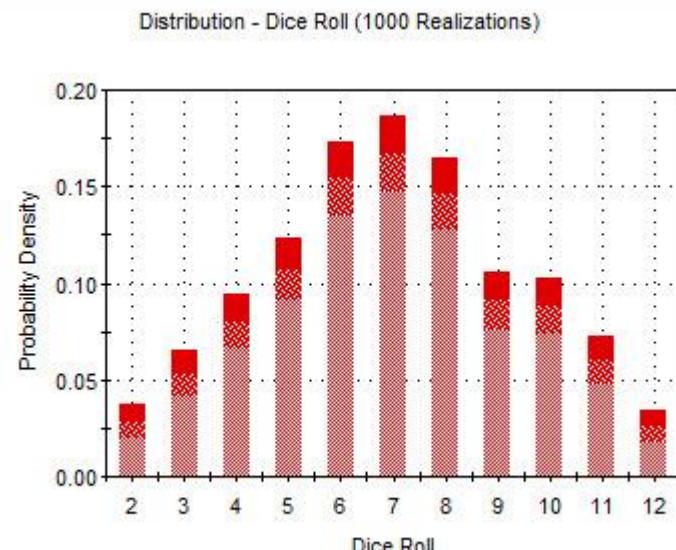
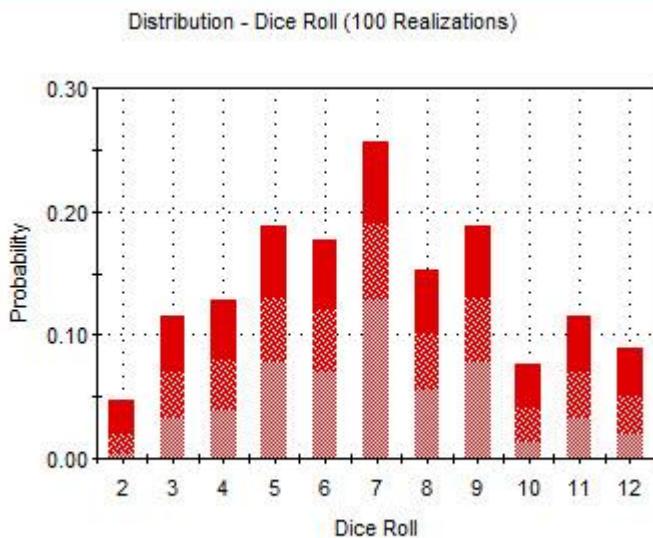
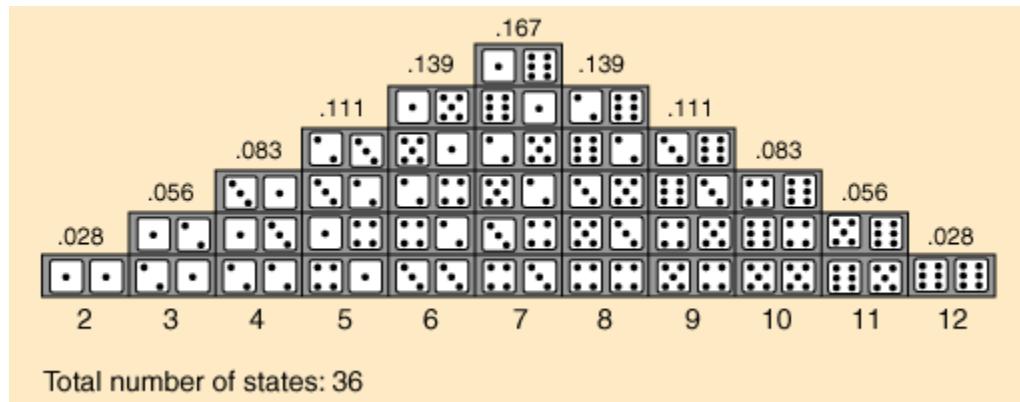
Simple Example



Simple Example



Simple Example



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

Why use it for medical imaging?

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

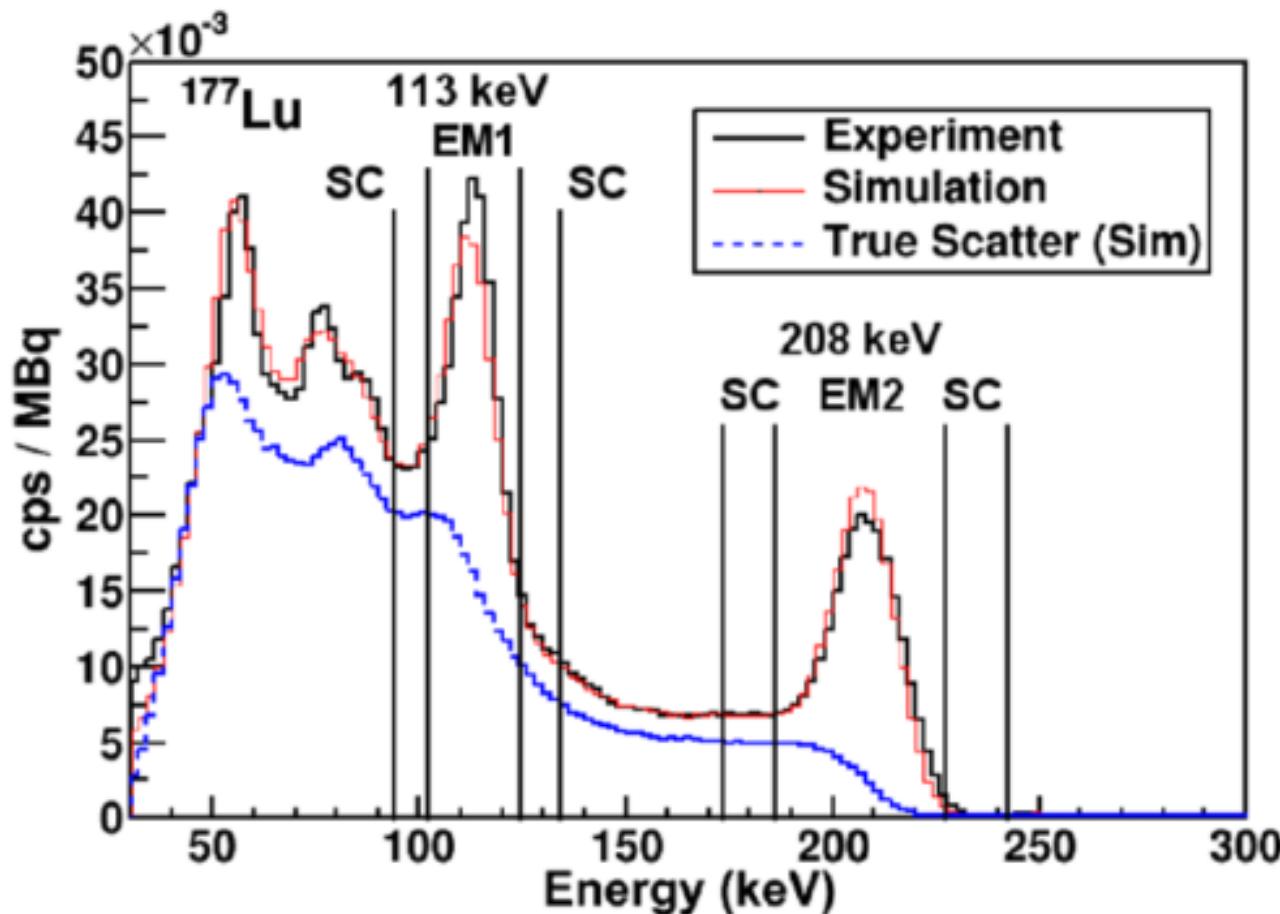


Figure 5. Emission spectrum for a water filled phantom measured

Optimisation of imaging windows using Monte Carlo Simulation

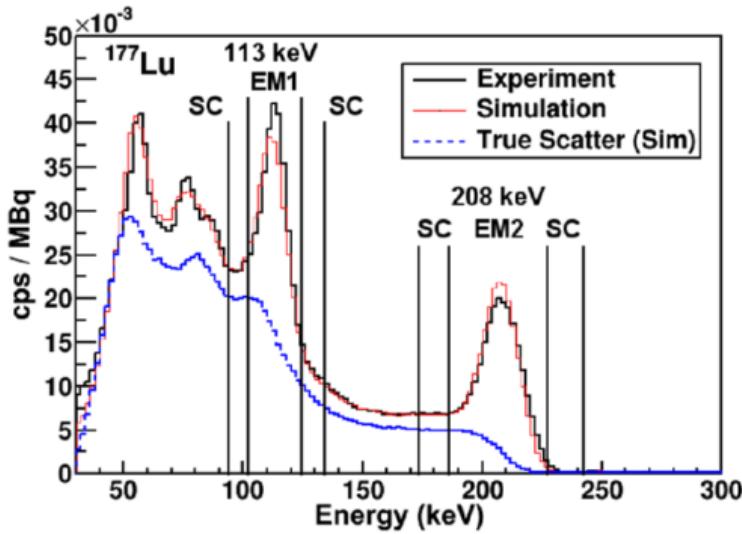
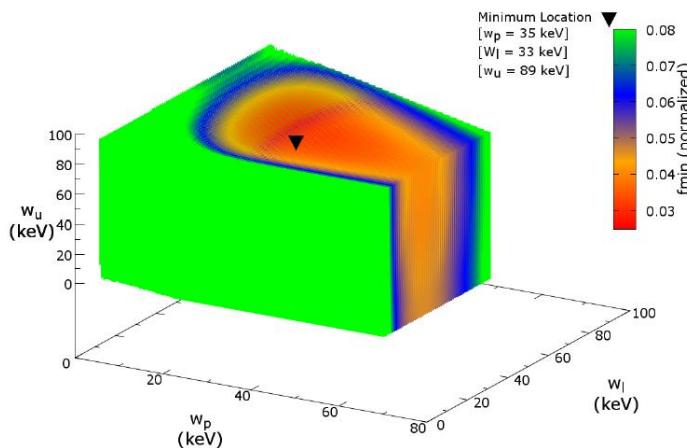


Figure 5. Emission spectrum for a water filled phantom measured



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

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

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

$$E_l + \frac{w_l}{2} > E_{min}$$

$$E_u + \frac{w_u}{2} < E_{max}.$$

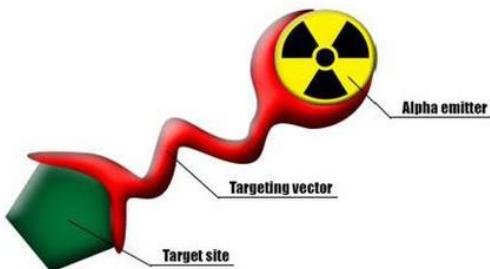
$$E_l + \frac{w_l}{2} \leq E_p - \frac{w_p}{2}$$

$$E_u - \frac{w_u}{2} \geq E_p + \frac{w_p}{2}.$$

Sensitive range
Camera.

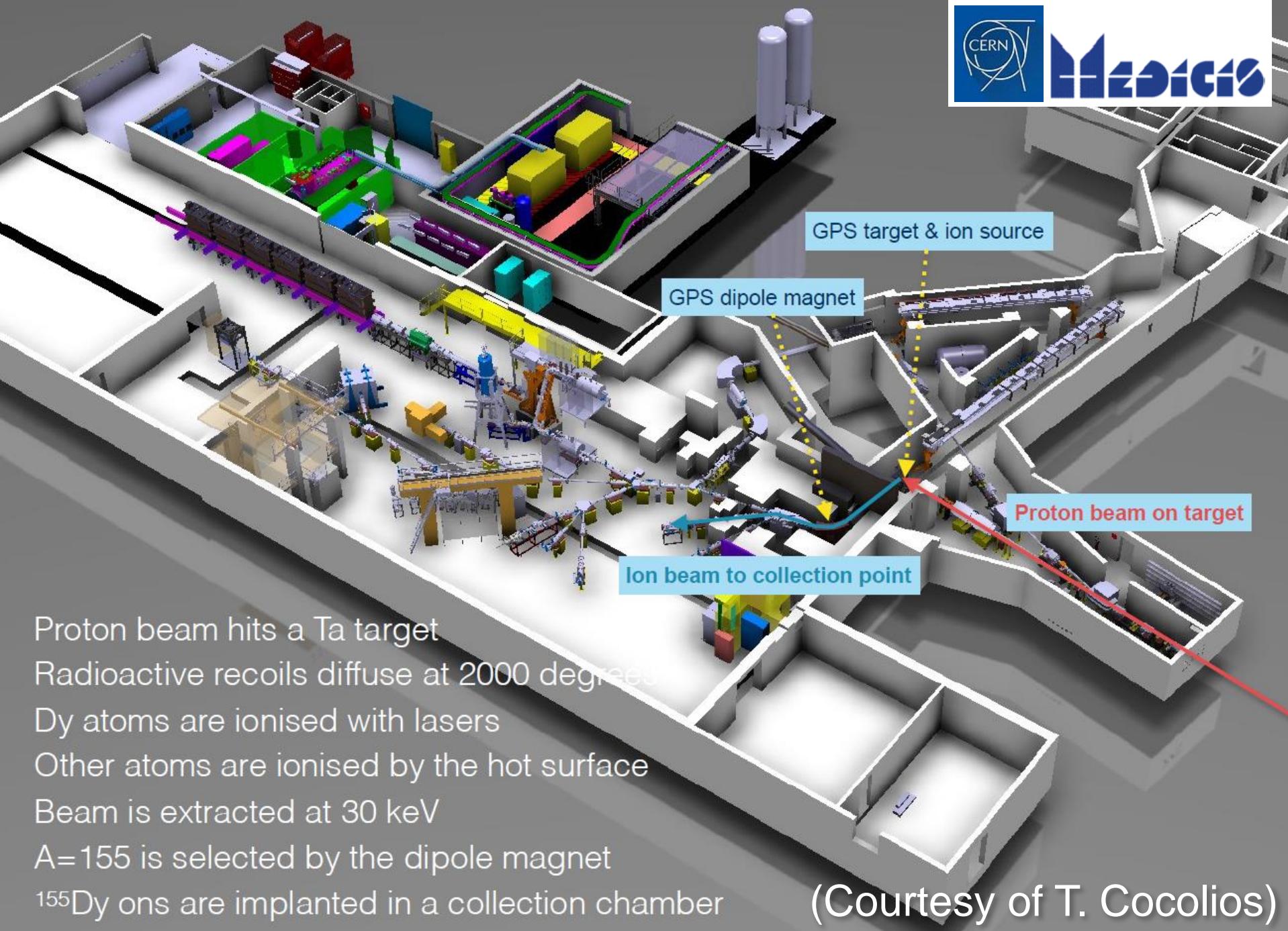
Over-lapping
windows.

Tb₆₅ (Theranostic Isotope Quartet)



Z	151Tm	152Tm	153Tm	154Tm	155Tm	156Tm	157Tm	158Tm	159Tm	160Tm	161Tm	162Tm	163Tm	164Tm	165Tm	166Tm	167Tm
87	150Er	151Er	152Er	153Er	154Er	155Er	156Er	157Er	158Er	159Er	160Er	161Er	162Er	163Er	164Er	165Er	166Er
85	149Ho	150Ho	151Ho	152Ho	153Ho	154Ho	155Ho	156Ho	157Ho	158Ho	159Ho	160Ho	161Ho	162Ho	163Ho	164Ho	165Ho
83	148Dy	149Dy	150Dy	151Dy	152Dy	153Dy	154Dy	155Dy	156Dy	157Dy	158Dy	159Dy	160Dy	161Dy	162Dy	163Dy	164Dy
81	147Tb	148Tb	149Tb 149	150Tb	151Tb	152Tb 152	153Tb	154Tb	155Tb 155	156Tb	157Tb	158Tb	159Tb	160Tb	161Tb 161	162Tb	163Tb
	146Gd	147Gd	148Gd	149Gd	150Gd	151Gd	152Gd	153Gd	154Gd	155Gd	156Gd	157Gd	158Gd	159Gd	160Gd	161Gd	162Gd
	145Eu	146Eu	147Eu	148Eu	149Eu	150Eu	151Eu	152Eu	153Eu	154Eu	155Eu	156Eu	157Eu	158Eu	159Eu	160Eu	161Eu
	144Sm	145Sm	146Sm	147Sm	148Sm	149Sm	150Sm	151Sm	152Sm	153Sm	154Sm	155Sm	156Sm	157Sm	158Sm	159Sm	160Sm
	143Pm	144Pm	145Pm	146Pm	147Pm	148Pm	149Pm	150Pm	151Pm	152Pm	153Pm	154Pm	155Pm	156Pm	157Pm	158Pm	159Pm
	82	84	86	88	90	92	94	96									N

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



Medical physics questions for ^{155}Tb

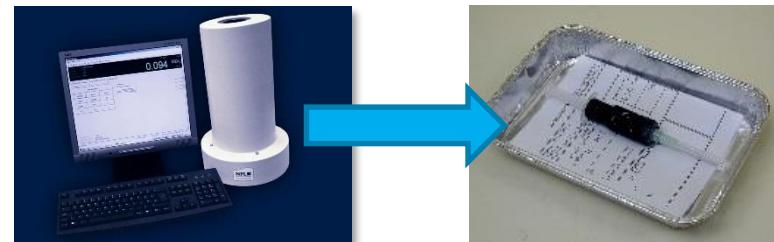
How to image it?

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



How to measure activity?

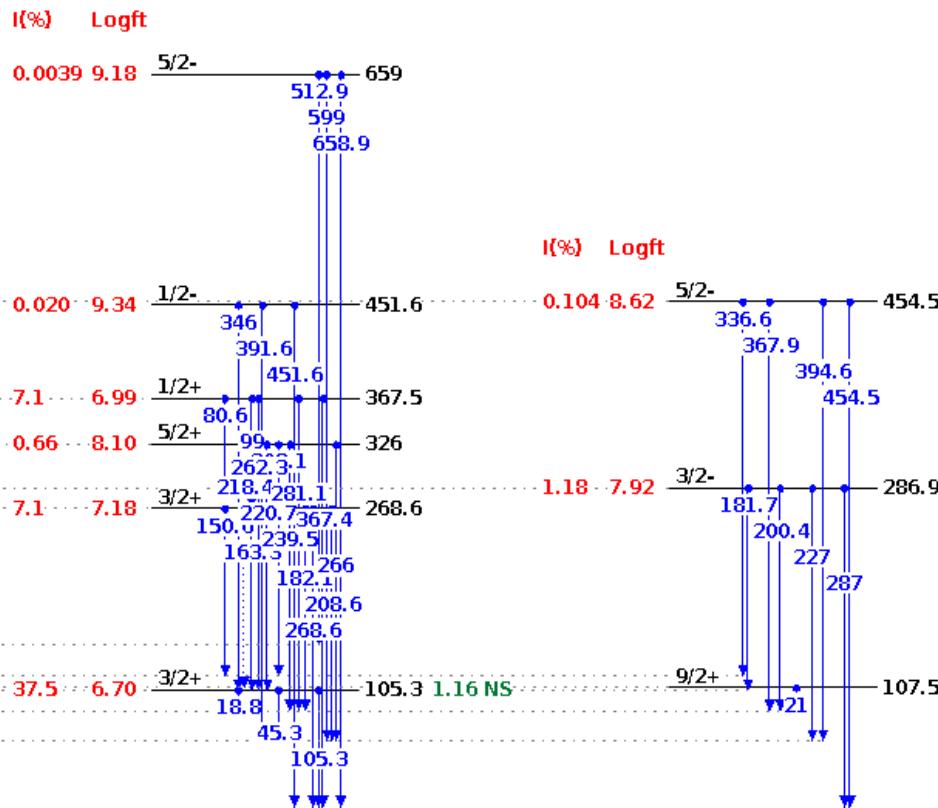
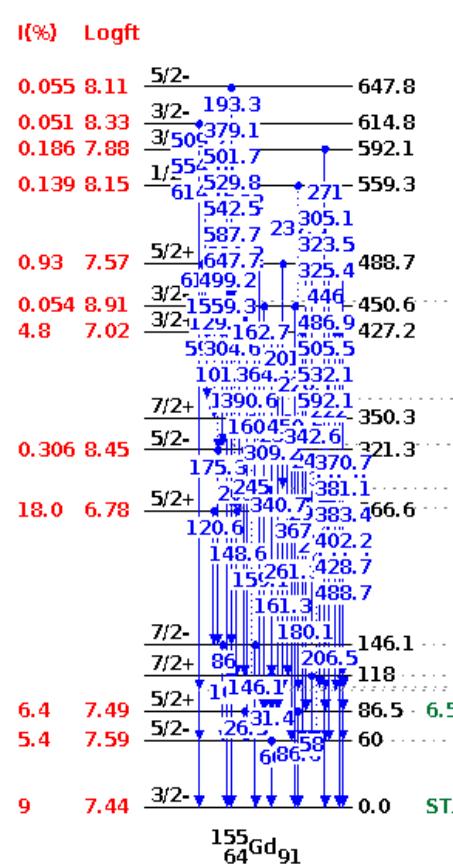
- Is there a primary standard?
- What dial factors to use on a hospital calibrator?



^{155}Tb (SPECT Imaging)

$^{155}\text{Tb}_{90}$
 $Q(\text{gs}) = 823 \text{ keV}$ 12
 $\epsilon : 100\%$

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

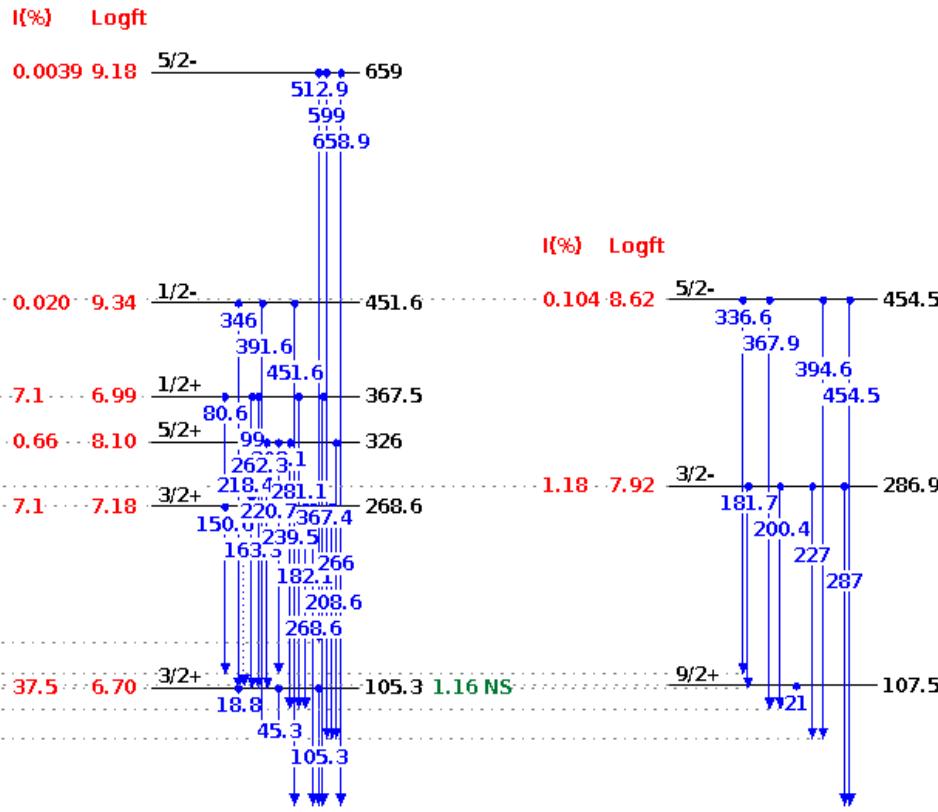
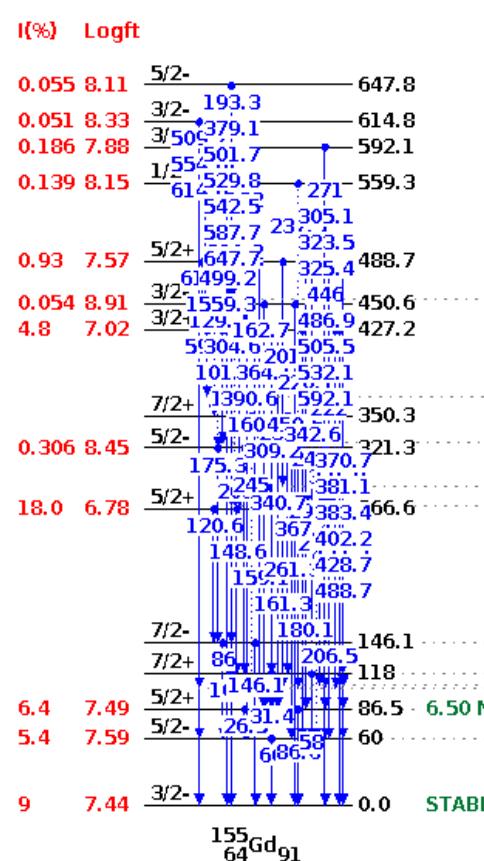


$^{155}\text{Gd}_{91}$
STABLE

^{155}Tb (SPECT Imaging)

$^{155}\text{Tb}_{90}$
 $Q(\text{gs}) = 823 \text{ keV}$ 12
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Validation of simulations

- Can you trust the results from a simulation?

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

Comparison with experimental data

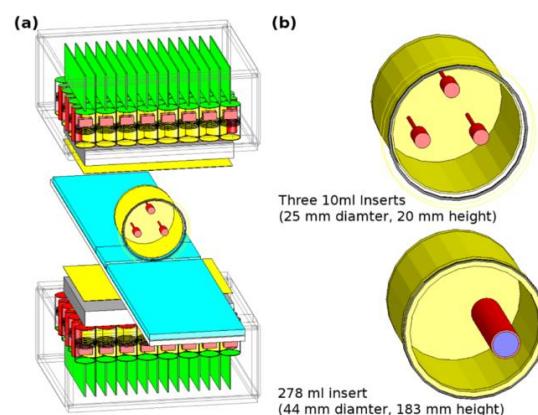
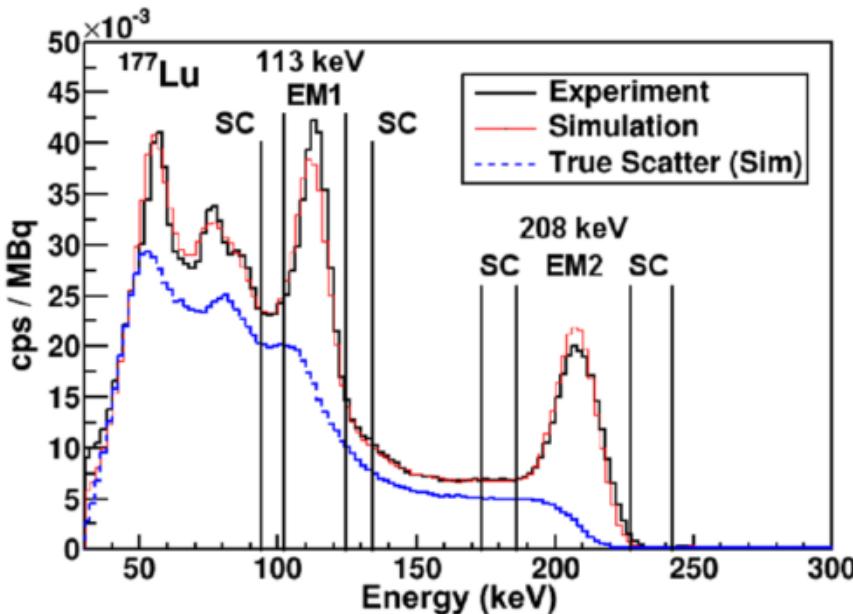
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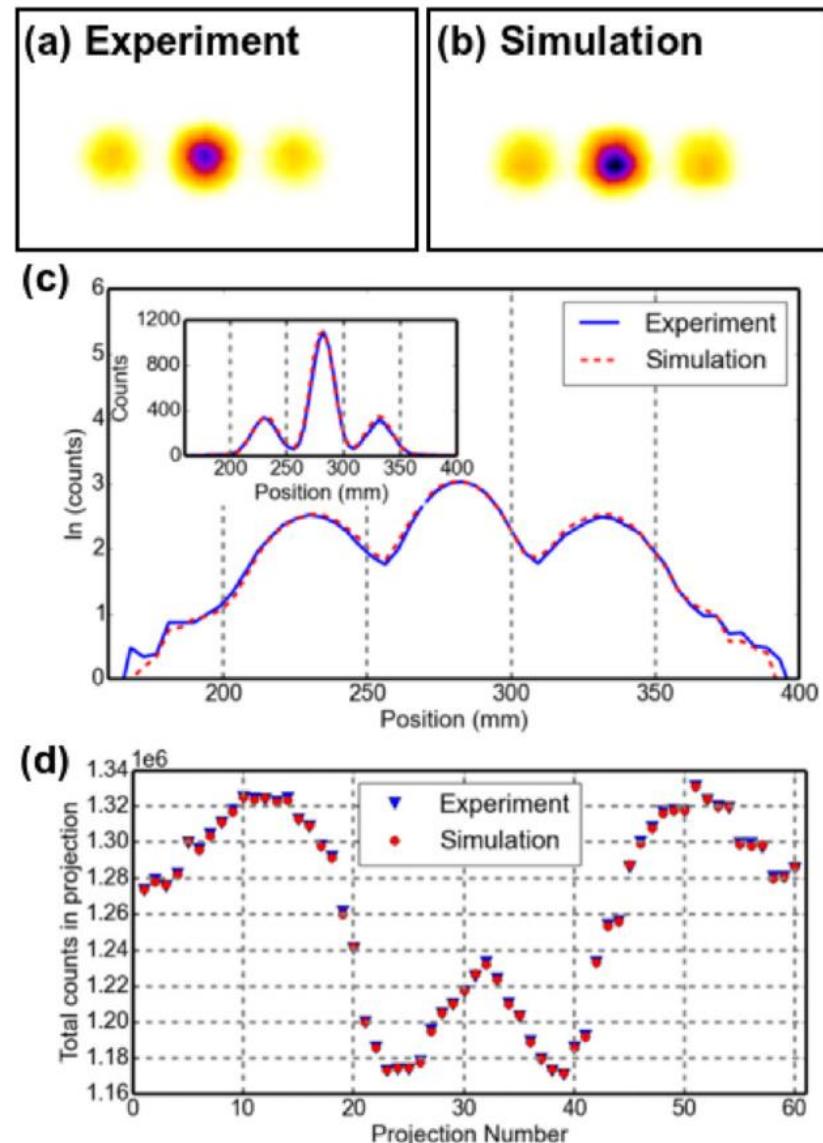
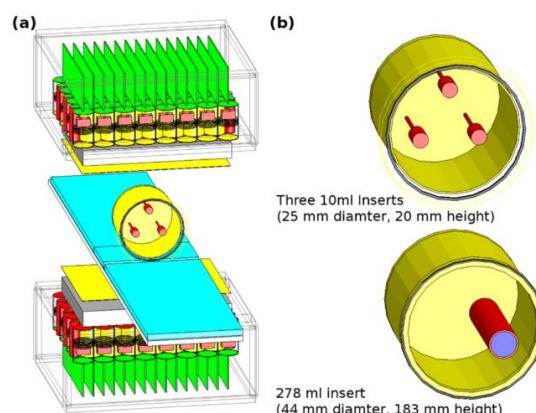
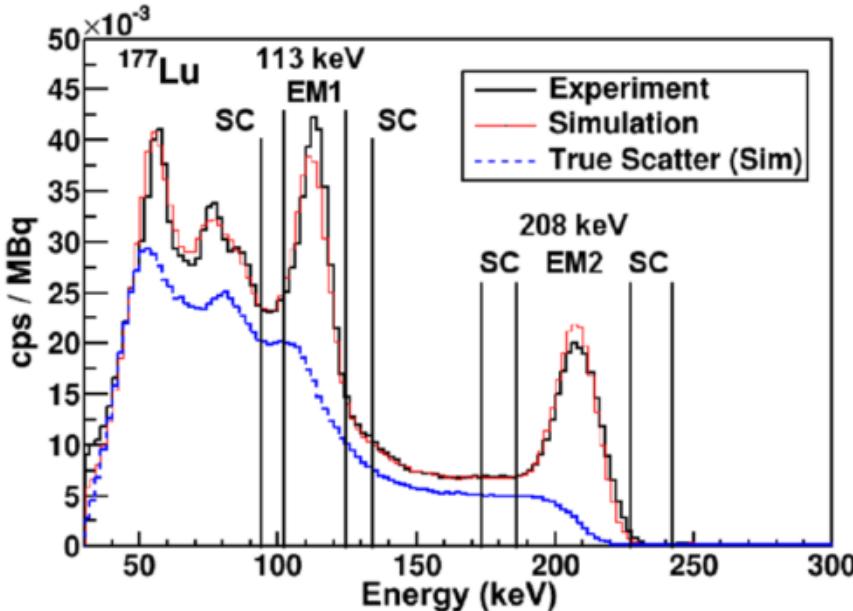
The influence of triple energy window scatter correction on activity quantification for ^{177}Lu molecular radiotherapy

Andrew P Robinson¹, Jill Tipping², David M Cullen¹
and David Hamilton²



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

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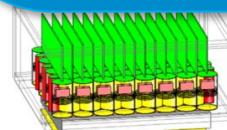
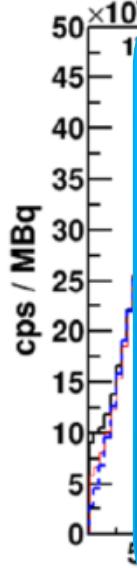
The influence of triple energy window scatter correction on activity quantification for ^{177}Lu molecular radiotherapy

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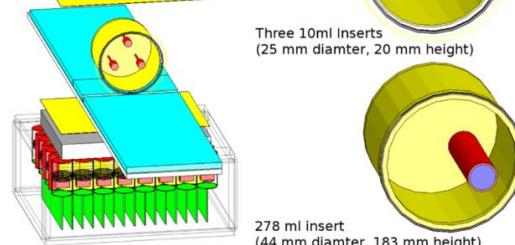
(a) Experiment

(b) Simulation

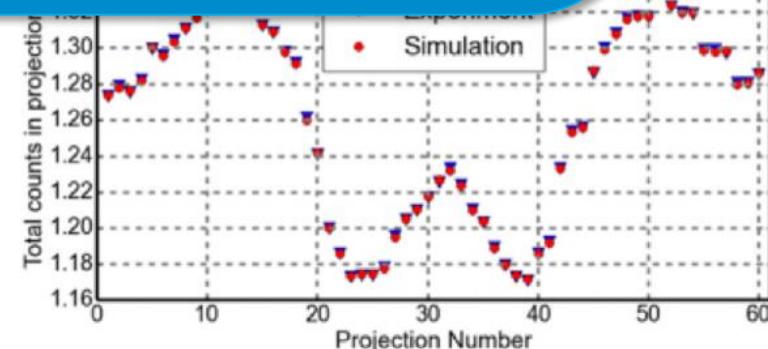
“Validates the global photon transport, geometry and material composition of the model for the full range of direct observables from a commercial SPECT camera.”



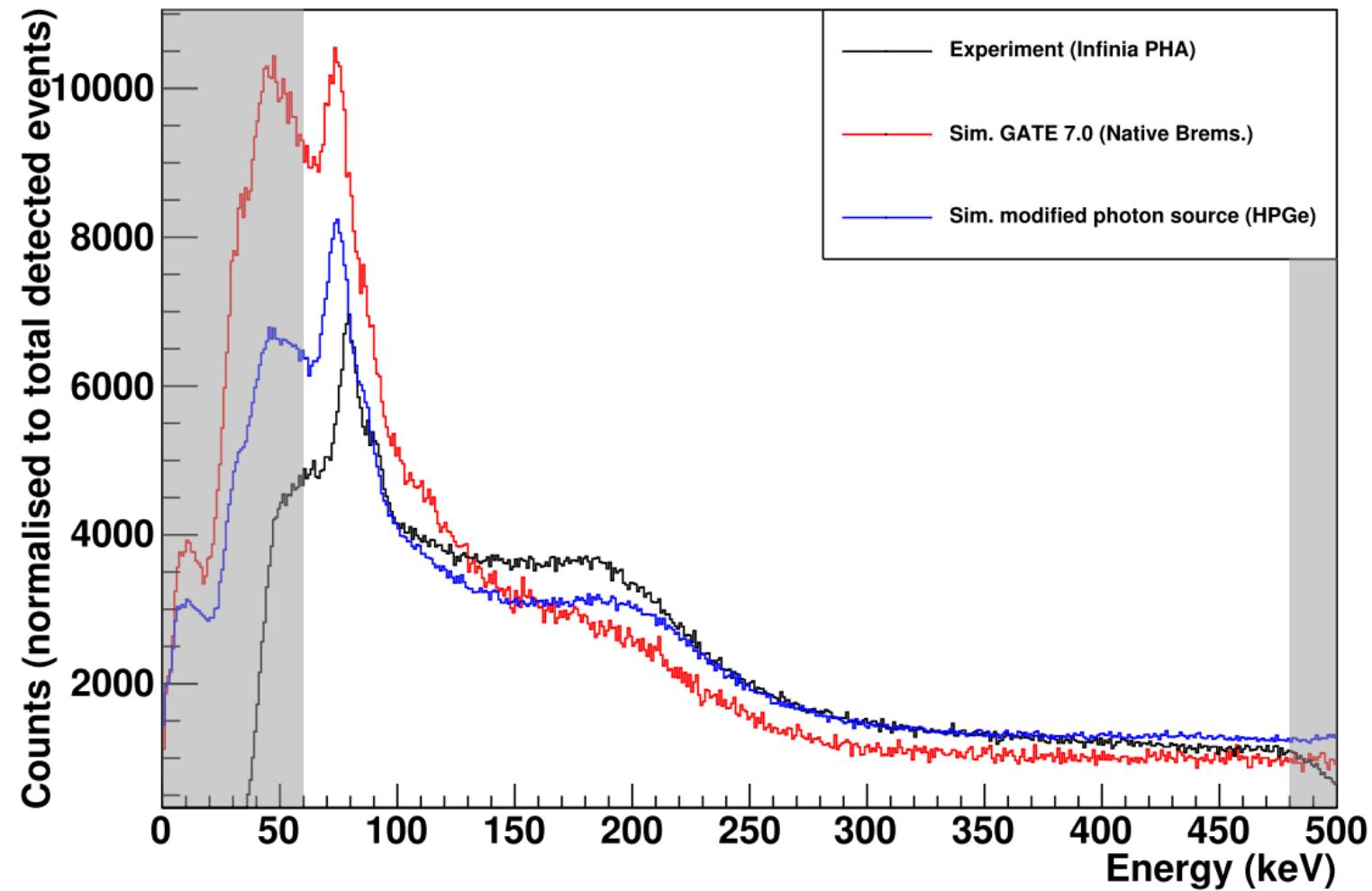
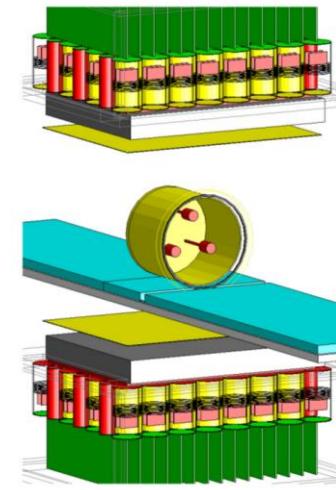
Three 10ml Inserts
(25 mm diameter, 20 mm height)



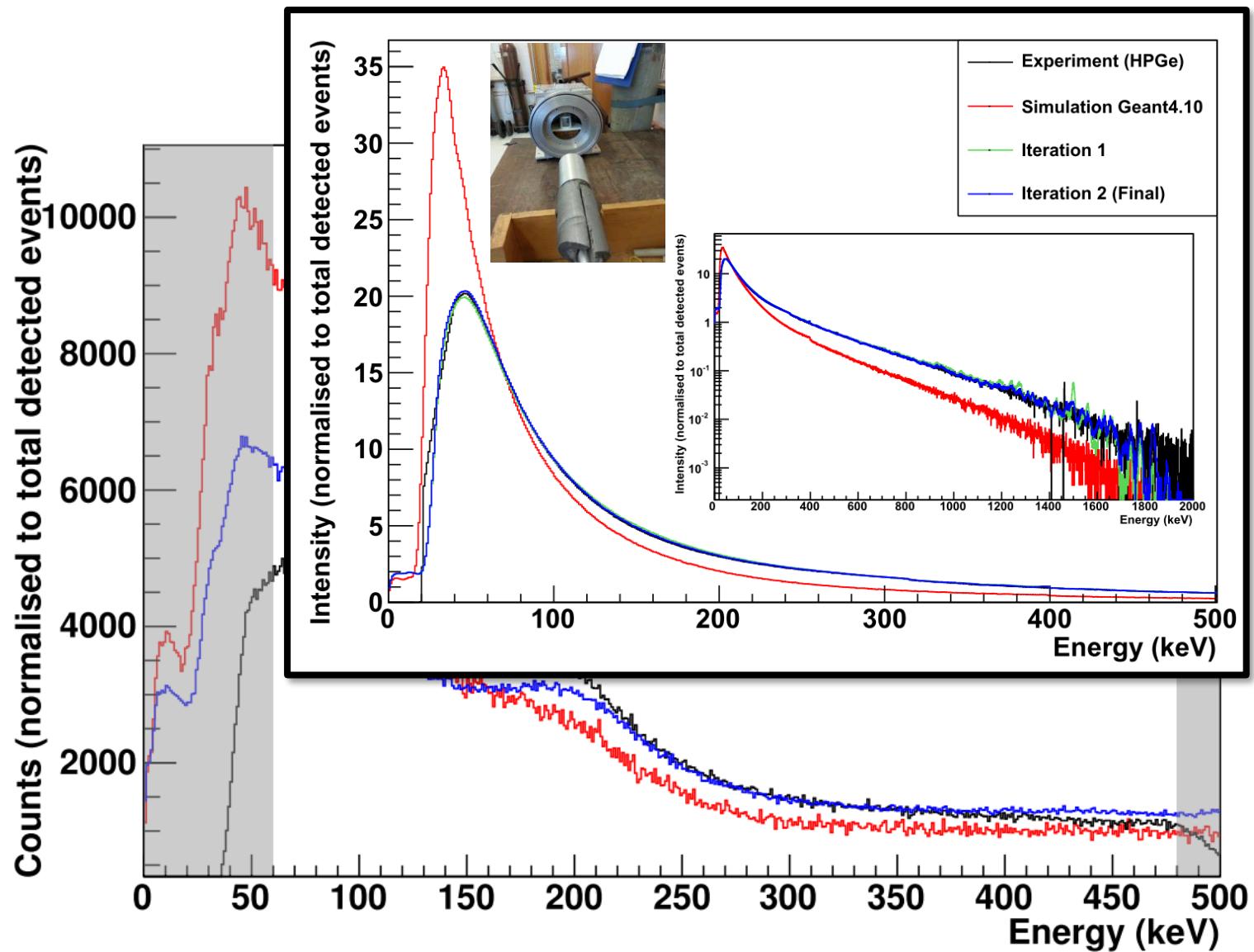
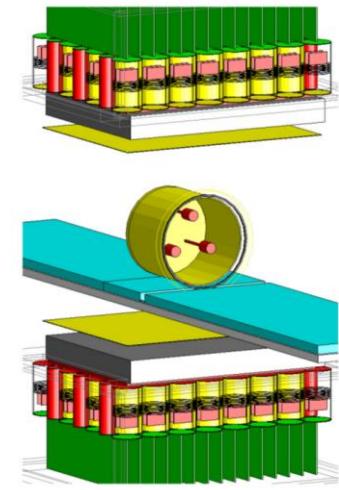
278 ml insert
(44 mm diameter, 183 mm height)



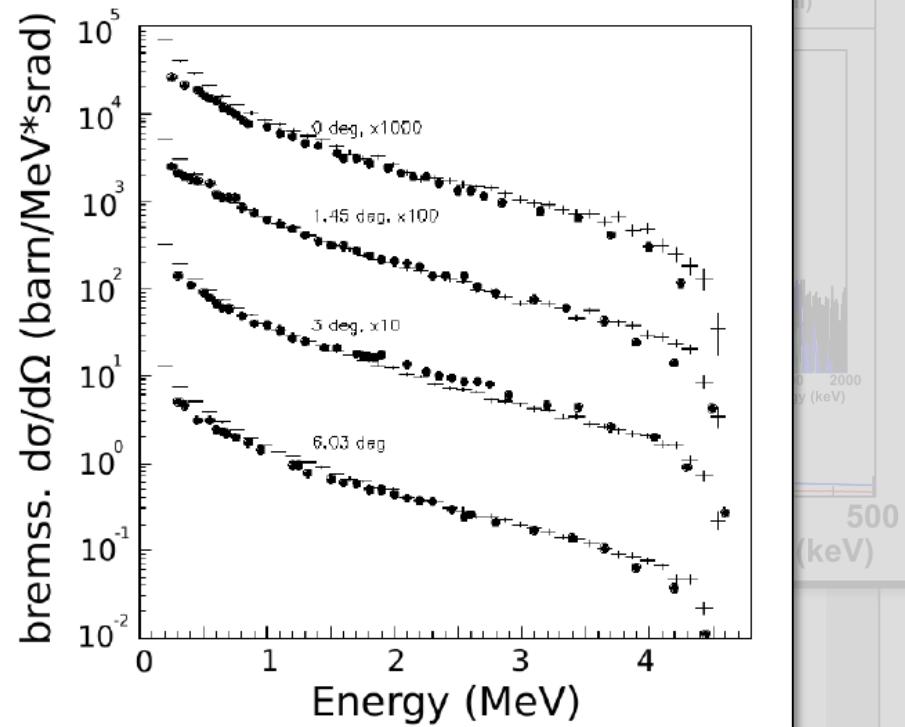
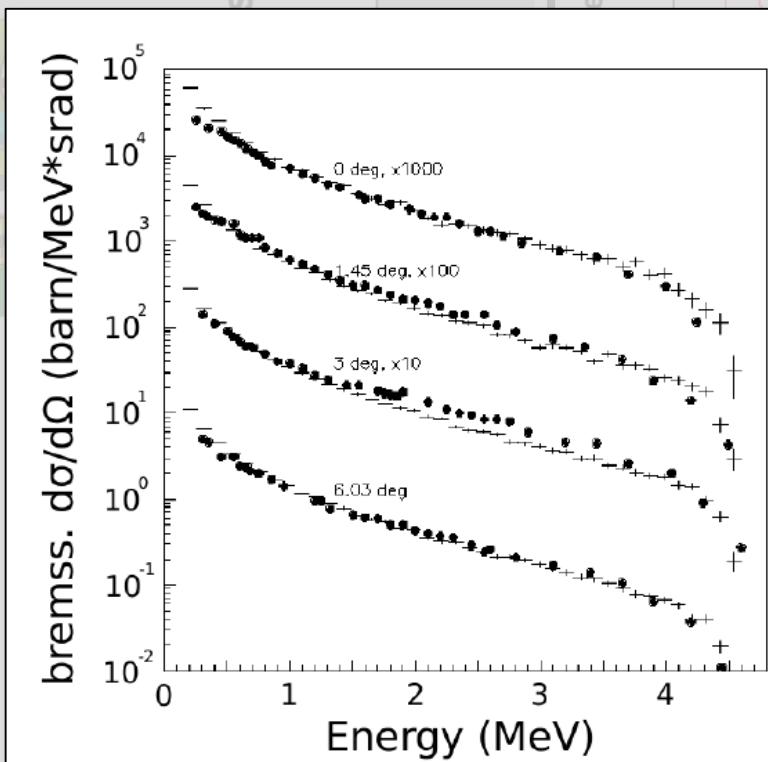
^{90}Y Bremsstrahlung Imaging



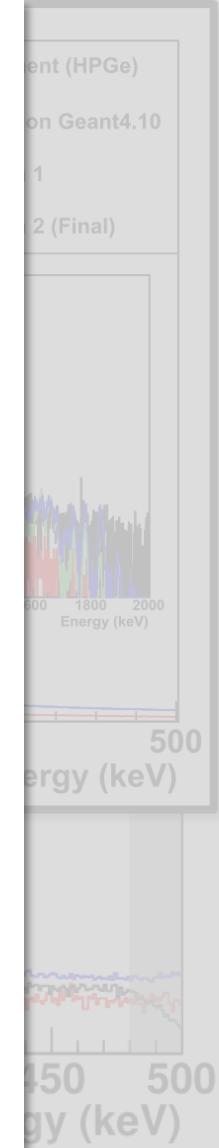
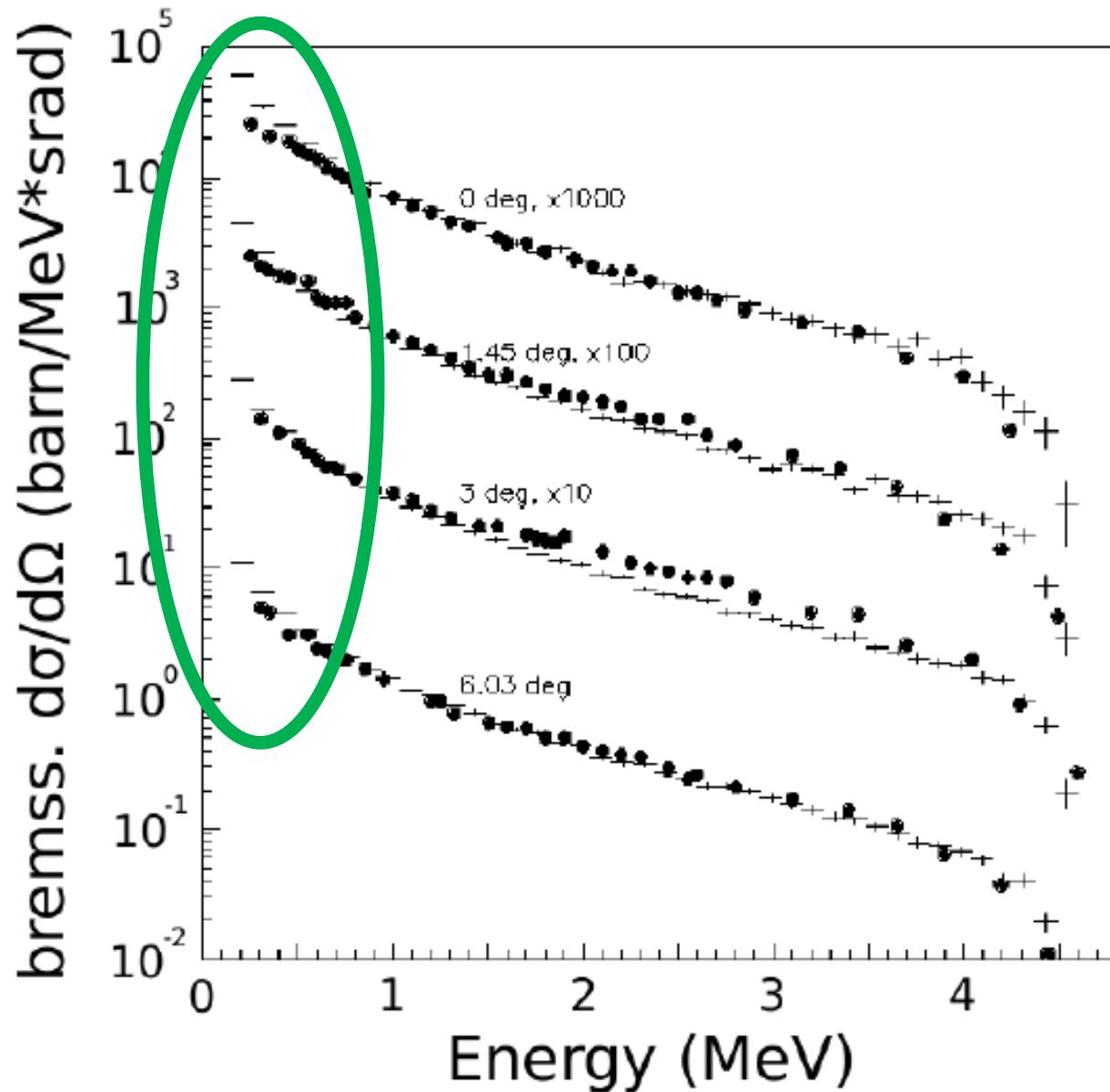
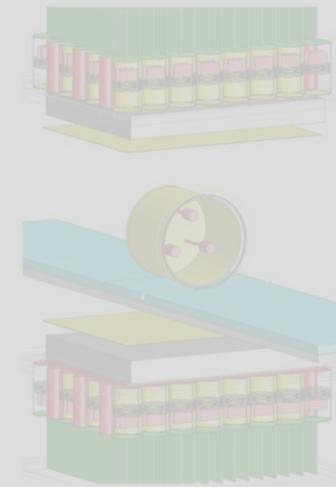
^{90}Y Bremsstrahlung Imaging



^{90}Y Bremsstrahlung Imaging



^{90}Y Bremsstrahlung Imaging





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 (LaBr₃/CeBr₃) 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)

⁹⁰Y Bremsstrahlung Imaging

- 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
- New 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



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.

14 research teams (18 institutes)

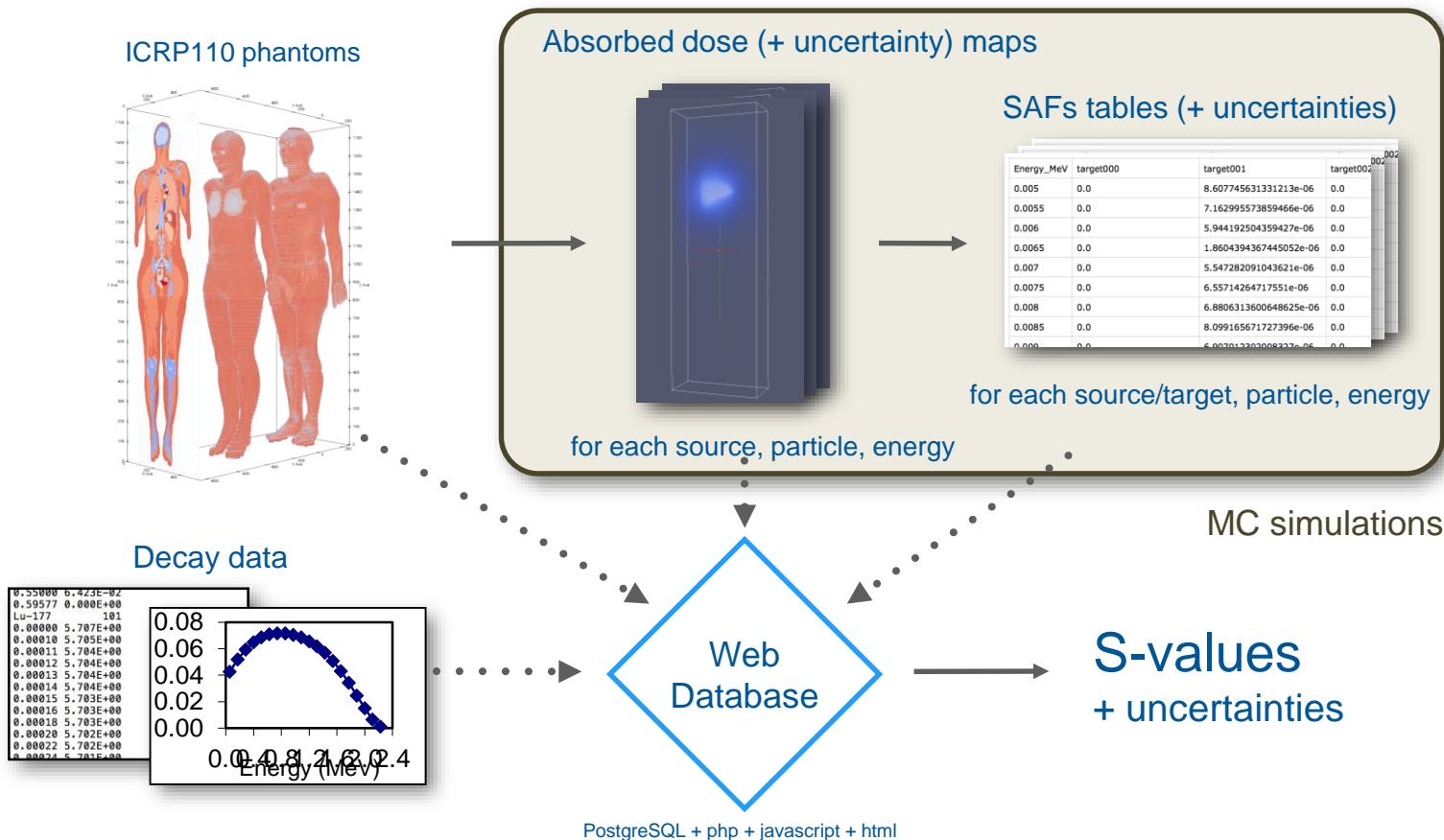


OpenDose: initial comparisons

- 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
 - $2 \text{ (sources)} \times 2 \text{ (e}^-/\text{g}) \times 7 \text{ (energies)} = 28 \text{ simulations / } \sim 1 \text{ week (1 core)}$
- But... $2 \text{ (female/male models)} \times 140 \text{ (sources)} \times 2 \text{ (e}^-/\text{p}) \times 91 \text{ (energies)} = 50960 !$



OpenDose: Framework



Validation of simulations

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Tools you can use

EGSnrc

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

The screenshot shows the official NRC website for the EGSnrc software. The header includes the Canadian flag, "Government of Canada / Gouvernement du Canada", and links for "Canada.ca | Services | Departments | Français". The main navigation bar features "Programs and services", "Areas of R&D", "Research facilities", "Publications", "Careers", and "About NRC". Below this, a breadcrumb trail shows the current page: "Home > Programs and services > Technical and advisory services > EGSnrc: software tool to model radiation transport". The main content area has a blue header "EGSnrc: software tool to model radiation transport". It includes a "Download EGSnrc from github" button. A sidebar on the left lists "Programs and services" such as "Research programs and collaboration opportunities", "Technical and advisory services" (with "EGSnrc: software tool to model radiation transport" highlighted), "Licensing opportunities", and "Industrial Research Assistance Program (IRAP)". The main text discusses the software's purpose in modeling radiation transport through matter, its applications in medical physics, and its use in various industries. It also mentions training for users and its widespread adoption. A section titled "Targeted audience" lists the intended users, and a "Description of the software" section provides a brief overview.

EGSnrc: software tool to model radiation transport

[Download EGSnrc from github](#)

Overview of the software

NRC's electron gamma shower (EGS) software toolkit can meet your specific requirements relating to modelling the passage of electrons and photons through matter. EGSnrc relies on Monte Carlo, which is the most accurate method to model the transport of radiation. The included BEAMnrc software component can meet your requirements relating to modelling beams travelling through consecutive material components, ranging from a simple slab to the full treatment head of a radiotherapy linear particle accelerator (linac).

EGSnrc is used to address a broad range of questions about the propagation of radiation in materials. It is particularly well-suited for medical physics purposes, such as the research and development of devices that allow medical professionals to detect radiation, image a patient's anatomy using x-rays, or deliver a prescribed radiation dose to a tumour while sparing healthy tissue. But given its flexible, modular design and companion utilities, EGSnrc can also be used for a vast range of applications, including the simulation of research and industrial linac beams, x-ray emitters, radiation shielding, and more.

NRC also trains Canadian and international physicists on use of the software.

NRC contributes to the development and application of the Monte Carlo method in the modelling of radiation transport since the early 1980s. The EGSnrc software is now downloaded more than 5,000 times per year by academic, medical and industrial researchers worldwide.

Targeted audience

- Medical physicists, universities and hospitals.
- Companies that develop radiotherapy equipment and software.
- Universities and industries working with radiation, including radiation measurement, radiotherapy, radiation protection, radiation processing, medical imaging, and other electron and photon radiation applications.

Description of the software

Tools you can use

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

The screenshot shows the homepage of the MCNP website. At the top left is the Los Alamos National Laboratory logo. A banner across the top center reads "A General Monte Carlo N-Particle (MCNP) Transport Code". The main content area features a title "Monte Carlo Code Group" and "Los Alamos National Laboratory". To the left is a sidebar with links for MCNP5, MCNP6, MCNP FAQ, MCNP Bugs, Upcoming Classes, Related Efforts, Monte Carlo Team Personnel, User Manual, Reference Collection, Forum For Users, and How to get MCNP. Below this is a "CONTACTS" section with links for MCNP Team and MCNP Web Admin. A circular "ENTRUST" seal is also present. A "MCNP Highlights" box contains news items about the MCNP6.2 release, updates to the Reference Collection, the MCNP6.1.1 update, and the MCNP6.1 production release. The footer at the bottom states: "MCNP® and Monte Carlo N-Particle® are registered trademarks owned by Los Alamos National Security, LLC, manager and operator of Los Alamos National Laboratory. Any third party use of such registered marks should be properly attributed to Los Alamos National Security, LLC, including the use of the ® designation as appropriate. Any questions regarding licensing, proper use, and/or proper attribution of Los Alamos National Security, LLC marks

Tools you can use

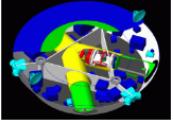
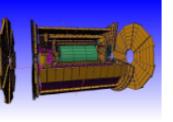
Geant4 (<http://geant4.web.cern.ch/geant4/>)

Geant 4

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Applications **User Support** **Publications** **Collaboration**

A sampling of applications, technology transfer and other uses of Geant4

Getting started, guides and information for users and developers

Validation of Geant4, results from experiments and publications

Who we are: collaborating institutions, members, organization and legal information

News

- 8 March 2017 - 2017 planned developments.
- 28 February 2017 - Patch-01 to release 10.3 is available from the [Download](#) area.
- 27 January 2017 - Patch-03 to release 10.2 is available from the [source archive](#) area.
- 17 February 2016 - Patch-03 to release 10.1 is available from the [source archive](#) area.

Events

- [45th Geant4 Technical Forum](#), CERN, Geneva (Switzerland), 23 March 2017.
- [12th Geant4 Space Users Workshop](#), Guildford (UK), 10-12 April 2017.
- Geant4 Course at the 14th Seminar on Software for Nuclear, Sub-nuclear and Applied Physics, Porto Conte, Alghero (Italy), 4-9 June 2017.
- Geant4 Tutorial and International Multidisciplinary User Workshop, Ton Duc Thang University, Ho Chi Minh City (Vietnam), 15-16 June 2017.
- Geant4 User Workshop, Sage Hotel, Wollongong (Australia), 19-22 September 2017.
- [22nd Geant4 Collaboration Meeting](#), UOW Campus, Wollongong (Australia), 25-29 September 2017.
- [Past events](#)

[Applications](#) | [User Support](#) | [Results & Publications](#) | [Collaboration](#) | [Site Map](#)

[Contact Webmaster](#)

Last updated: 08 Mar 2017

Tools you can use

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

The screenshot shows the GATE website homepage. At the top left is the GATE logo with a blue and green circular icon. The main title "GATE" is in large blue letters, followed by the subtitle "Simulations of Preclinical and Clinical Scans in Emission Tomography, Transmission Tomography and Radiation Therapy". A navigation bar at the top includes links for Home, Download, Documentation, Collaborative Wiki, Mailing-list, Training, Publications, Meetings, Opportunities, Awards, and About GATE.

User login: A form with fields for Username and Password, and buttons for Create new account, Request new password, and Log in.

PMB Citations Prize: A section about the journal Physics in Medicine & Biology awarding the GATE team twice for their work. It includes a thumbnail of the journal cover and a link to the PMB citations prize.

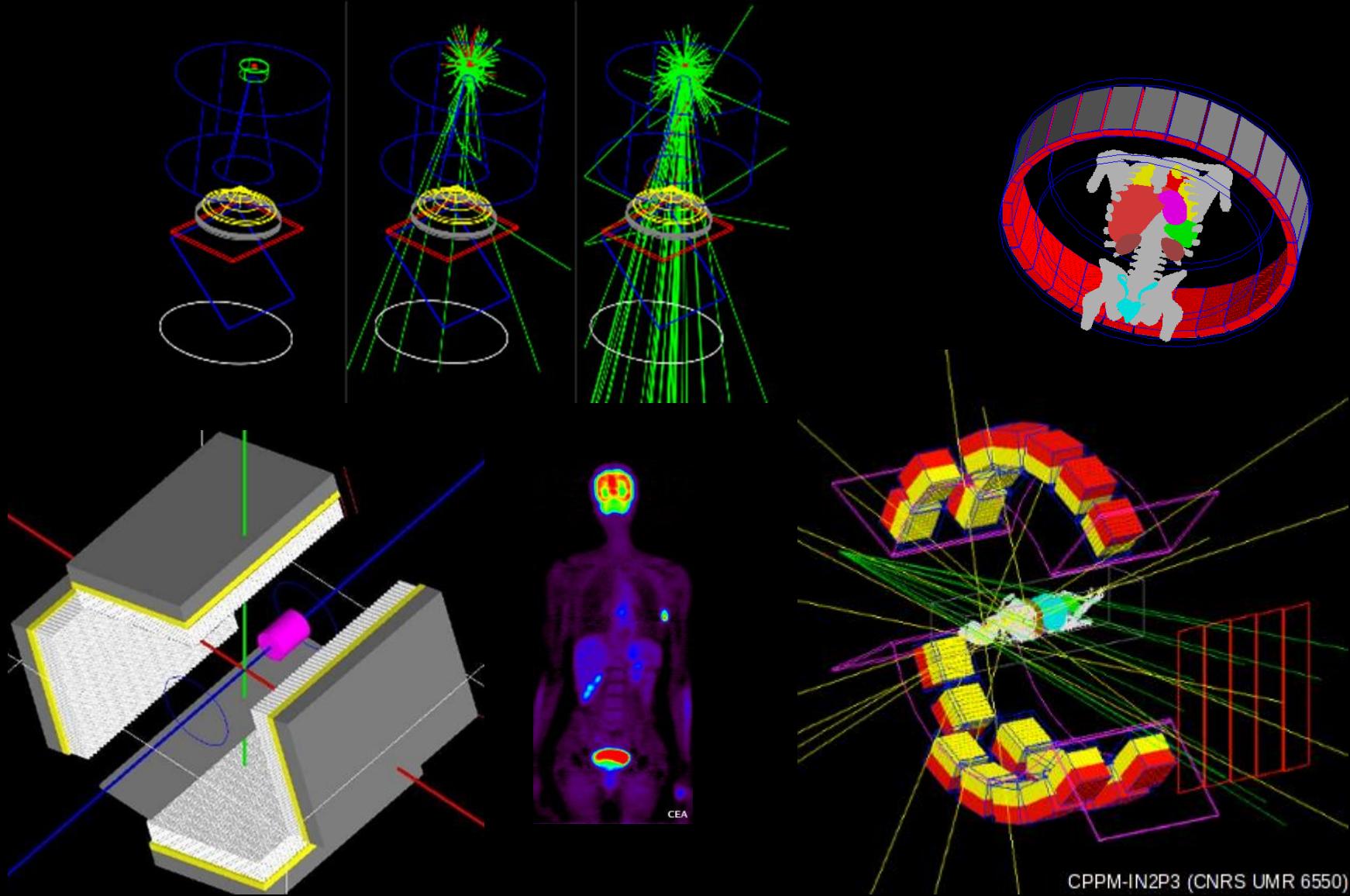
Forewords: A section explaining GATE's purpose and how to contribute. It lists steps for contributing to the mailing list, documentation, bugs, source code, and GitHub. It also encourages joining the collaboration.

Shortcuts: A sidebar with icons and links for subscribing to the mailing list, requesting an account on the collaborative wiki, accessing the GitHub project, taking a SurveyMonkey survey, and downloading GATE.

GATE: sample results: A preview image showing a 3D simulation of a medical scan, likely a PET or SPECT reconstruction.

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
-
- ✗ Still requires validation
 - ✗ Develop data analysis tools
 - ✗ 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)
libby.osborn@manchester.ac.uk

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 validation – 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 - if the simulation has been validated
 - ✓ Geometry
 - ✓ Detector modelling
 - ✓ Physics models (dependent on energy range)

Comparison with experimental data

