Monte Carlo Simulation
Optimisation in Imaging - HSST

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March 2022

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

What is Monte Carlo simulation?

What is Monte Carlo simulation?

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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?

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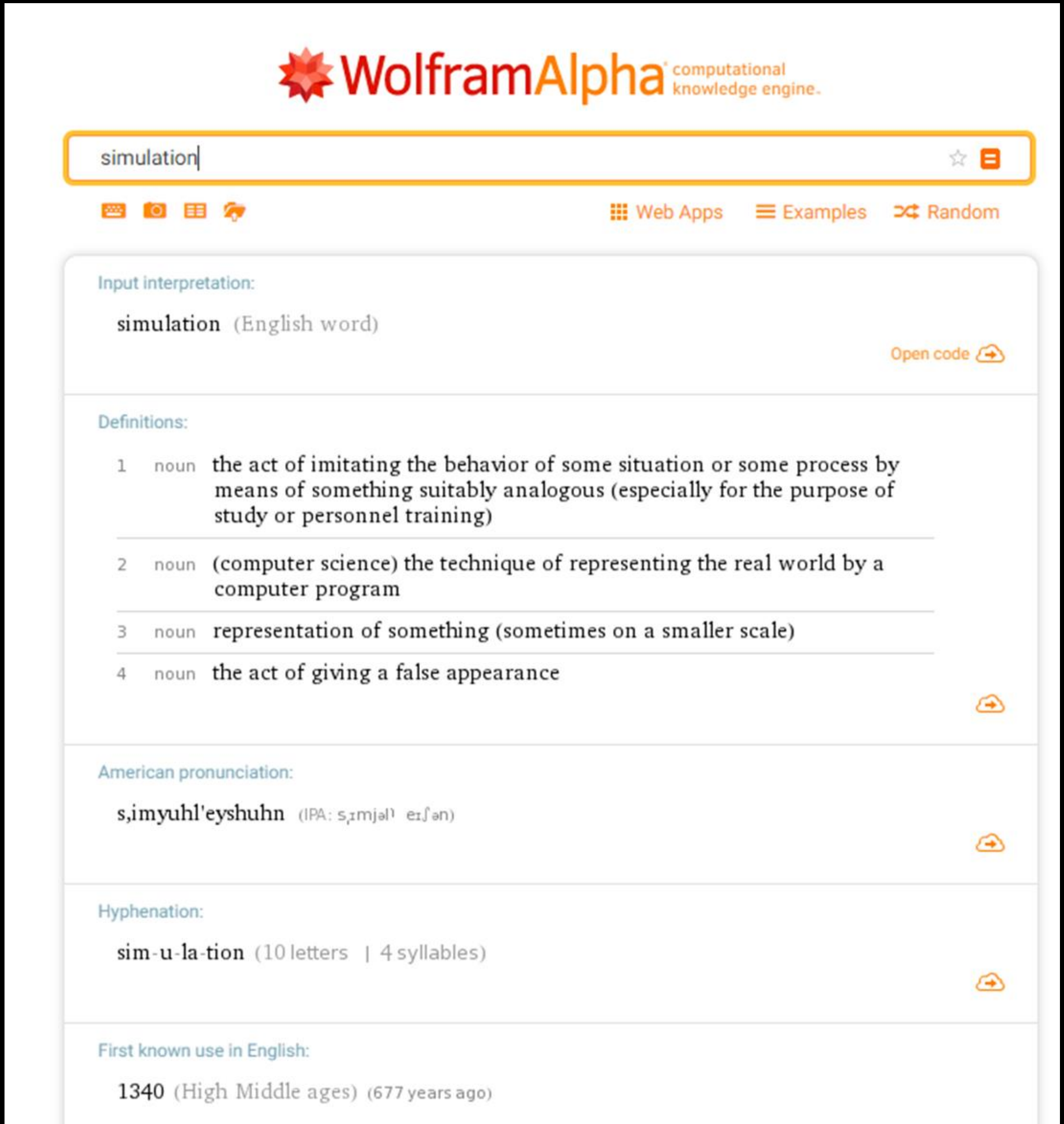

What is Monte Carlo simulation?

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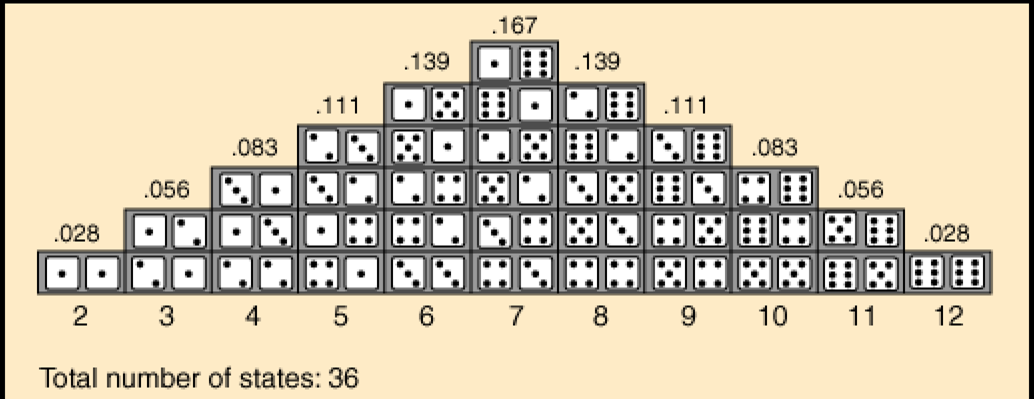
"A method which solves a problem by generating suitable random numbers and observing that fraction of the numbers obeying some property or properties. The method is useful for obtaining numerical solutions to problems which are **too complicated to solve analytically."**

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

Simple Example



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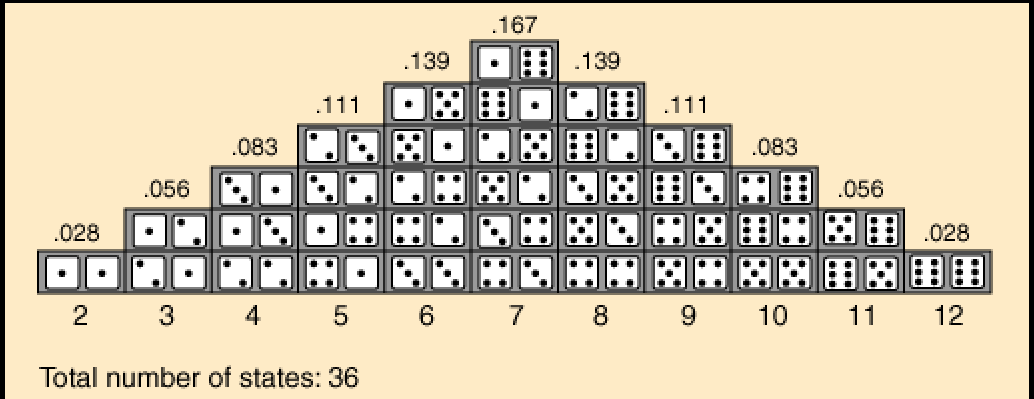

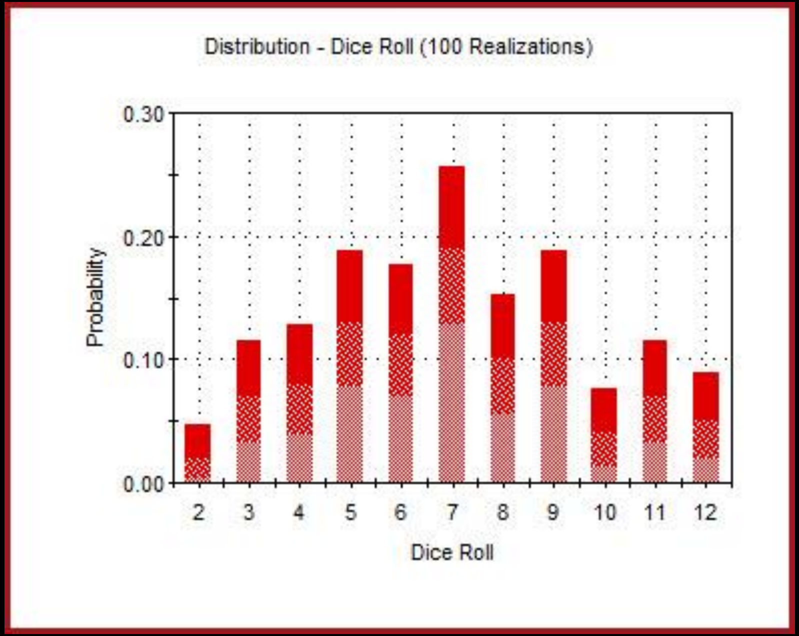

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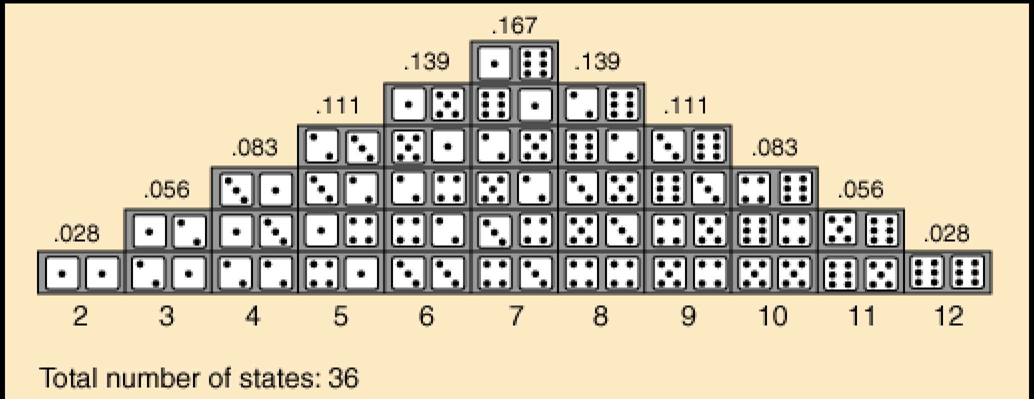
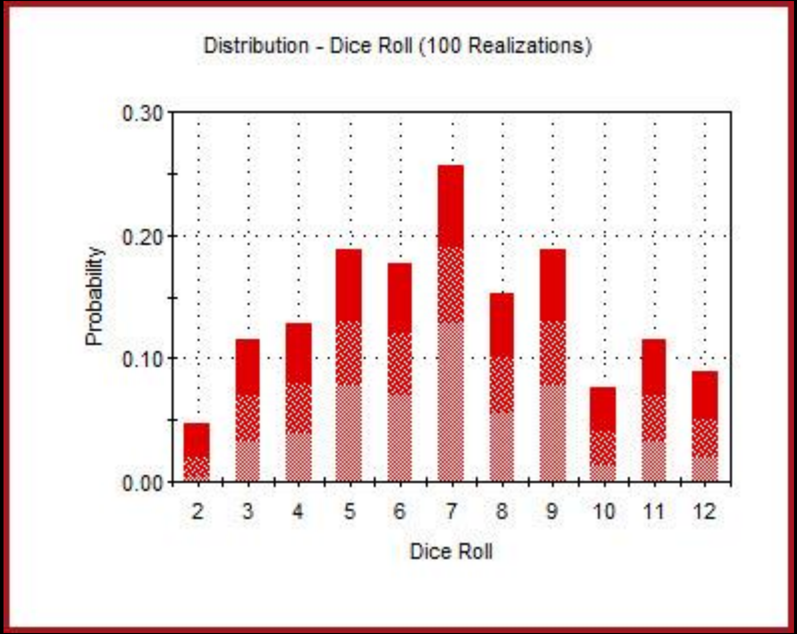
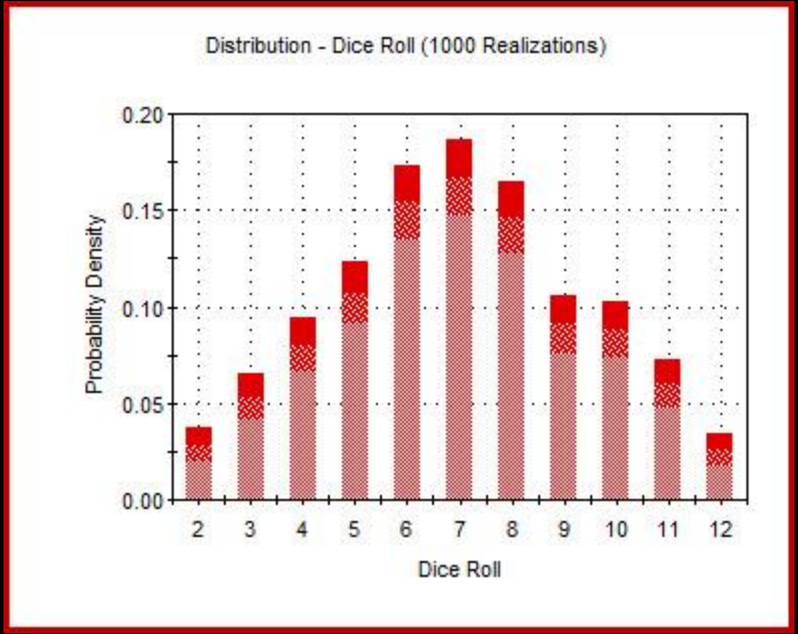
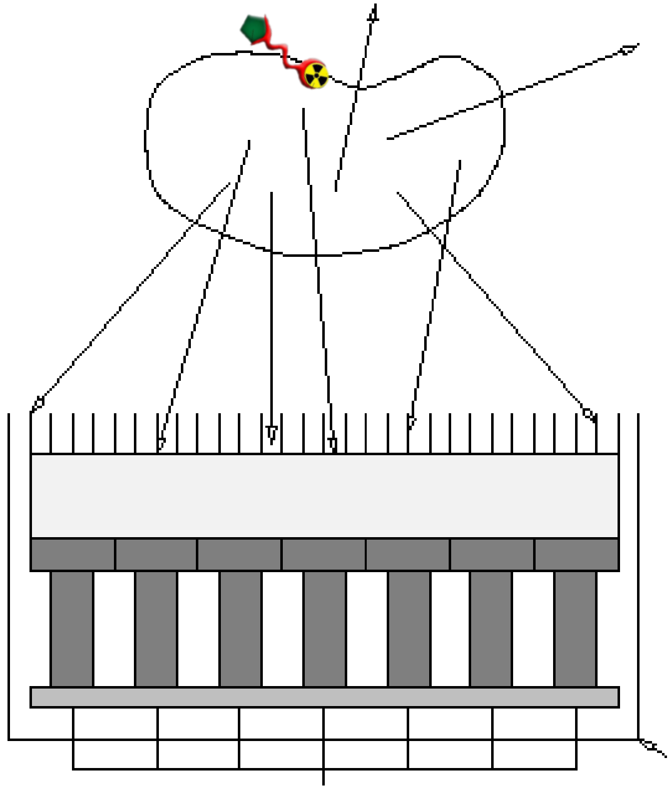






Physics and Probability



Physics and Probability

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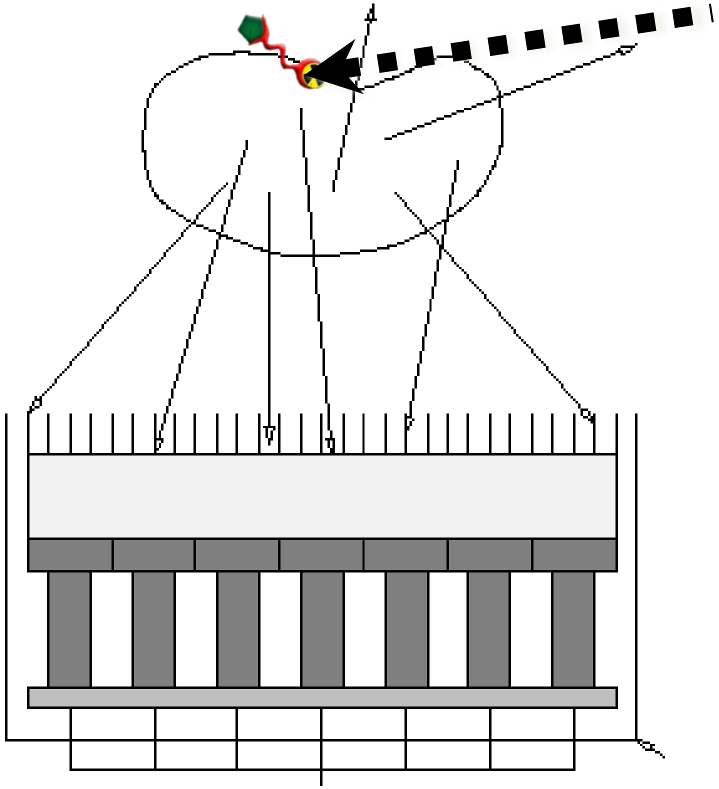
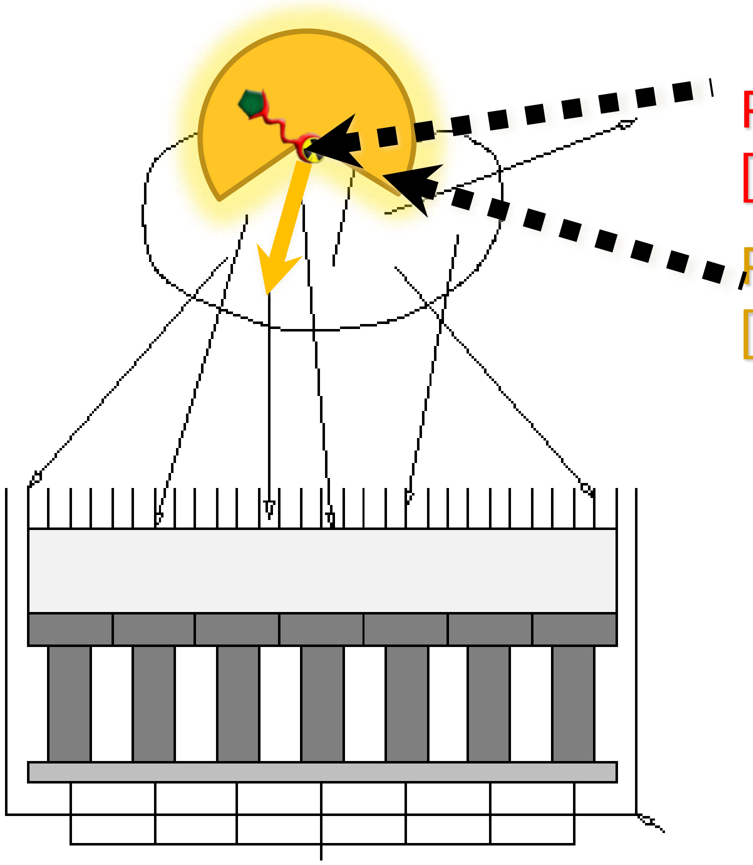


P1 = Probability of decay
[half-life]

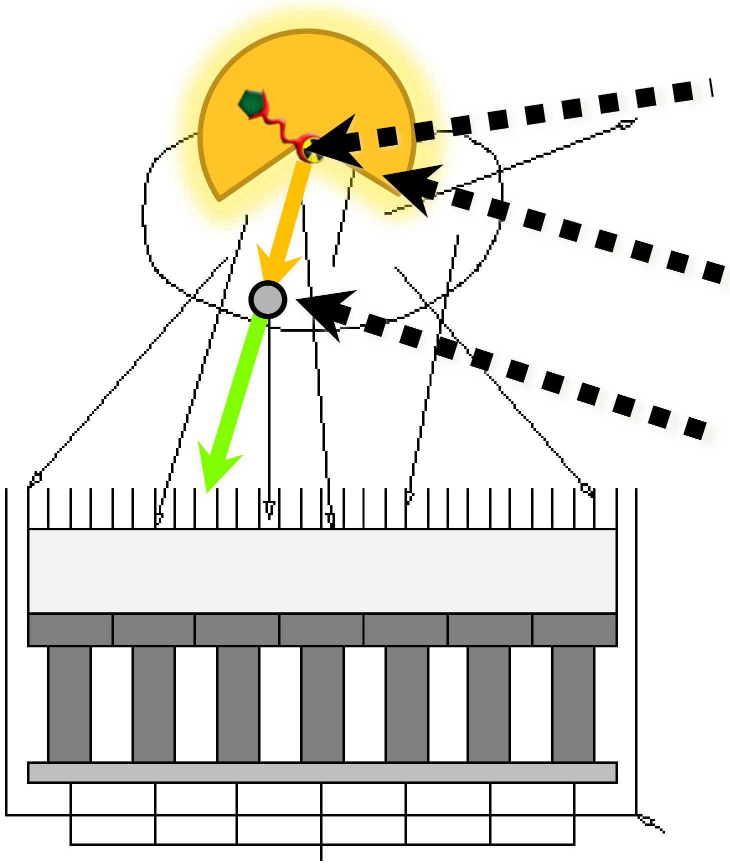
Physics and Probability



P1 = Probability of decay
[half-life]

P2 = Probability of emission direction
[isotropic]

Physics and Probability

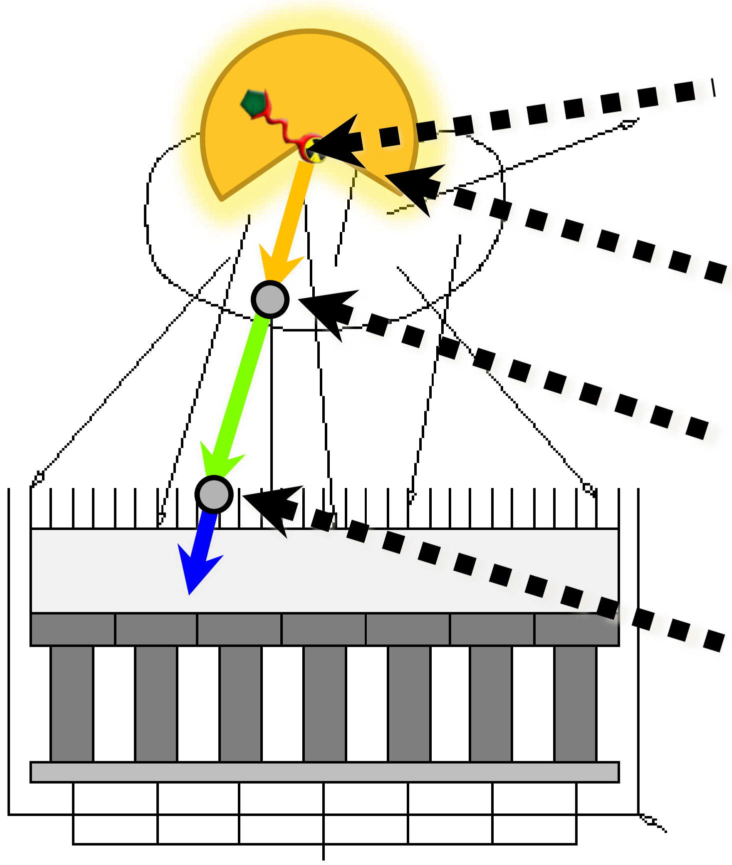


P1 = Probability of decay [half-life]

P2 = Probability of emission direction [isotropic]

P3 = Probability of interaction in body [cross-section, material]

Physics and Probability



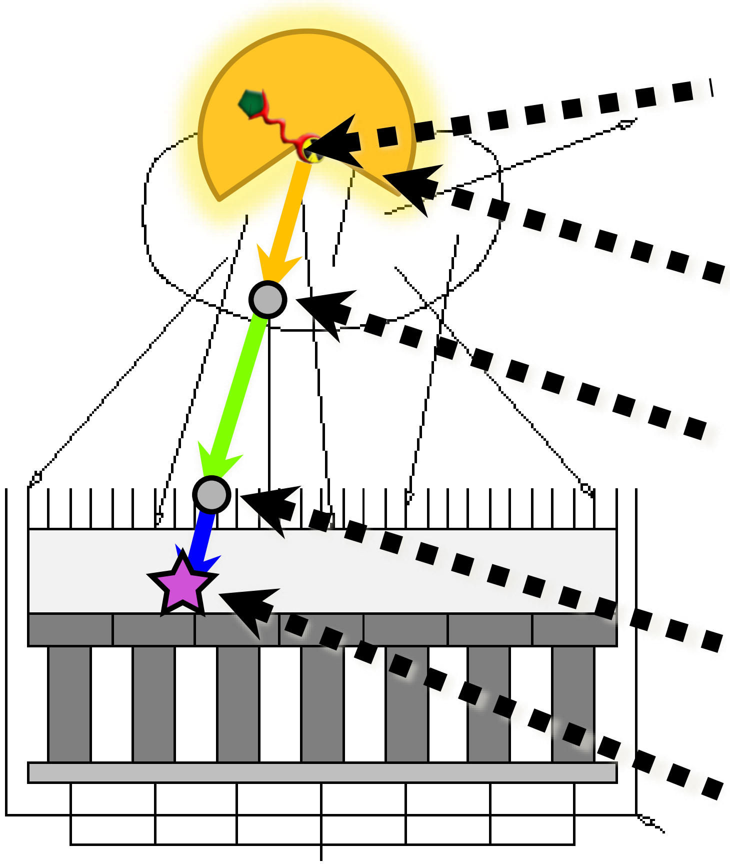
P1 = Probability of decay [half-life]

P2 = Probability of emission direction [isotropic]

P3 = Probability of interaction in body [cross-section, material]

P4 = Probability of interaction with collimator [cross-section, material]

Physics and Probability



P1 = Probability of decay
[half-life]

P2 = Probability of emission direction
[isotropic]

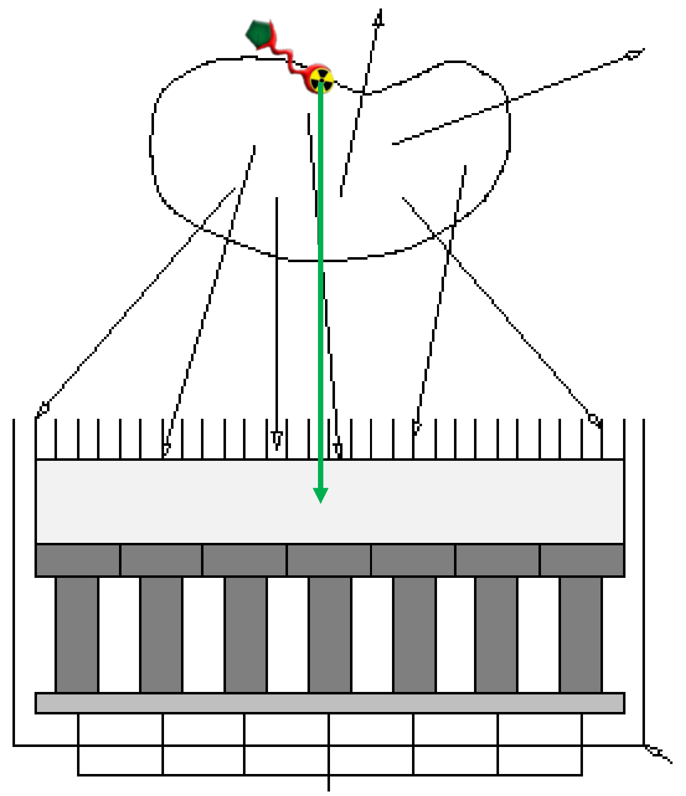
P3 = Probability of interaction in body
[cross-section, material]

P4 = Probability of interaction with collimator
[cross-section, material]

P5 = Probability of absorption in crystal
[cross-section]

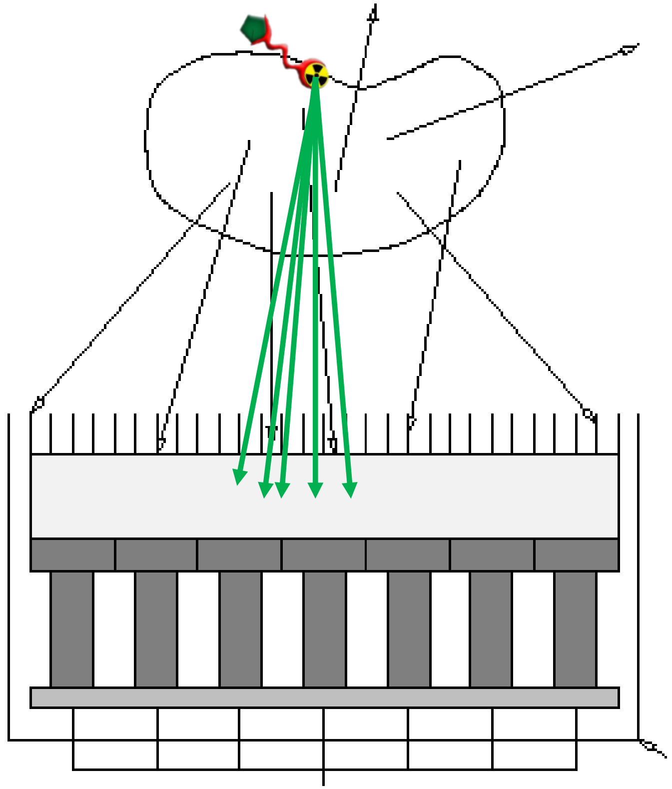
$$p(E\gamma) = p1 * p2 * p3 * p4 * p5$$

Physics and Probability



$p(E\gamma) = p1 * p2 * p3 * p4 * p5$

Physics and Probability



$p(E\gamma) = p1 * p2 * p3 * p4 * p5$

Physics and Probability

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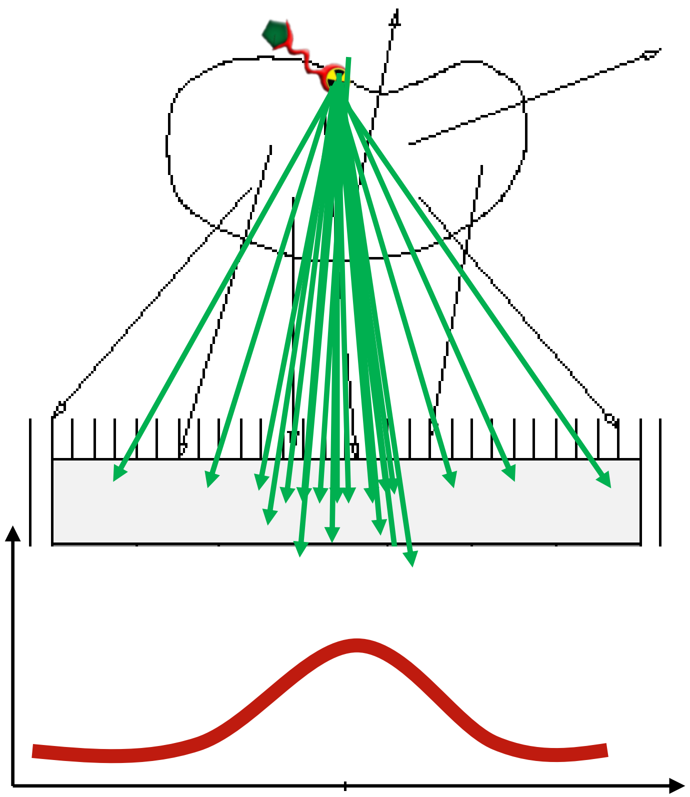

$p(E\gamma) = p1 * p2 * p3 * p4 * p5$

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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”

Infinitely repeatable

No radiation dose (patient or operator)

Optimise imaging protocols

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

Optimisation of imaging windows using Monte Carlo Simulation

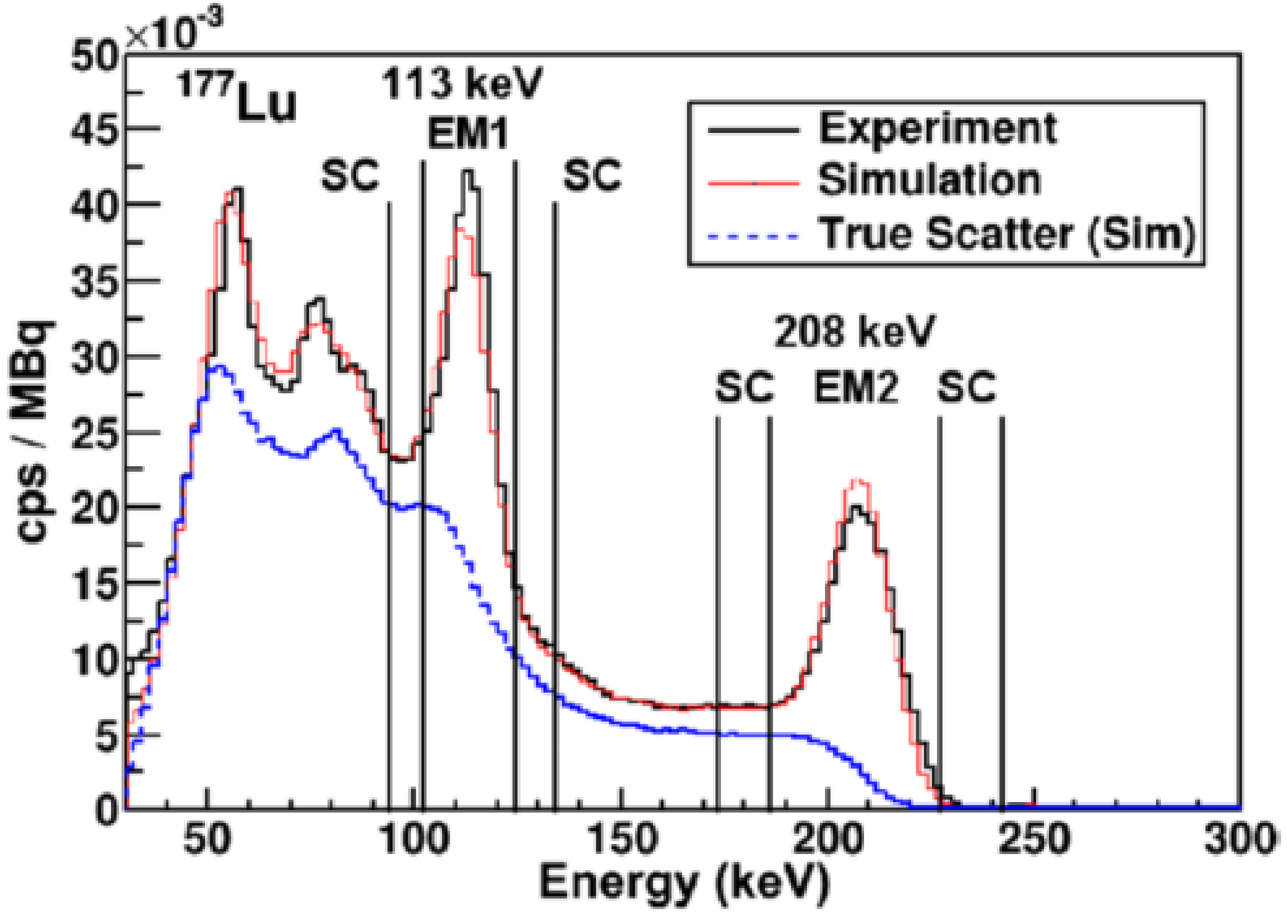


Figure 5. Emission spectrum for a water filled phantom measured

Optimisation of imaging windows using Monte Carlo Simulation

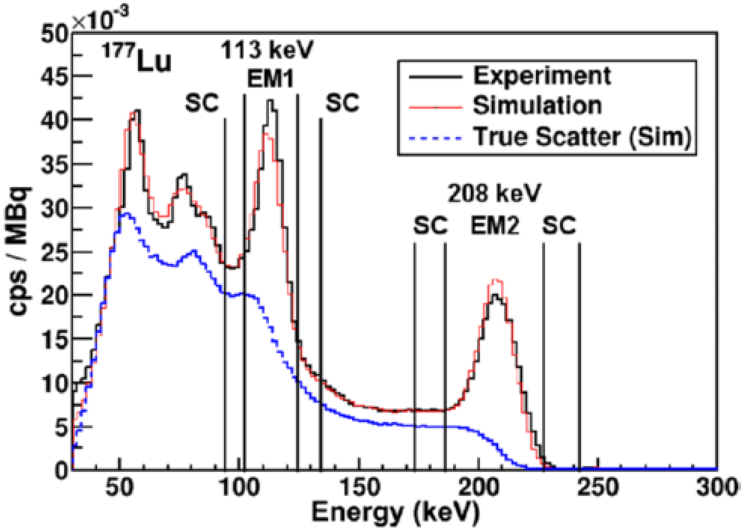
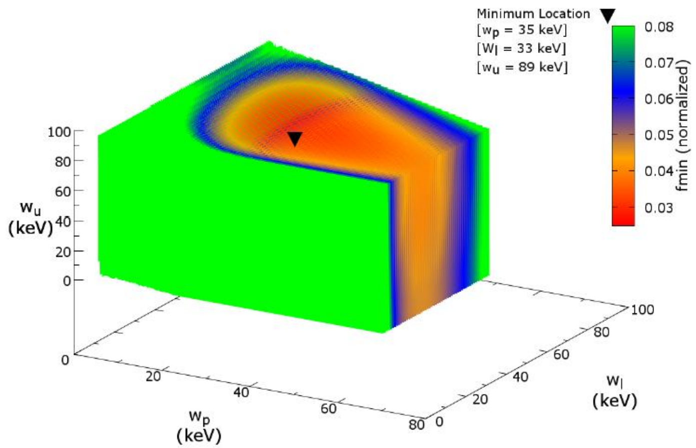


Figure 5. Emission spectrum for a water filled phantom measured



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

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

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

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

Sensitive range Camera.

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

Over-lapping windows.

Tb_{65} (Theranostic Isotope Quartet)

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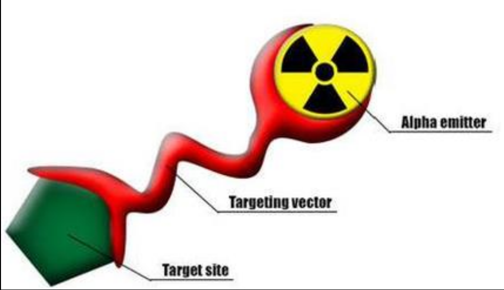
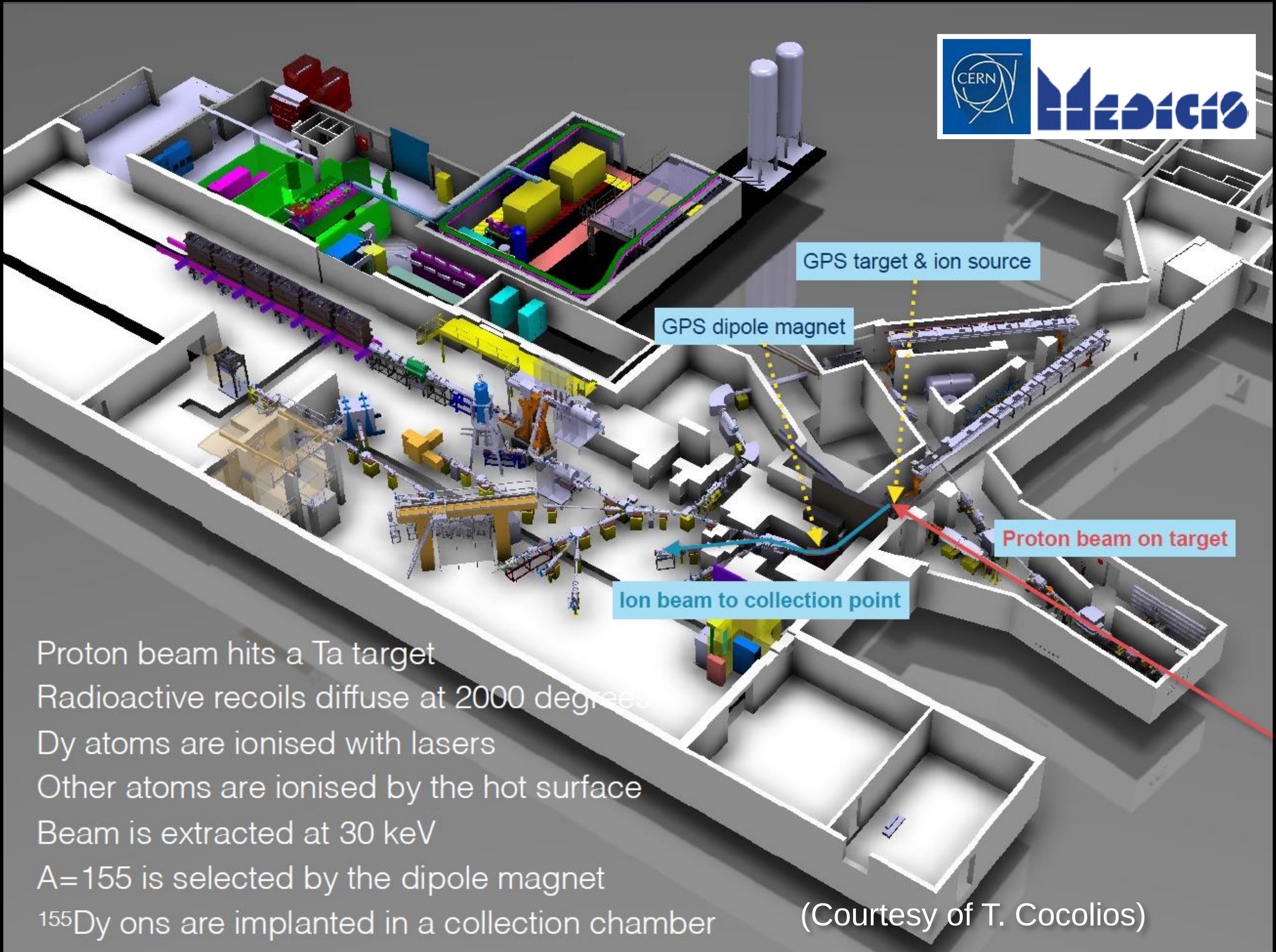


Z	151Tm	152Tm	153Tm	154Tm	155Tm	156Tm	157Tm	158Tm	159Tm	160Tm	161Tm	162Tm	163Tm	164Tm	165Tm	166Tm	167Tm
	150Er	151Er	152Er	153Er	154Er	155Er	156Er	157Er	158Er	159Er	160Er	161Er	162Er	163Er	164Er	165Er	166Er
67	149Ho	150Ho	151Ho	152Ho	153Ho	154Ho	155Ho	156Ho	157Ho	158Ho	159Ho	160Ho	161Ho	162Ho	163Ho	164Ho	165Ho
	148Dy	149Dy	150Dy	151Dy	152Dy	153Dy	154Dy	155Dy	156Dy	157Dy	158Dy	159Dy	160Dy	161Dy	162Dy	163Dy	164Dy
65	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
63	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
61	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
^{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-)



(Courtesy of T. Cocolios)

Medical physics questions for ^{155}Tb

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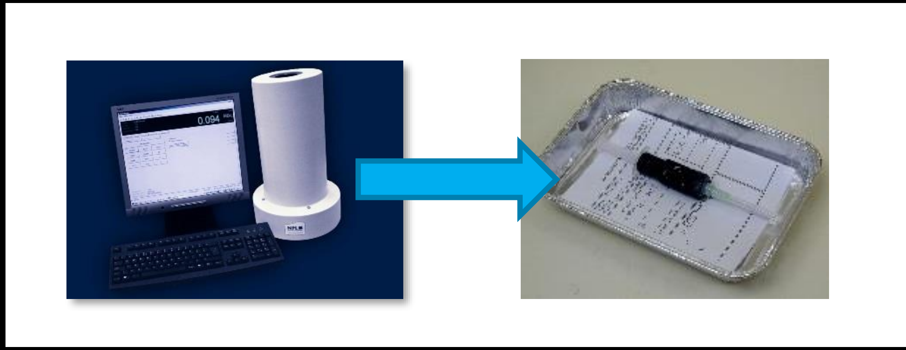
How to image it?

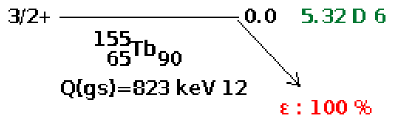
- Which gamma-rays to look at?
- What energy gate to set?
- Which collimators to use?

How to measure activity?

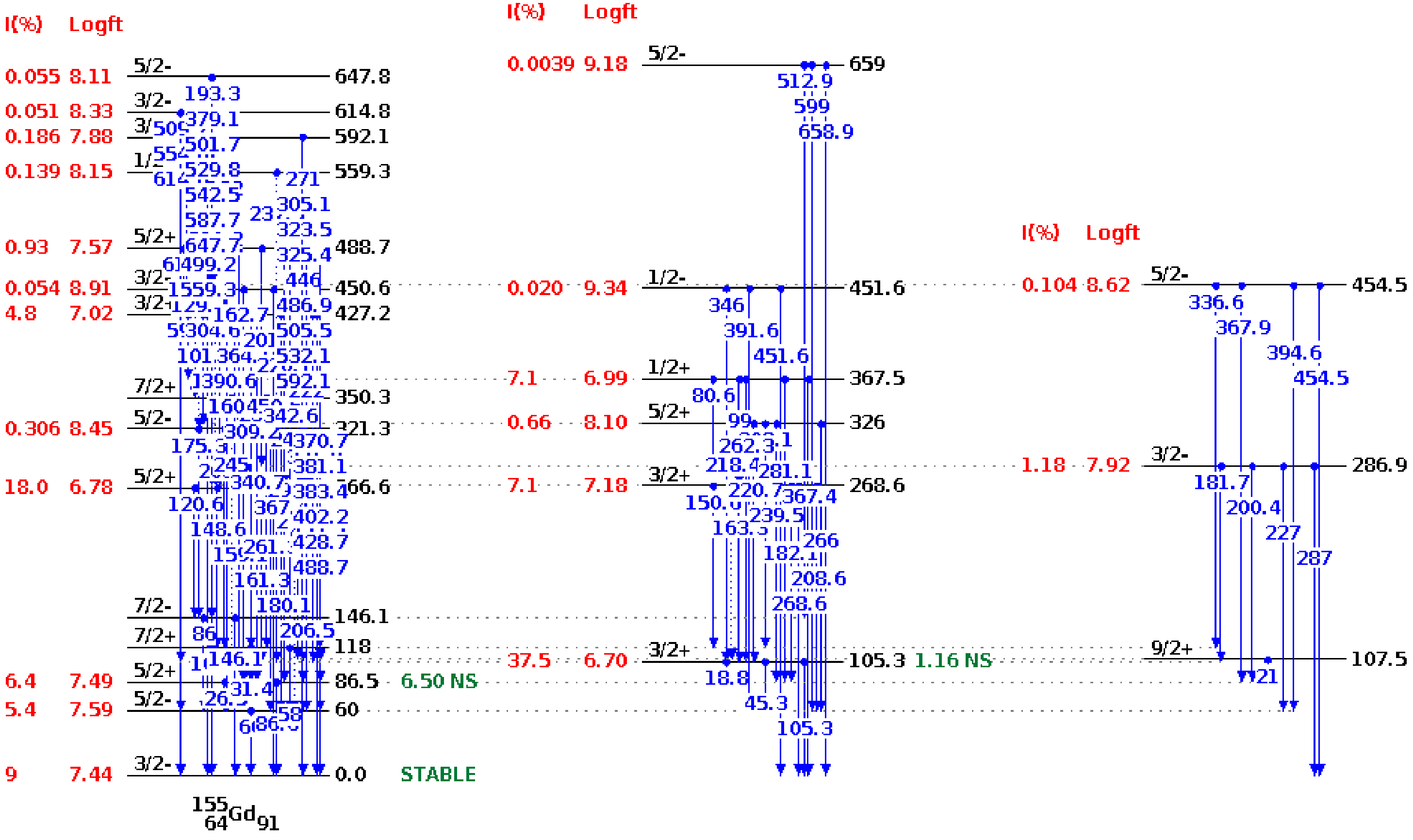
- Is there a primary standard?
- What dial factors to use on a hospital calibrator?



^{155}Tb (SPECT Imaging)



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}Tb (SPECT Imaging)

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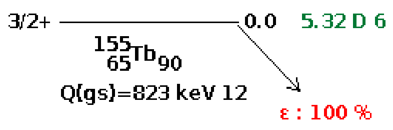

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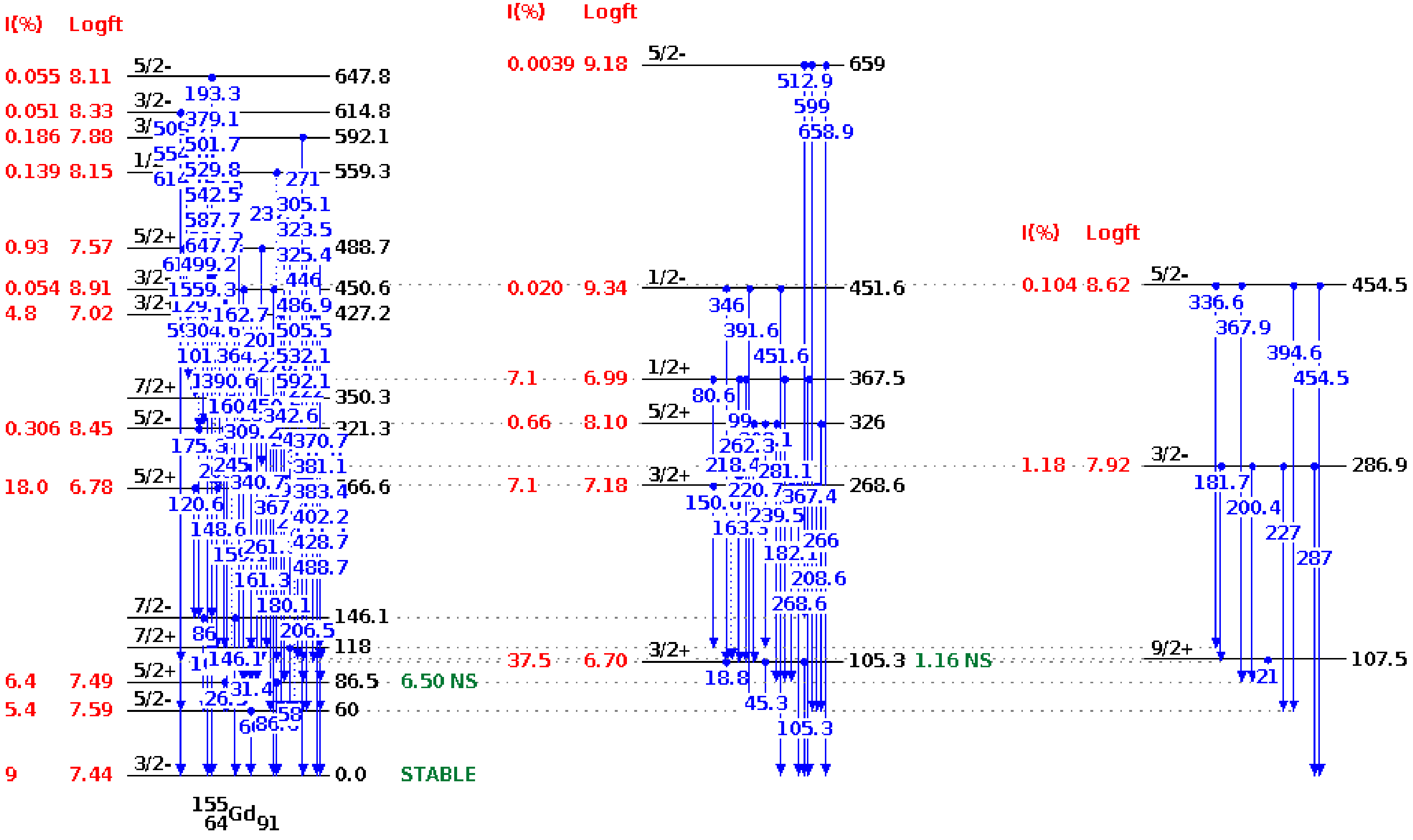

Tb-155 SPECT

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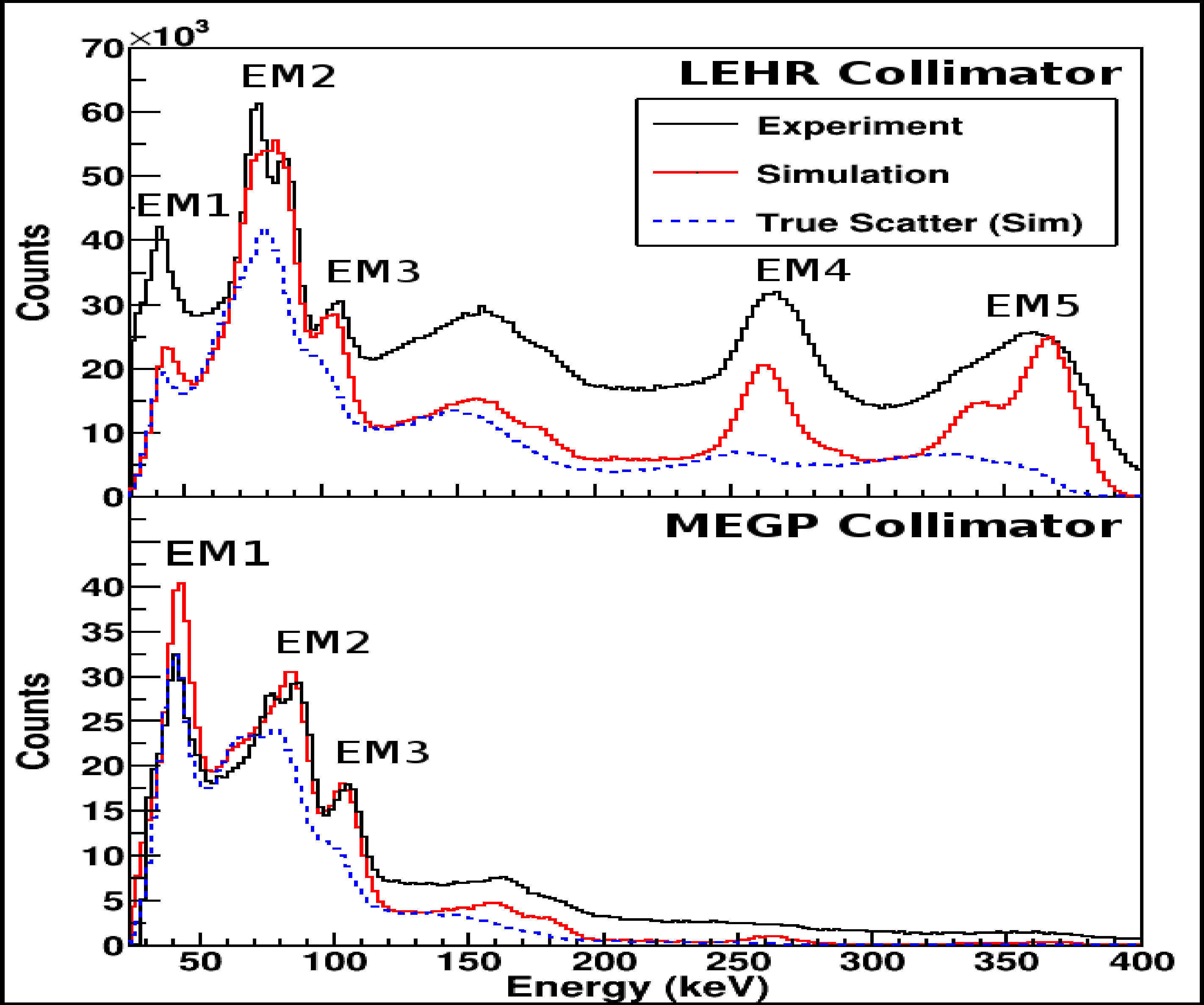
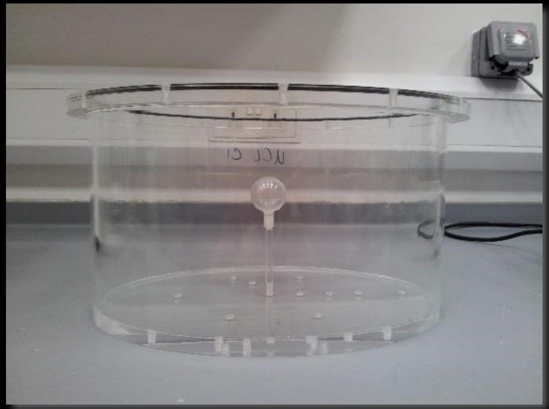
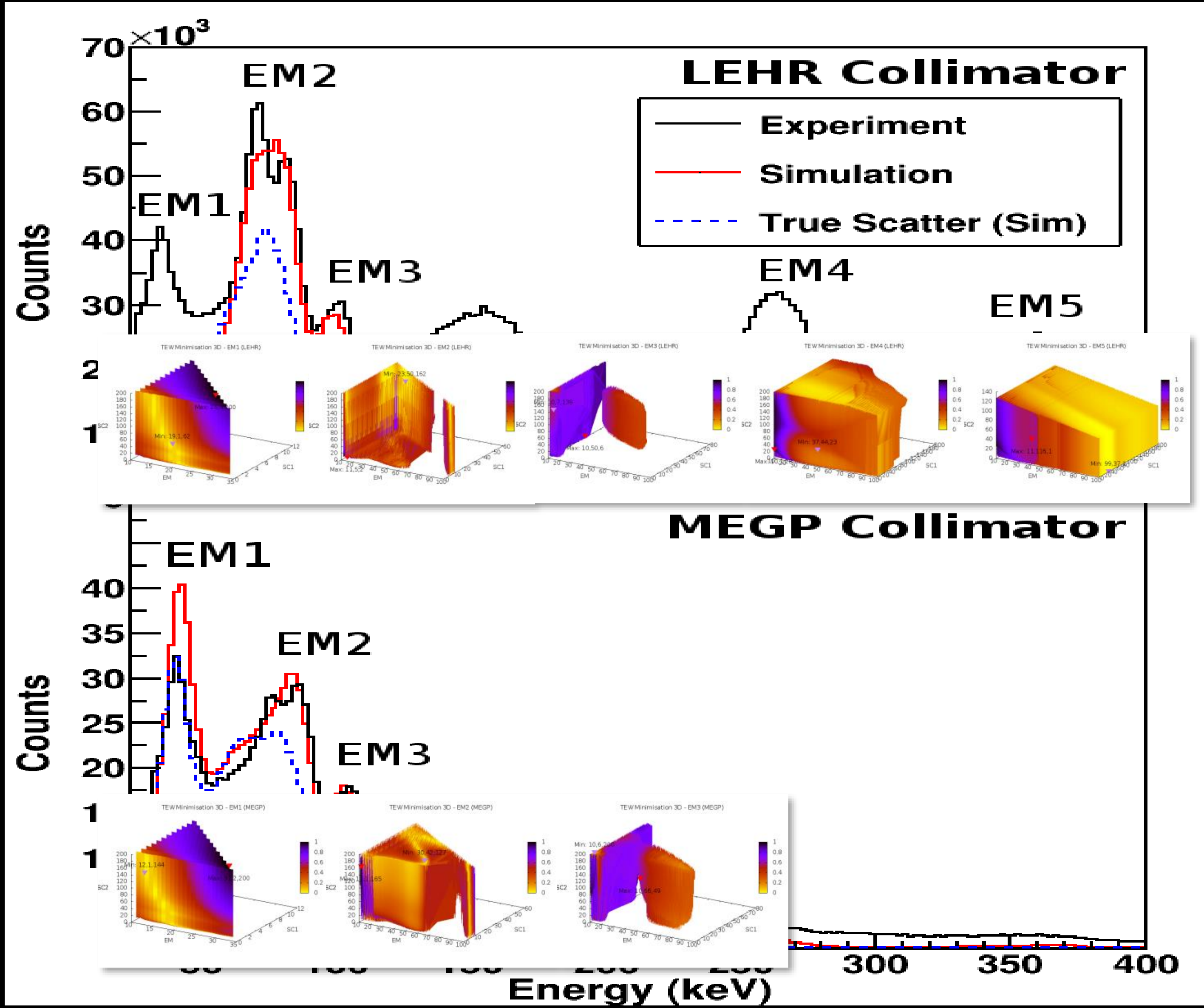
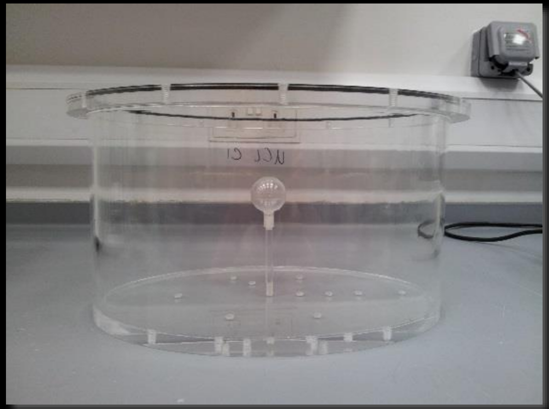




Tb-155 SPECT

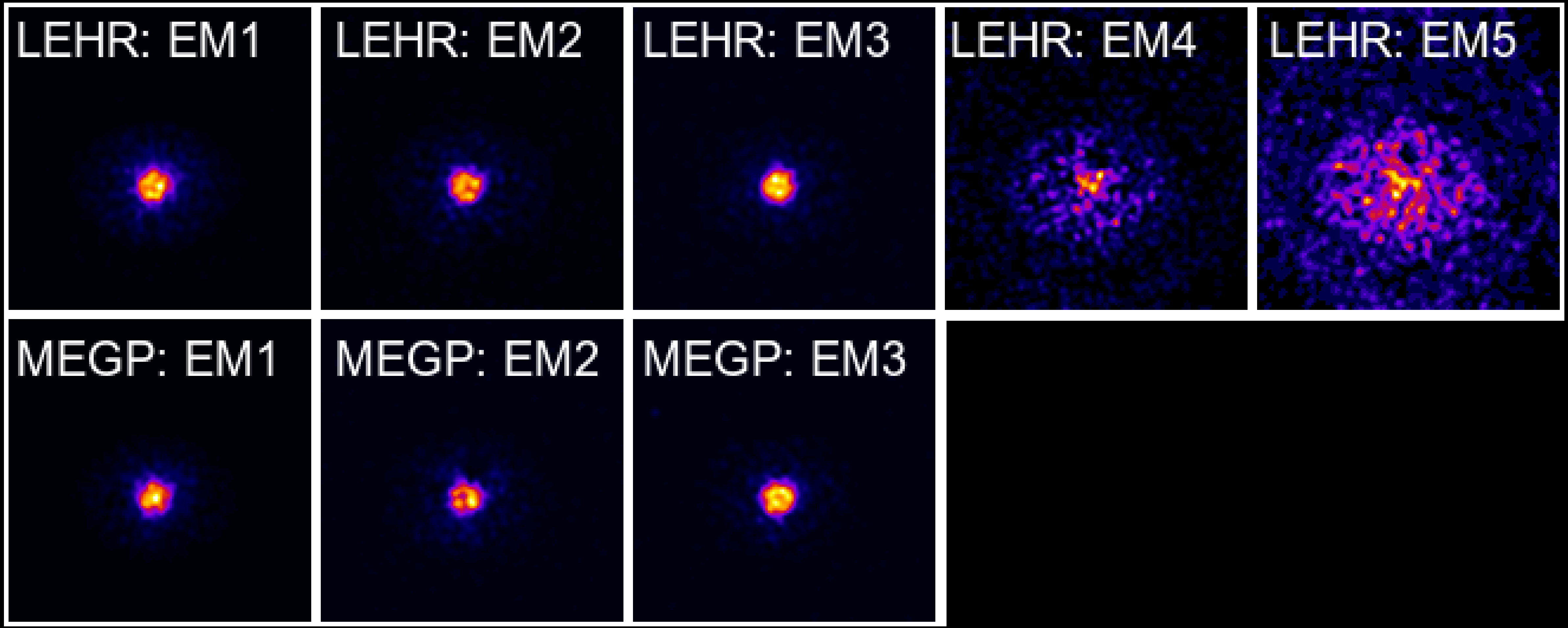


LEHR Collimator
Experiment
Simulation
True Scatter (Sim)
EM1
EM2
EM3
EM4
EM5
MEGP Collimator
EM1
EM2
EM3
Counts
Energy (keV)
70
60
50
40
30
×10³
40
35
30
25
20
300
350
400



Discovery NM 630

SPECT Imaging (List mode)



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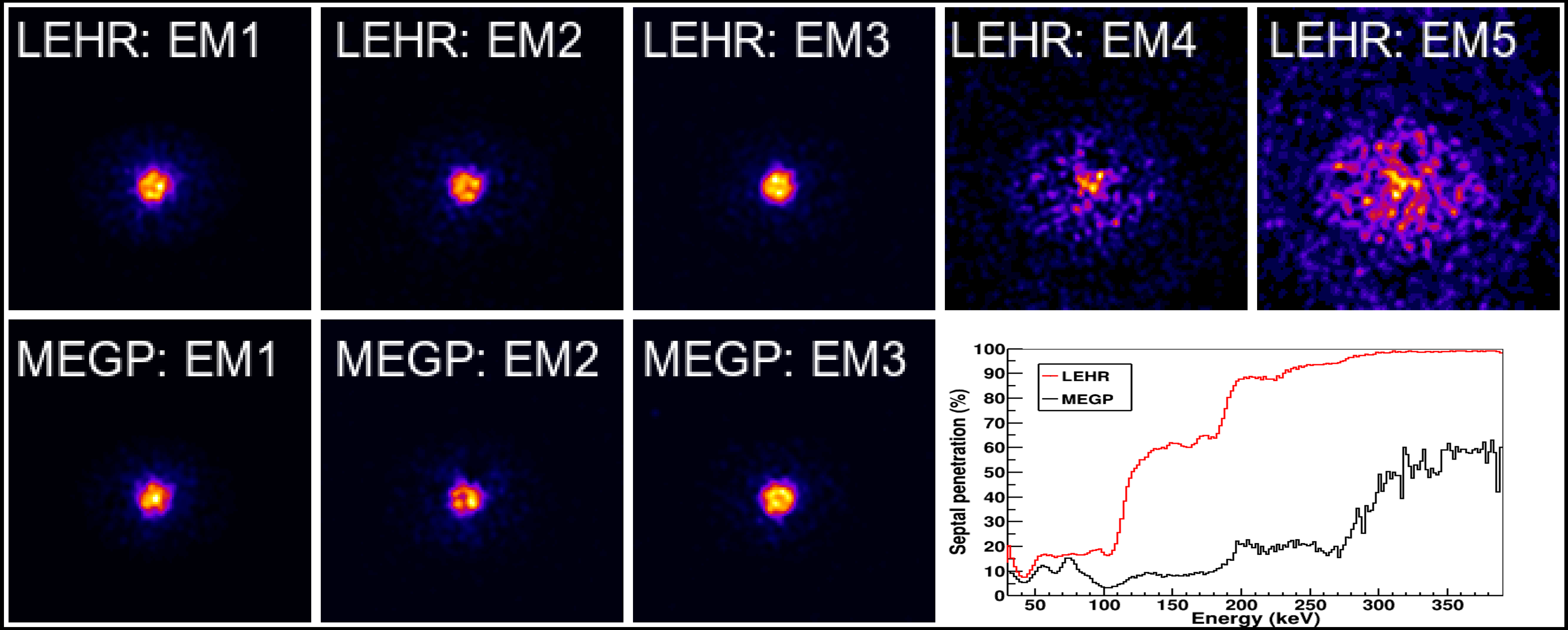

SPECT Imaging (List mode)

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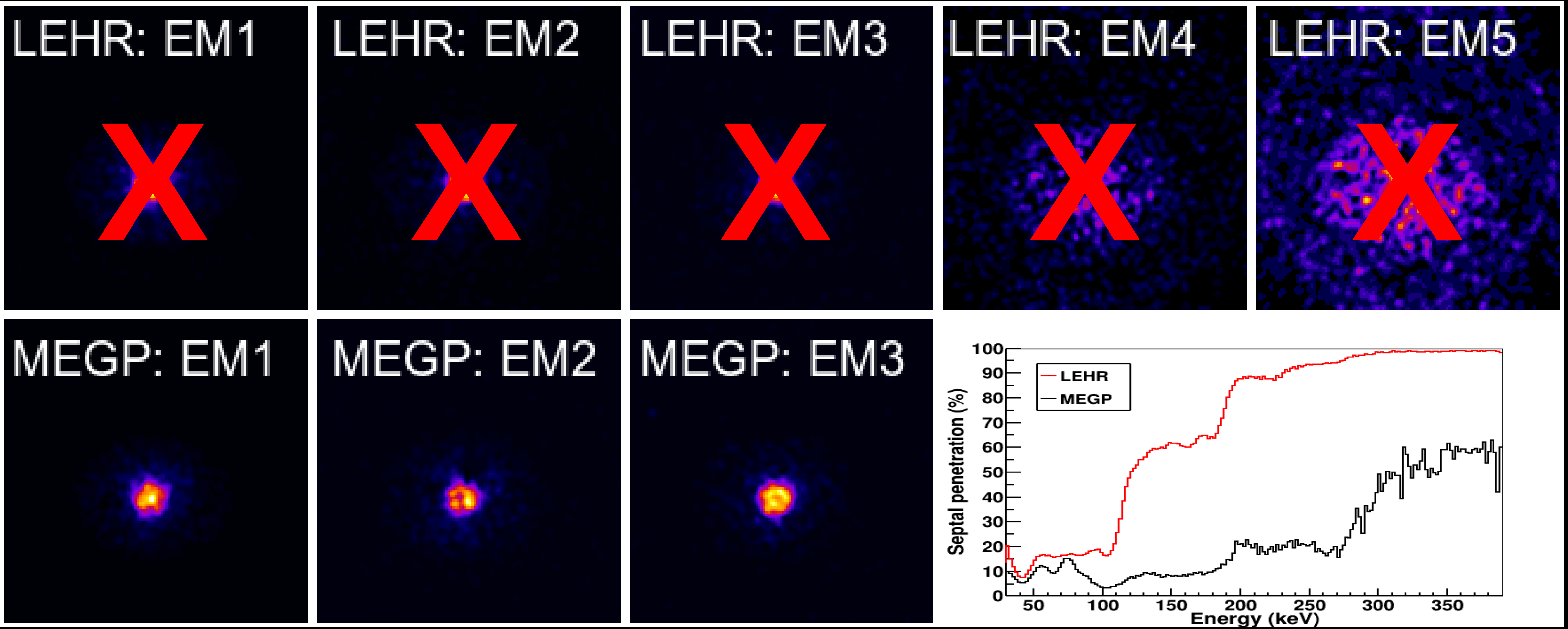

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- Can you trust the results from a simulation?

Validation of simulations

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- 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)
  - ✓ (Nuclear) Data

<u>Comparison with experimental data</u>

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<u>Comparison with experimental data</u>

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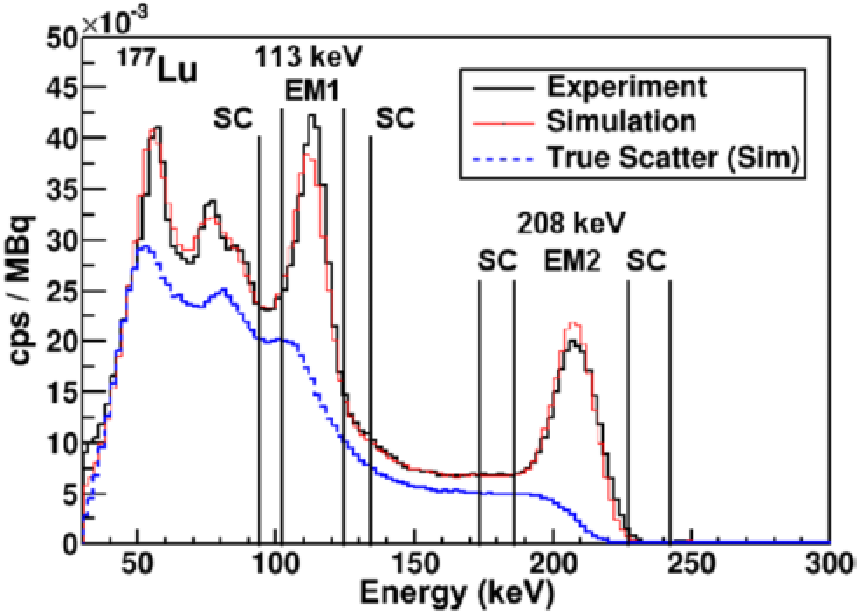
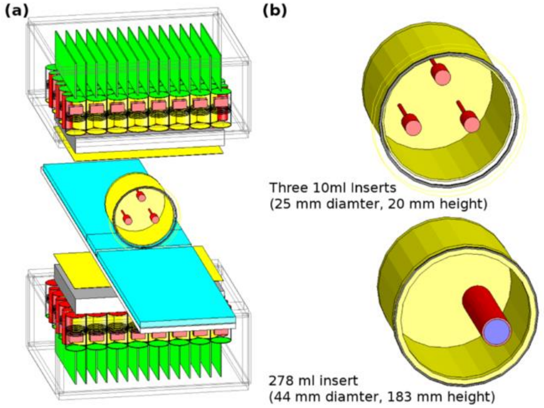
Phys. Med. Biol. 61 (2016) 5107–5127
doi:10.1088/0031-9155/61/14/5107

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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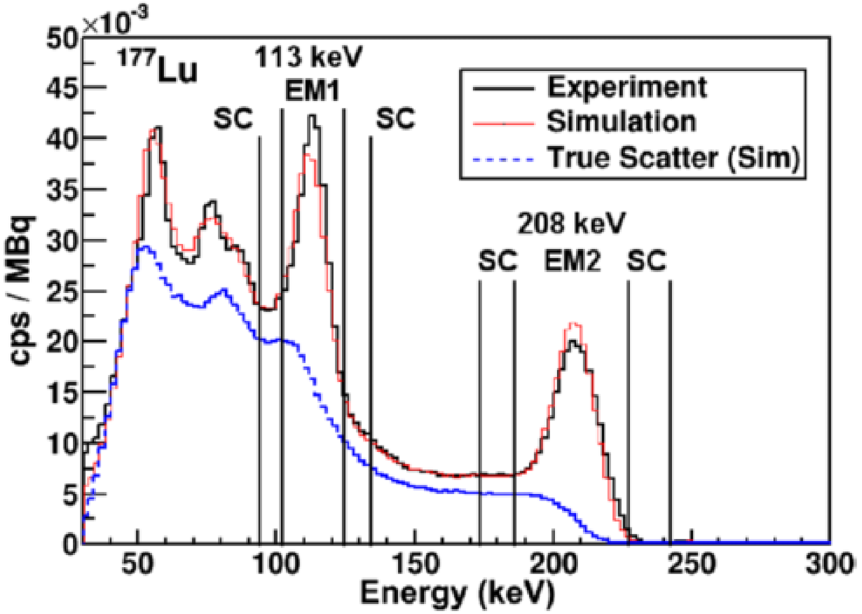

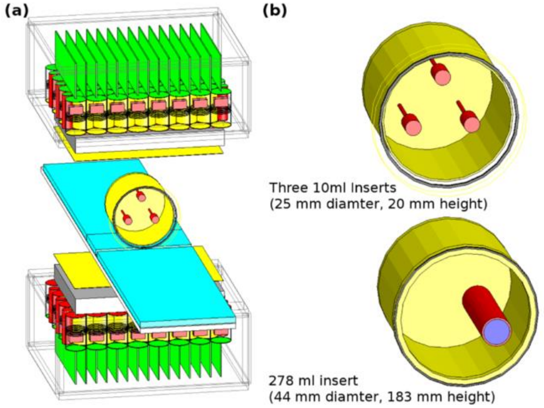

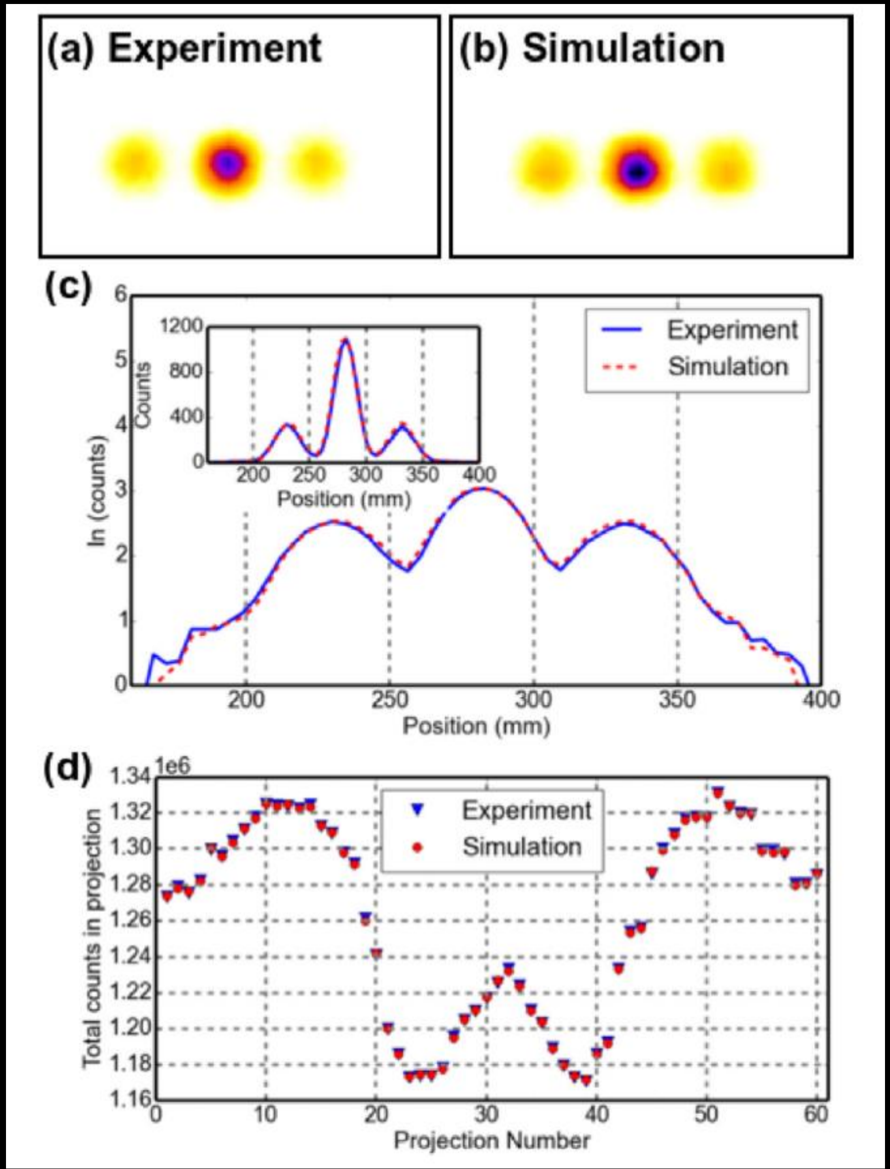

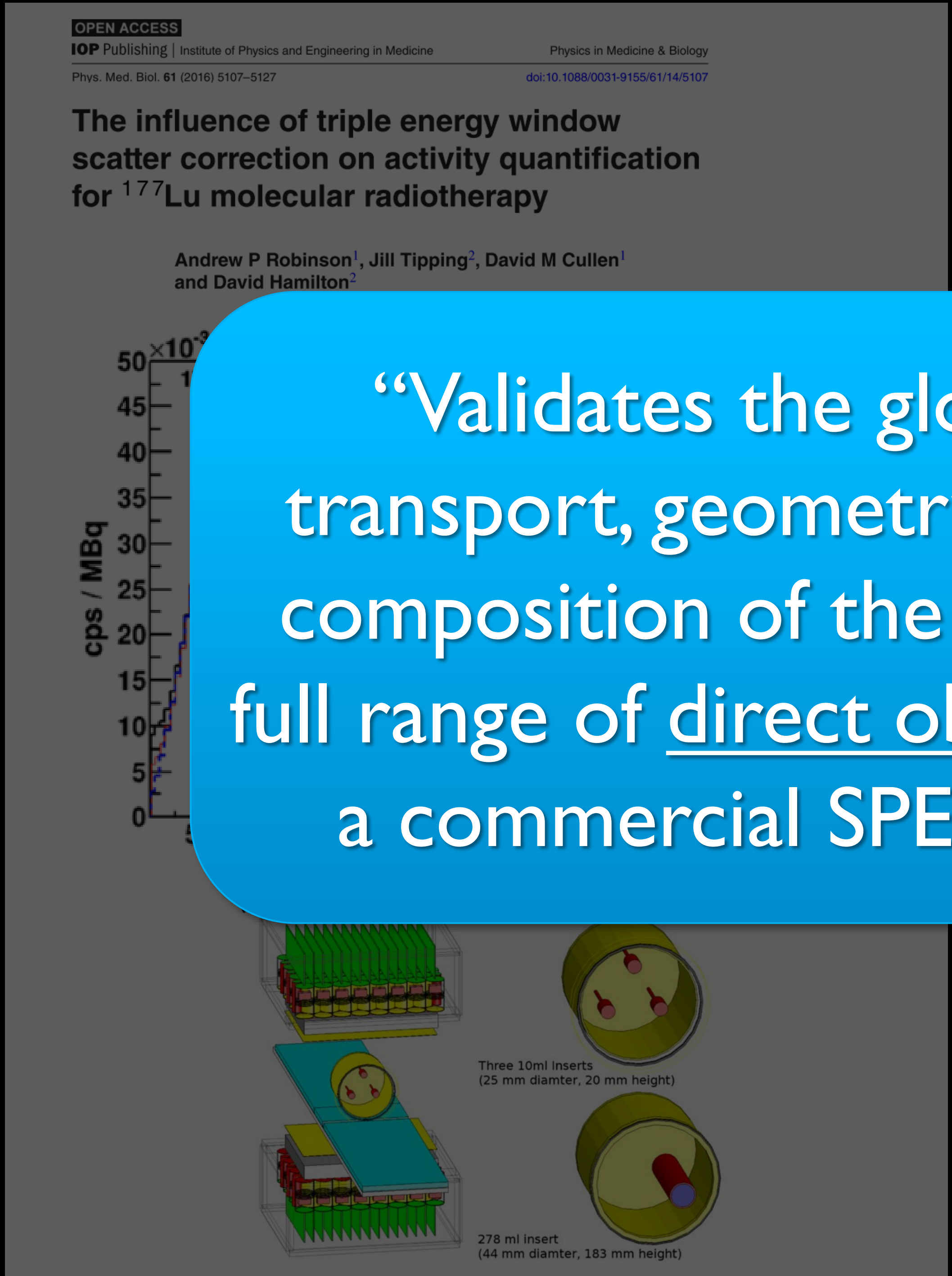
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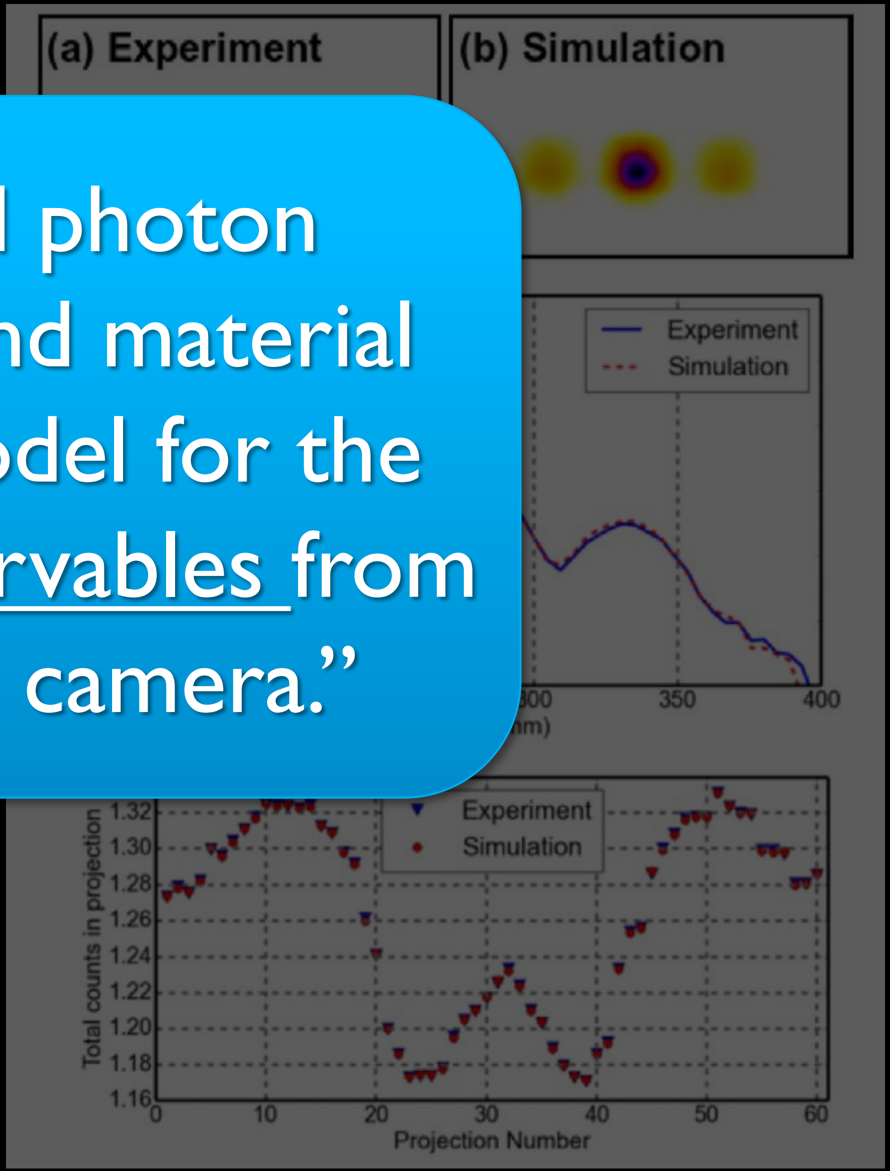


“Validates the global photon transport, geometry and material composition of the model for the full range of direct observables from a commercial SPECT camera.”

Uncertainties….

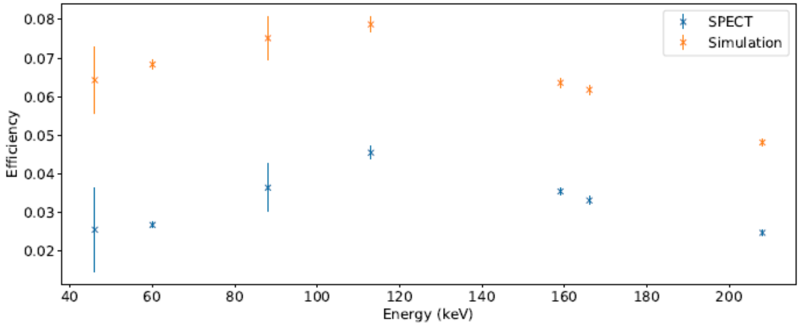


Figure 4: A comparison of the absolute detection efficiency of the SPECT camera and the simulation for the calibration sources stated in Table 2.

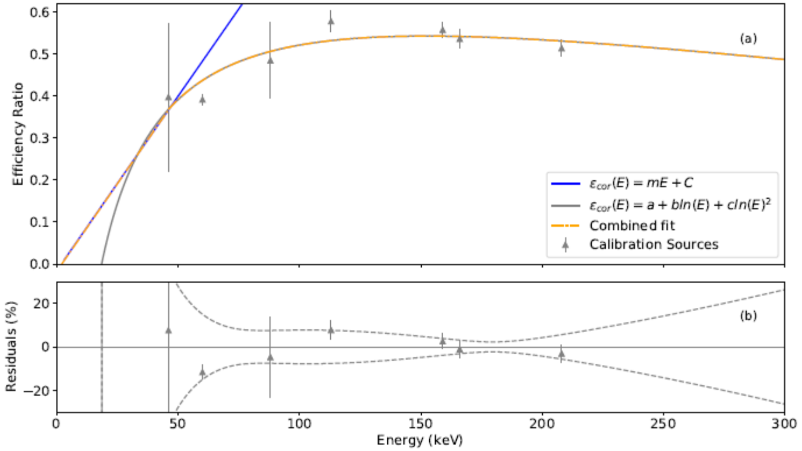


Figure 5: The data used to create the efficiency correction. The grey points show the ratio of experimentally-measured and simulated efficiency for the calibration sources. (a): the data points with the two fits discussed in the text and the superposition of the two functions, shown as an orange dot-dashed line, used for the efficiency correction. (b): the residuals of the fit to the data. The error bars on the residuals are the standard uncertainty of each data point and the dashed lines represent the uncertainty of the fit.

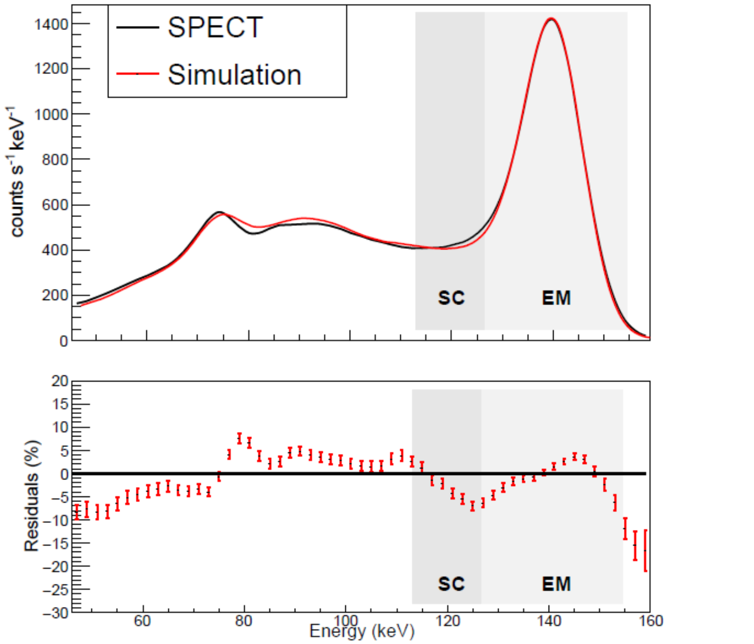
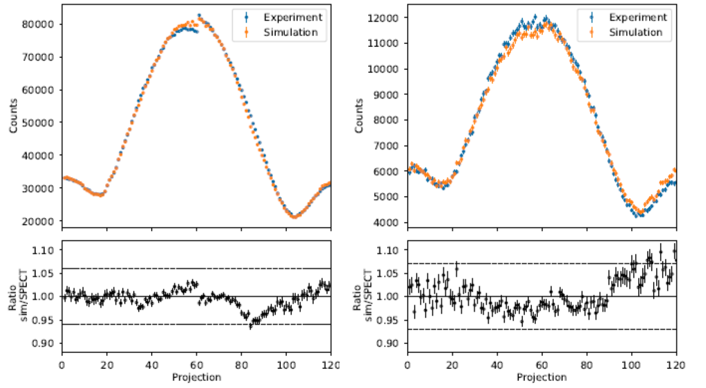


Figure 6: A comparison of the total simulated energy spectrum and the total spectrum extracted from the SPECT images for the cylindrical phantom of ^{99m}Tc. Each spectrum has been plotted with 2 keV bins, with a smooth curve through the bins. The bottom plot shows the percentage residuals. The emission (EM) and scatter (SC) windows are shaded.



(a) EM (b) SC

S. Pells, PhD Thesis, Uni. Of Manchester (2022)

^{90}Y Bremsstrahlung Imaging

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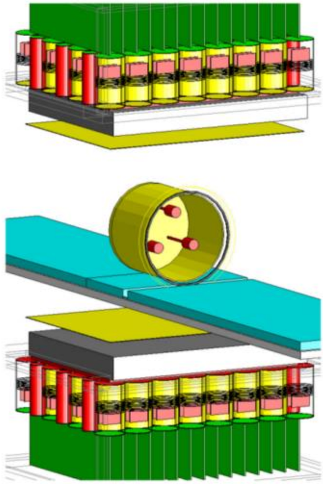
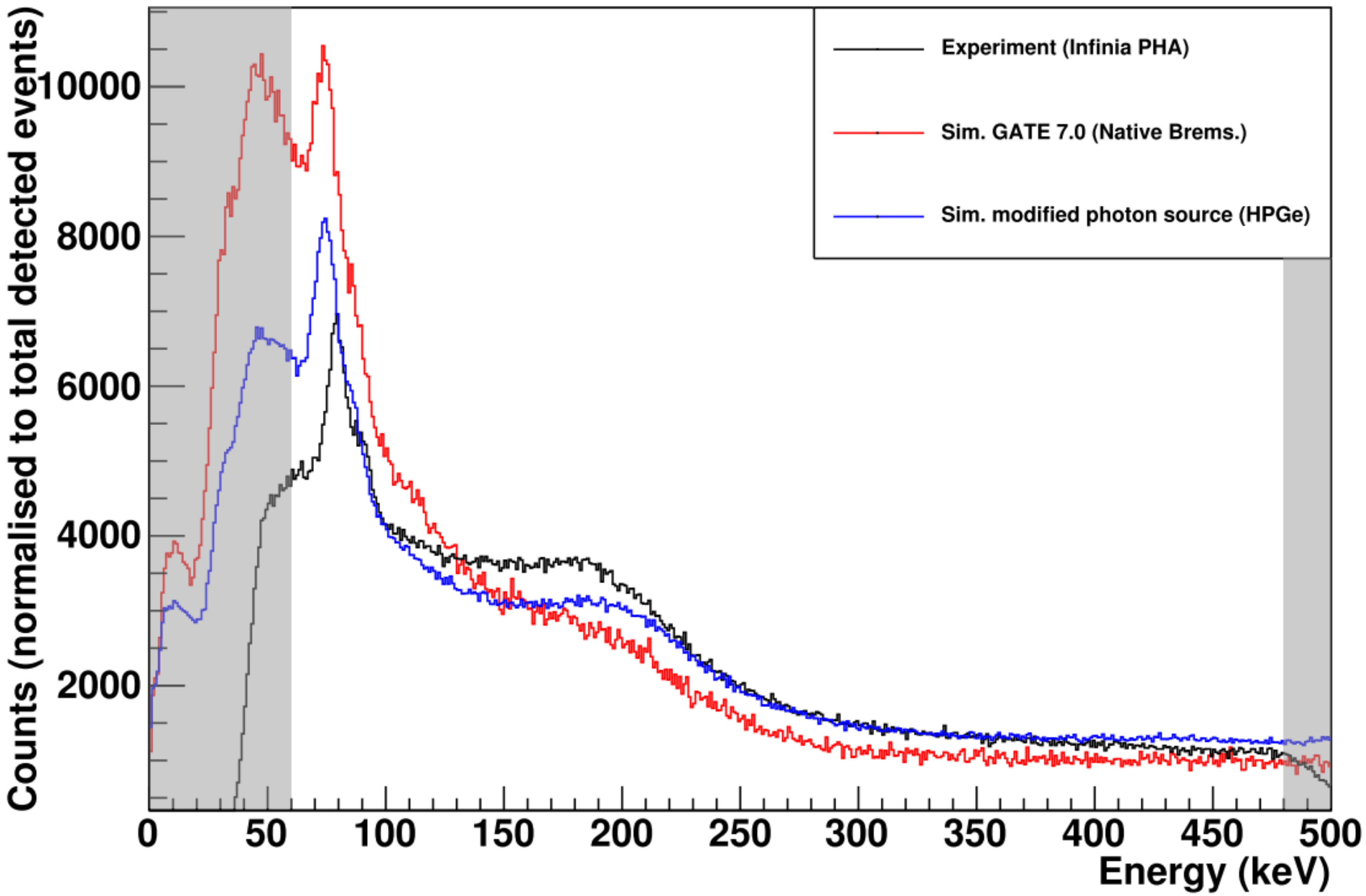
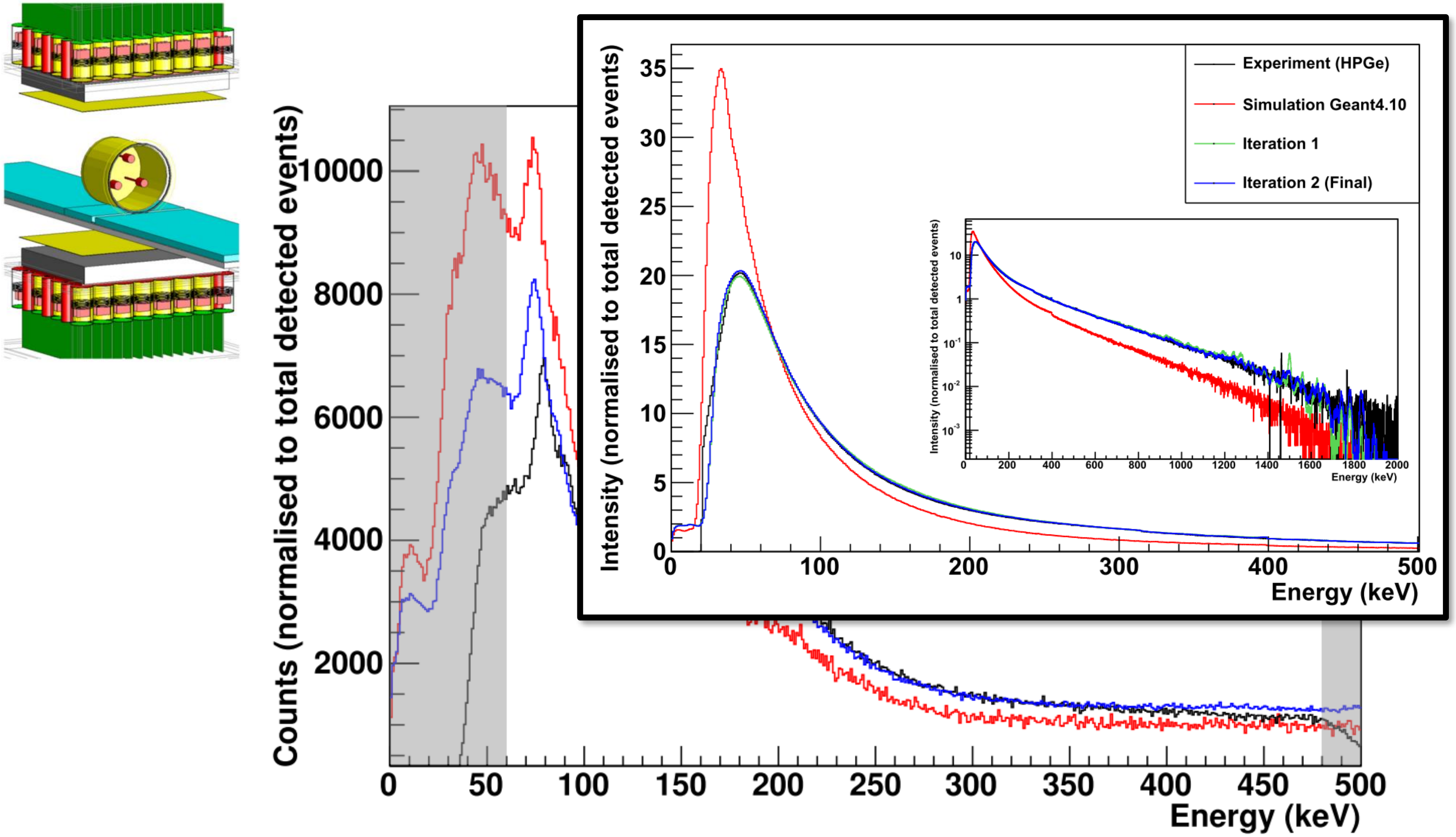




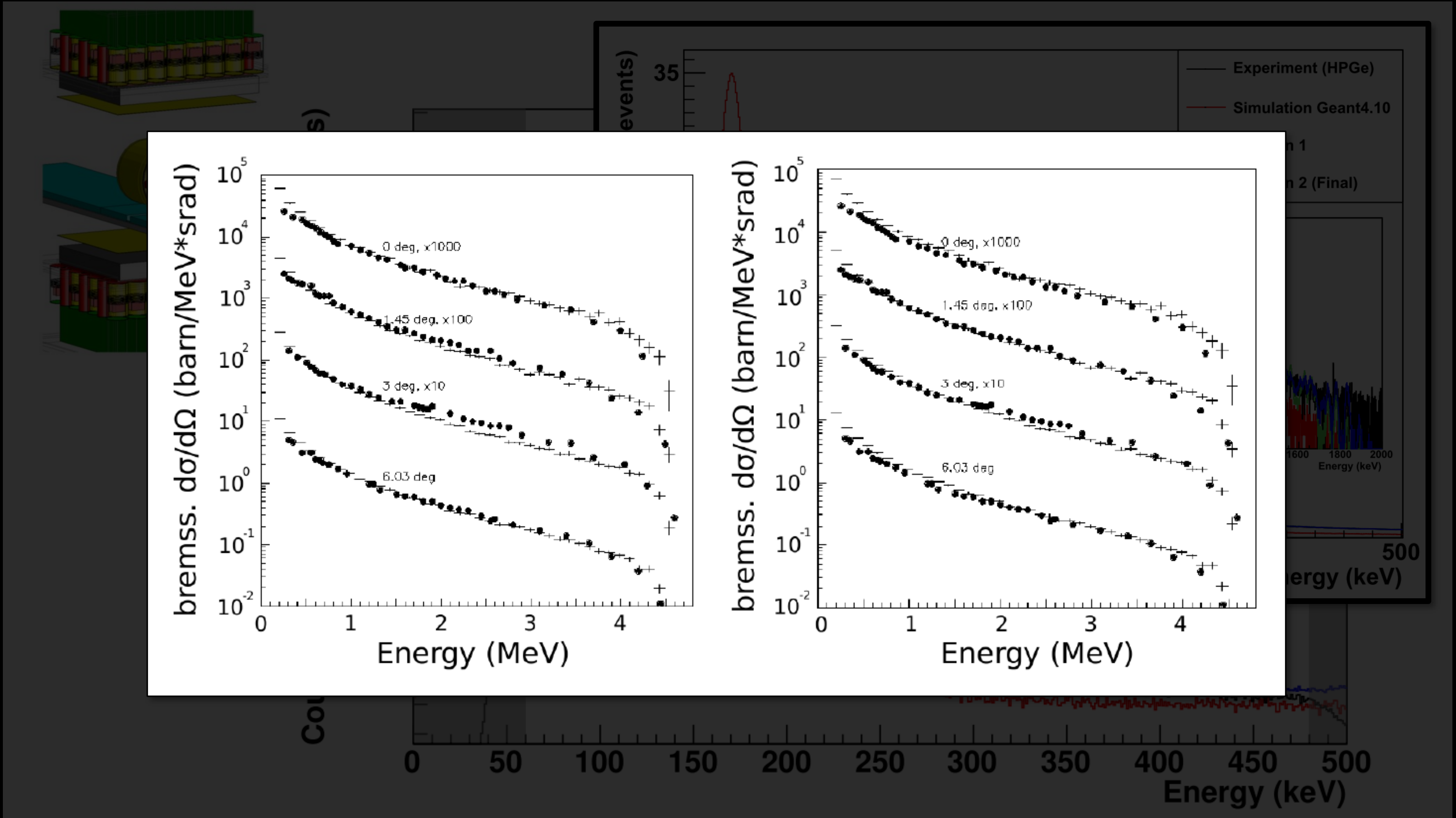
C. Oldfield, PhD Thesis, Uni. Of Manchester (2017)

^{90}Y Bremsstrahlung Imaging



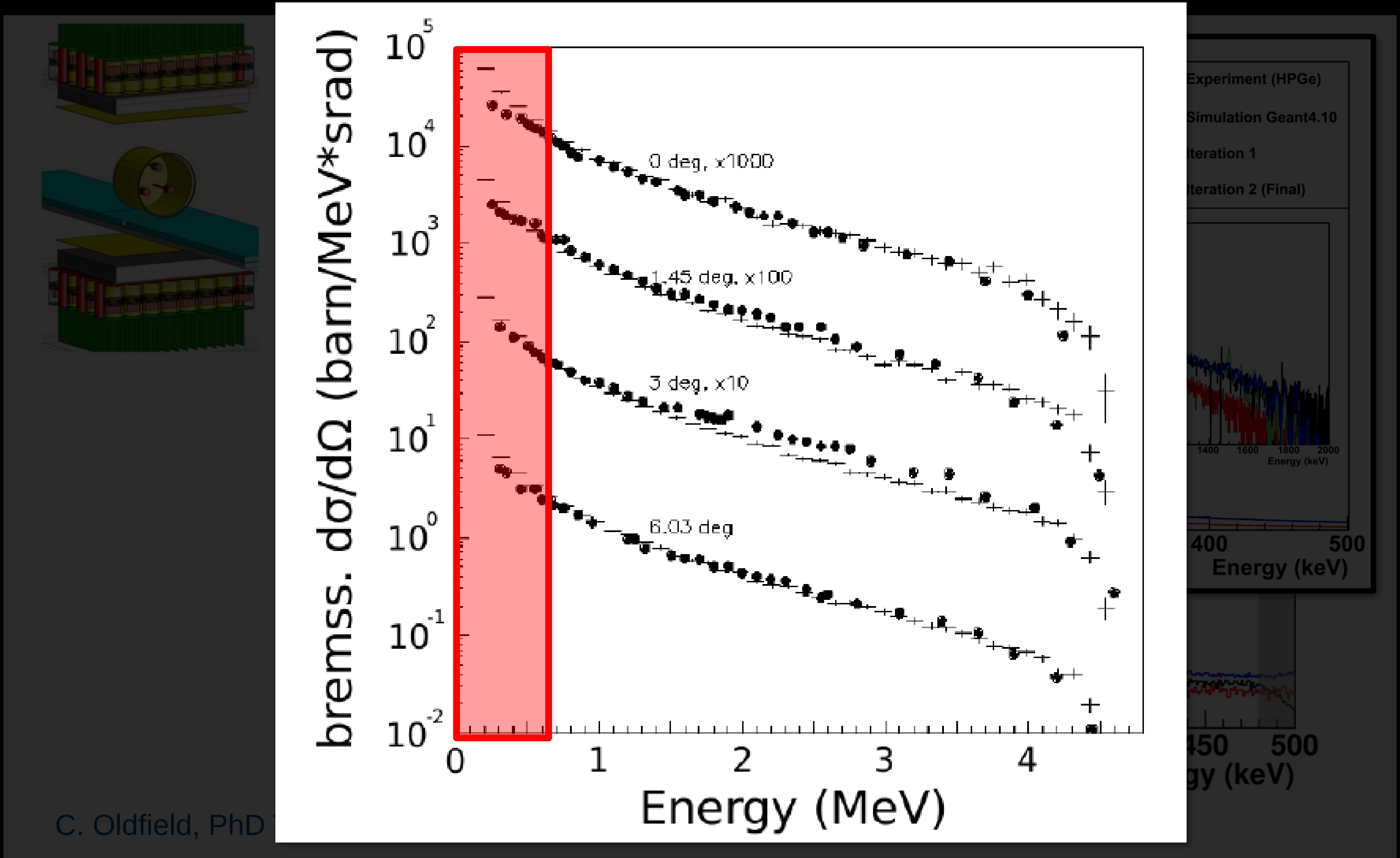
C. Oldfield, PhD Thesis, Uni. Of Manchester (2017)

^{90}Y Bremsstrahlung Imaging



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

^{90}Y Bremsstrahlung Imaging



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**

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

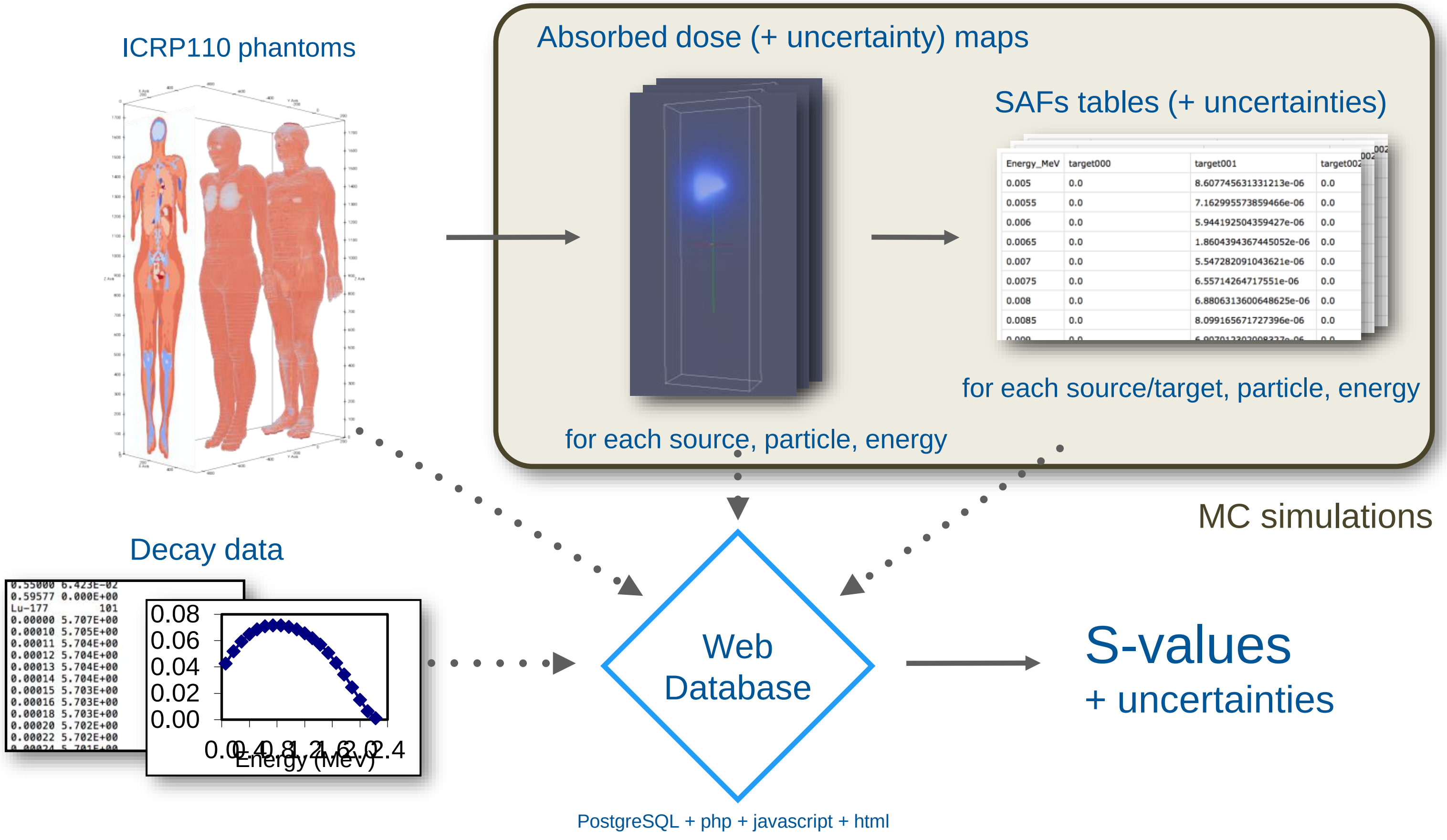
14 research teams (18 institutes)

5 Monte Carlo codes:

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

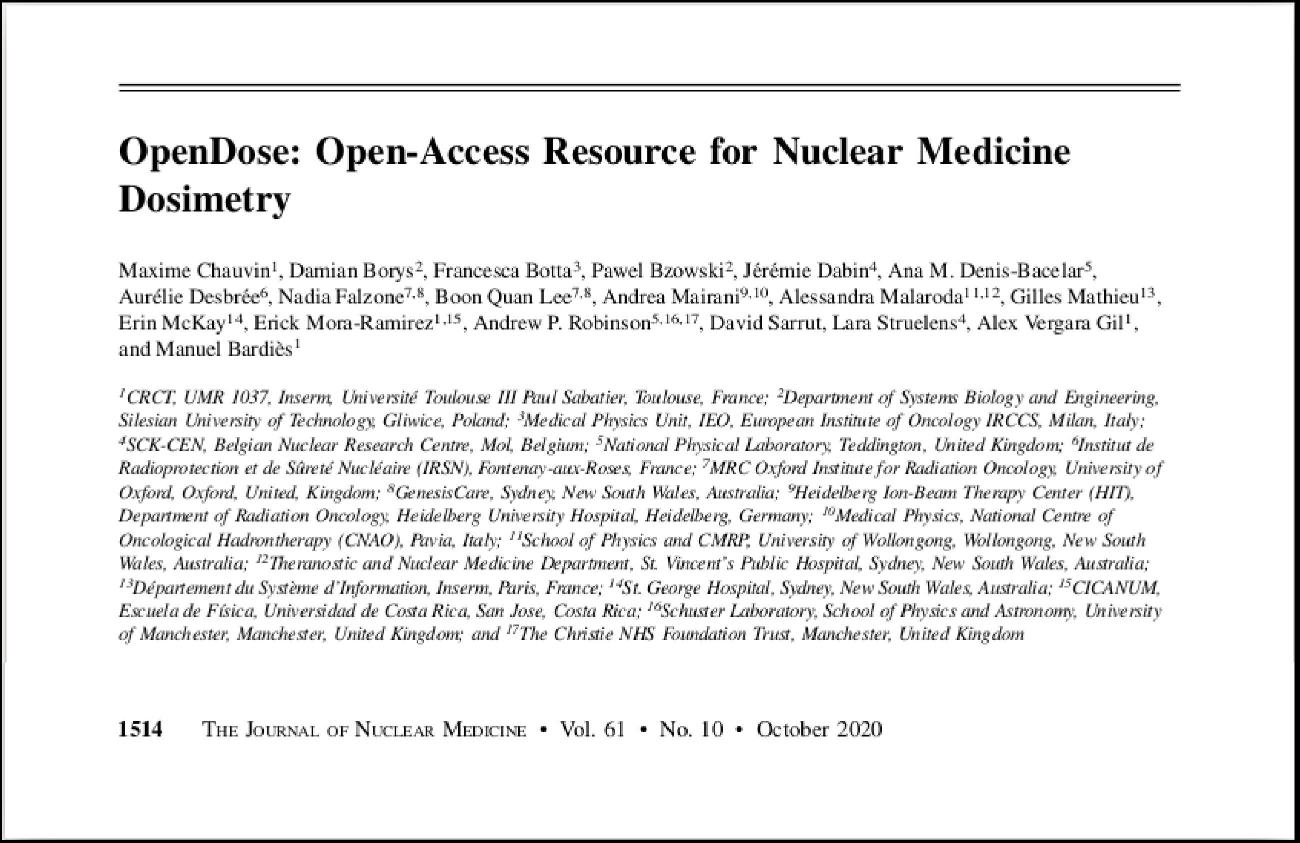
Courtesy of Dr A. Denis-Bacelar

OpenDose



Courtesy of Dr A. Denis-Bacelar

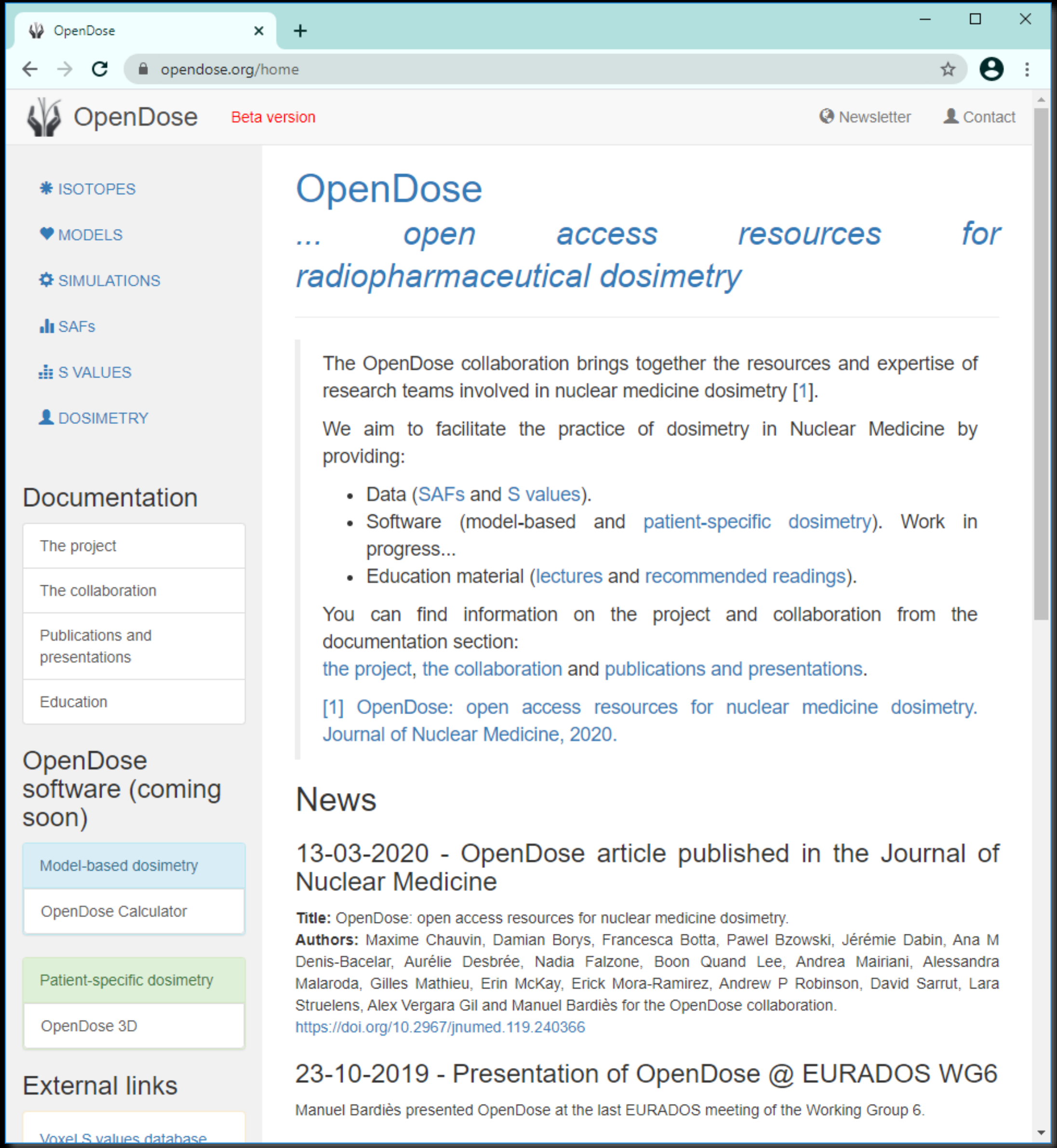
OpenDose



OpenDose: Open-Access Resource for Nuclear Medicine Dosimetry

Maxime Chauvin[1], Damian Borys[2], Francesca Botta[3], Pawel Bzowski[2], Jérémie Dabin[4], Ana M. Denis-Bacelar[5], Aurélie Desbrée[6], Nadia Falzone[7,8], Boon Quan Lee[7,8], Andrea Mairani[9,10], Alessandra Malaroda[11,12], Gilles Mathieu[13], Erin McKay[14], Erick Mora-Ramirez[1,15], Andrew P. Robinson[5,16,17], David Sarrut, Lara Struelens[4], Alex Vergara Gil[1], and Manuel Bardiès[1]

[1]CRCT, UMR 1037, Inserm, Université Toulouse III Paul Sabatier, Toulouse, France; [2]Department of Systems Biology and Engineering, Silesian University of Technology, Gliwice, Poland; [3]Medical Physics Unit, IEO, European Institute of Oncology IRCCS, Milan, Italy; [4]SCK-CEN, Belgian Nuclear Research Centre, Mol, Belgium; [5]National Physical Laboratory, Teddington, United Kingdom; [6]Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay-aux-Roses, France; [7]MRC Oxford Institute for Radiation Oncology, University of Oxford, Oxford, United, Kingdom; [8]GenesisCare, Sydney, New South Wales, Australia; [9]Heidelberg Ion-Beam Therapy Center (HIT), Department of Radiation Oncology, Heidelberg University Hospital, Heidelberg, Germany; [10]Medical Physics, National Centre of Oncological Hadrontherapy (CNAO), Pavia, Italy; [11]School of Physics and CMRP, University of Wollongong, Wollongong, New South Wales, Australia; [12]Theranostic and Nuclear Medicine Department, St. Vincent's Public Hospital, Sydney, New South Wales, Australia; [13]Département du Système d'Information, Inserm, Paris, France; [14]St. George Hospital, Sydney, New South Wales, Australia; [15]CICANUM, Escuela de Física, Universidad de Costa Rica, San Jose, Costa Rica; [16]Schuster Laboratory, School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom; and [17]The Christie NHS Foundation Trust, Manchester, United Kingdom



SAF results: Pancreas ← Liver (electrons)

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OpenDose Beta version

Newsletter Contact

- ISOTOPES
- MODELS
- SIMULATIONS
- SAFs
- S VALUES
- DOSIMETRY

Selection

Model: ICRP 110 AF

Source: Liver

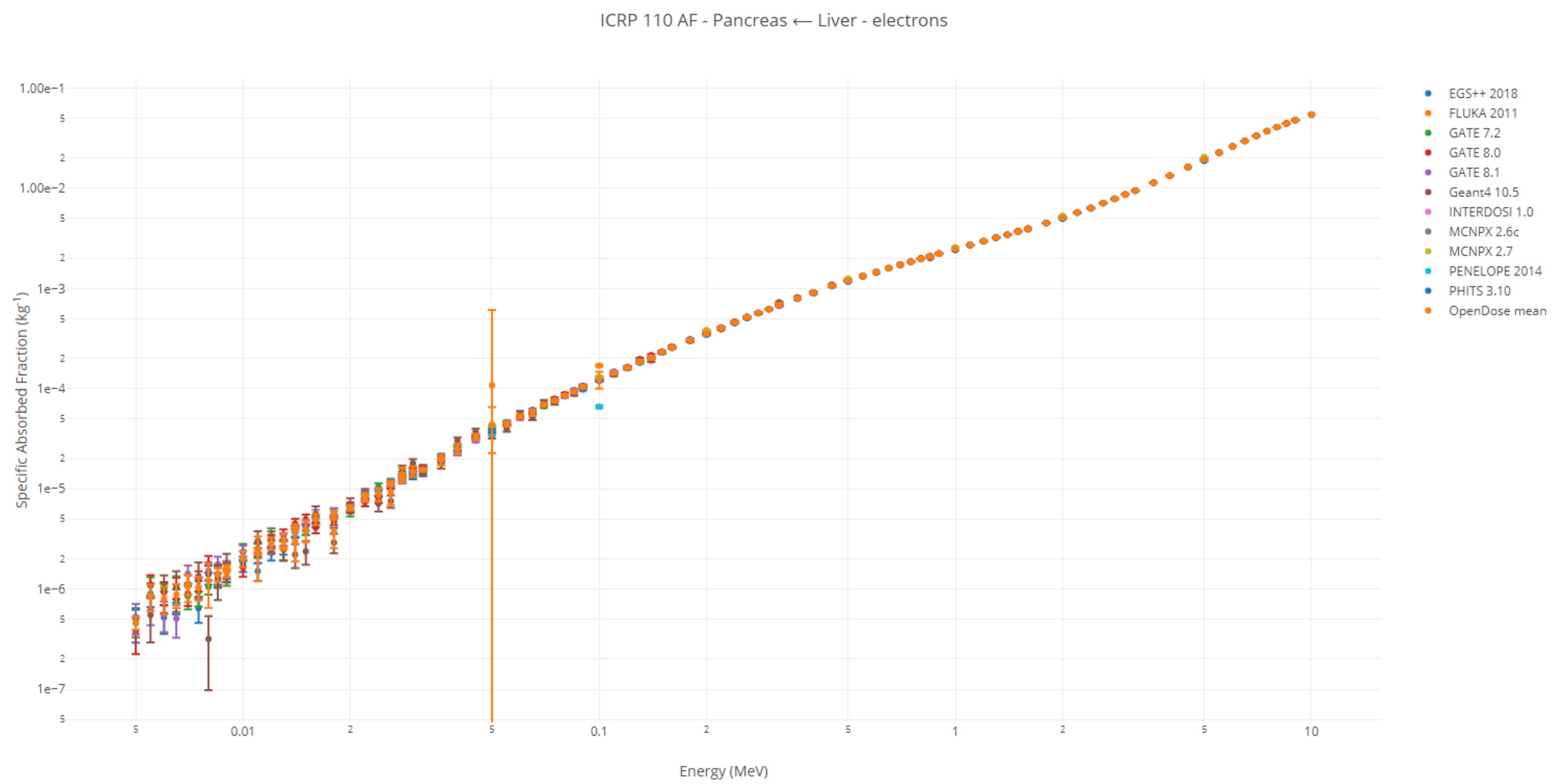
Target: Pancreas

Particle: electrons

Submit

Specific Absorbed Fractions

The interactive chart shows SAFs from the different Monte Carlo codes and the OpenDose mean. You can hover the chart to see values, span the axes, zoom and select data from the legend entries.



SAF results: Pancreas ← Liver (electrons)

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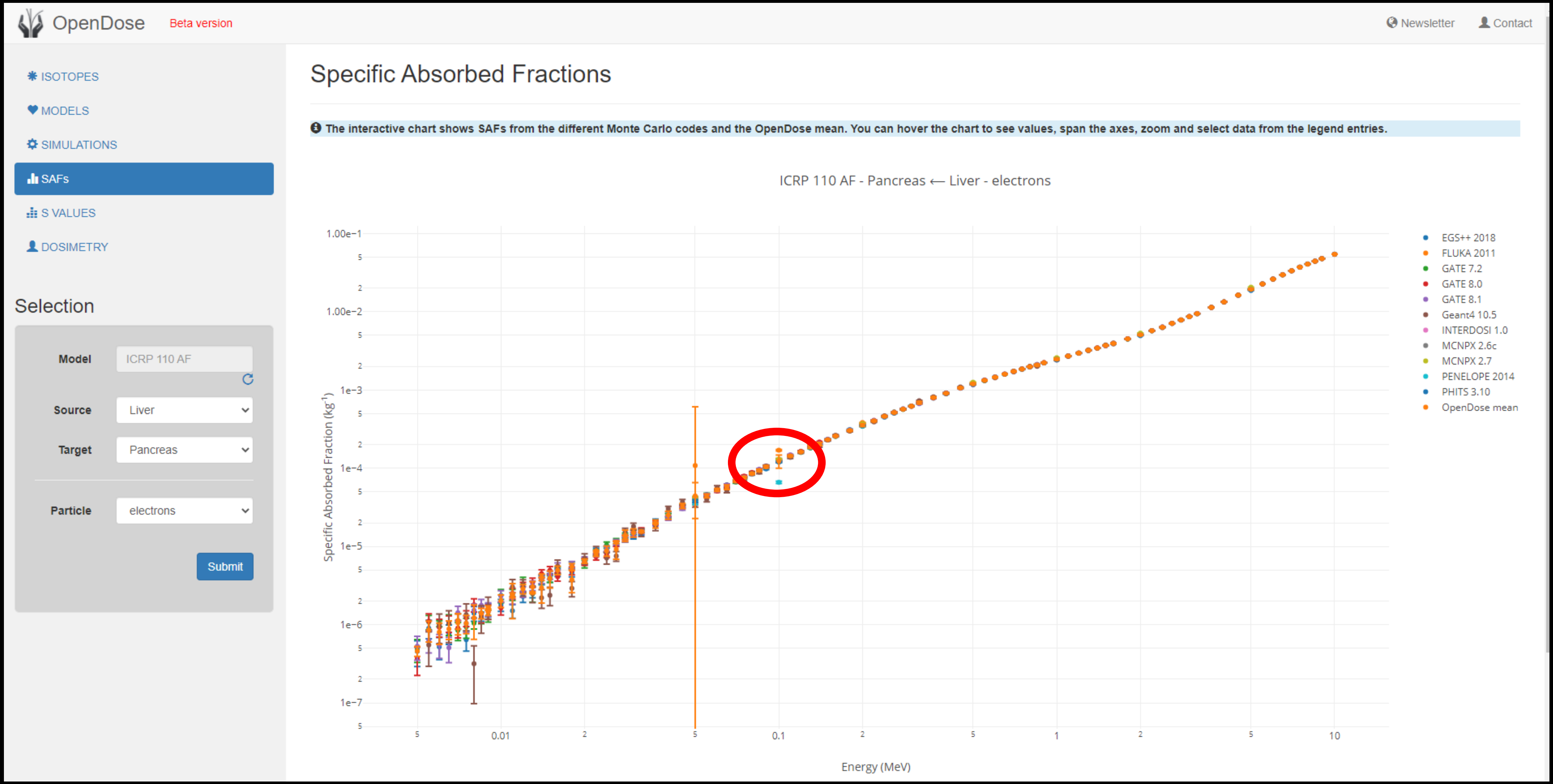

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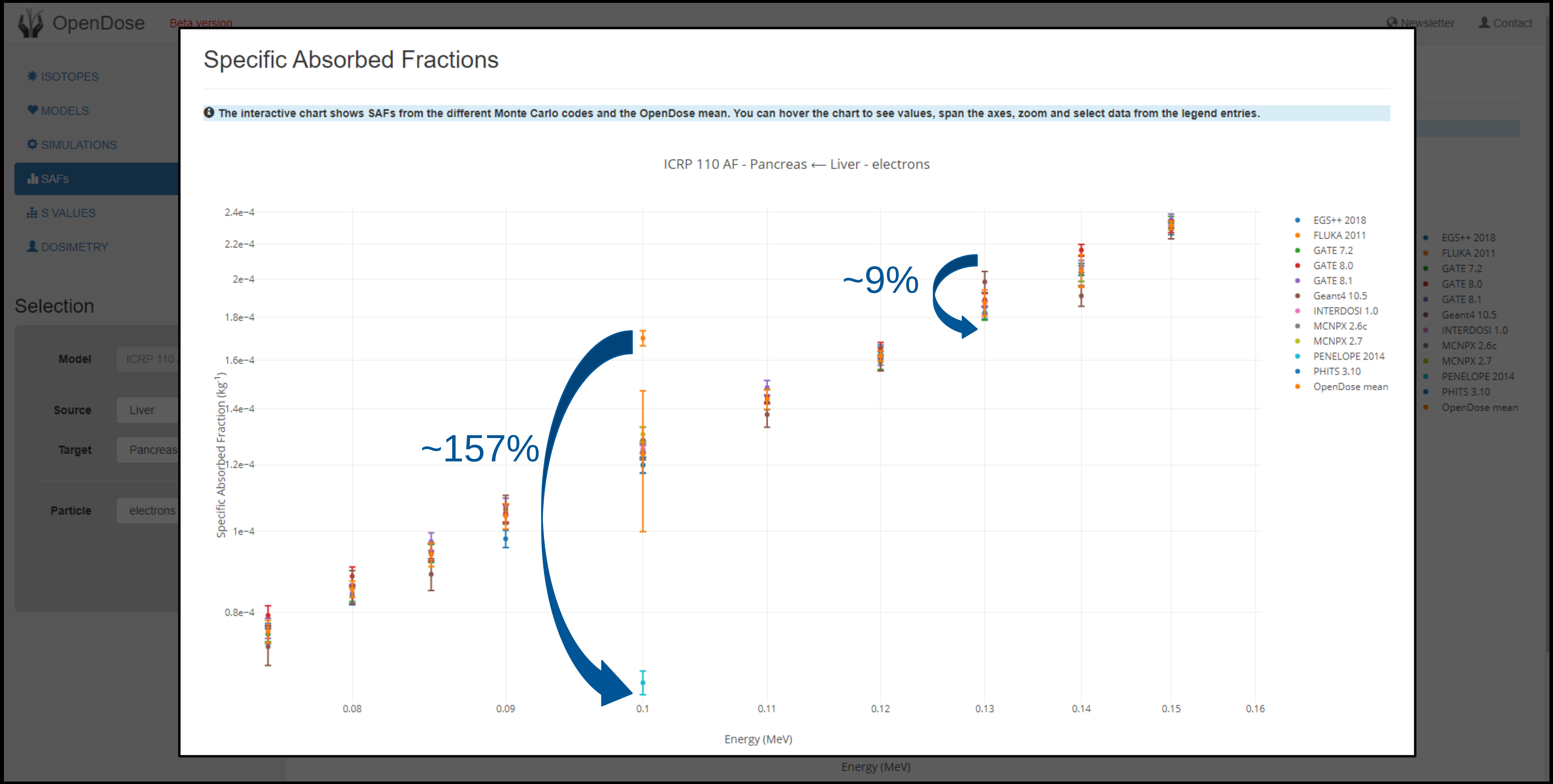
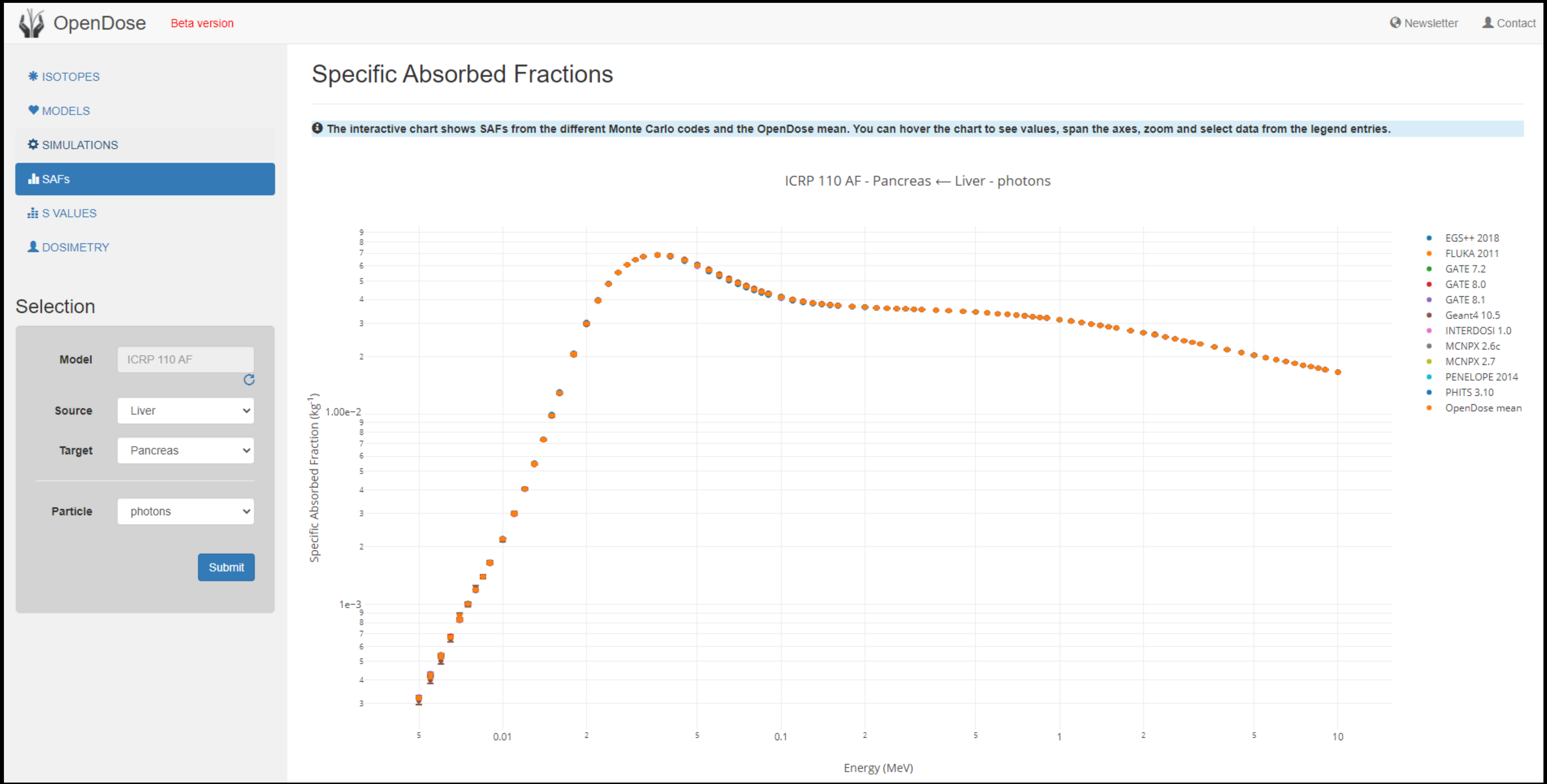


SAF results: Pancreas ← Liver (photons)



SAF results: Pancreas ← Liver (photons)

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OpenDose Beta version

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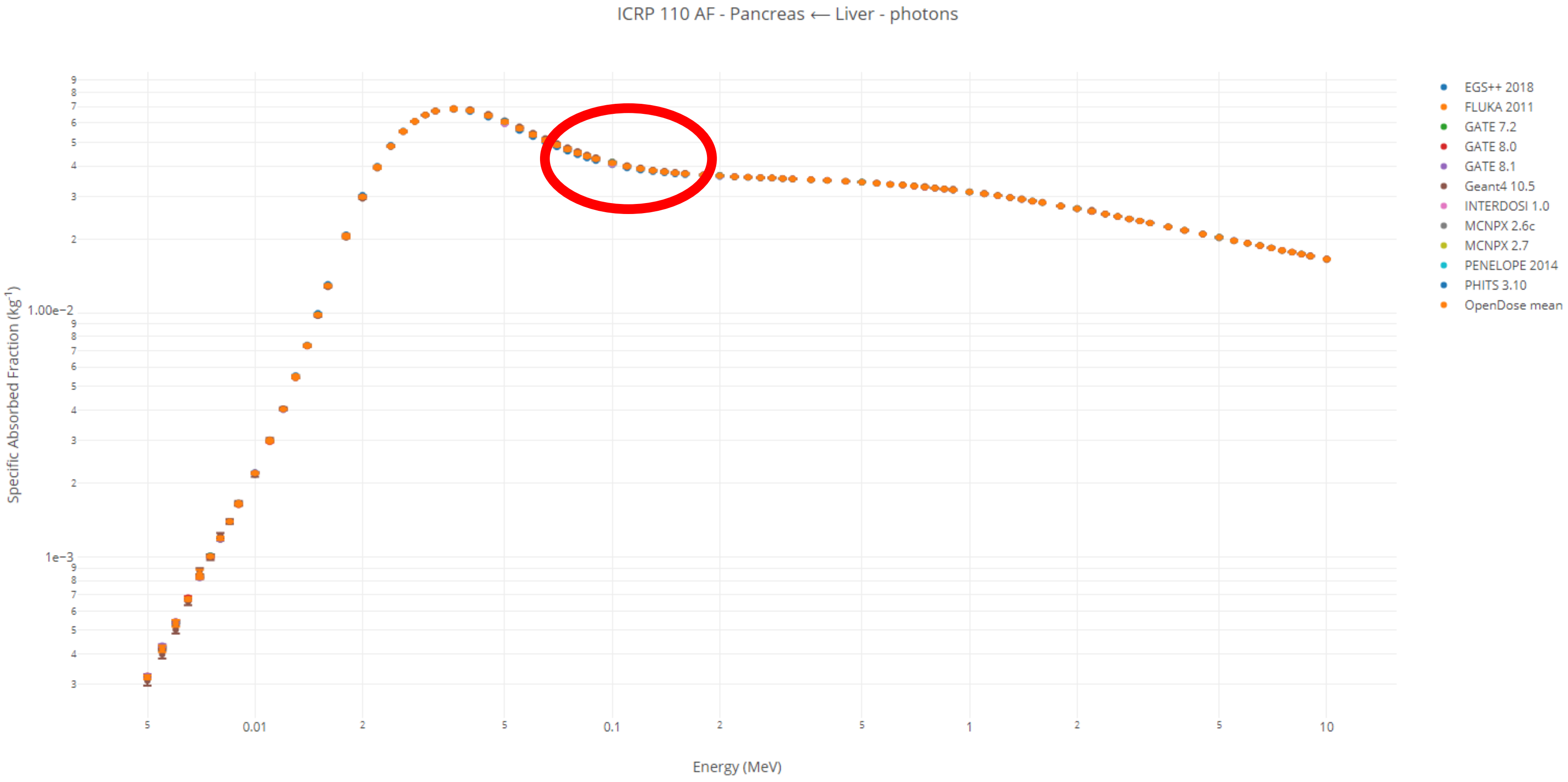
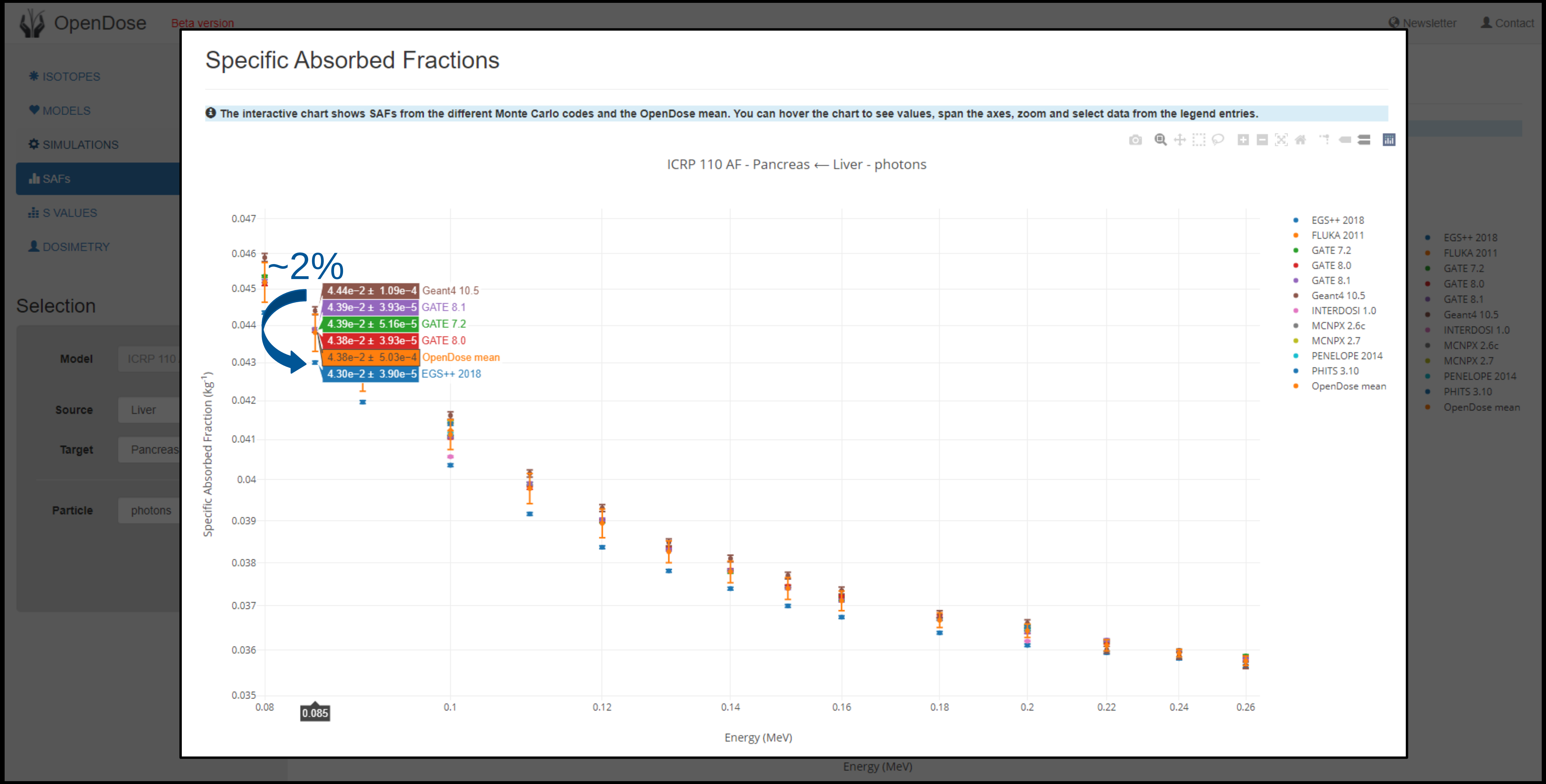


SAF results: Pancreas ← Liver (photons)



Validation of simulations

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- Can you trust the results from a simulation?

- Yes - **if the simulation has been validated**
  - ✓ Geometry
  - ✓ Detector modelling
  - ✓ Physics models (dependent on energy range)
  - ✓ (Nuclear) Data

Comparison with experimental data

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

Tools you can use

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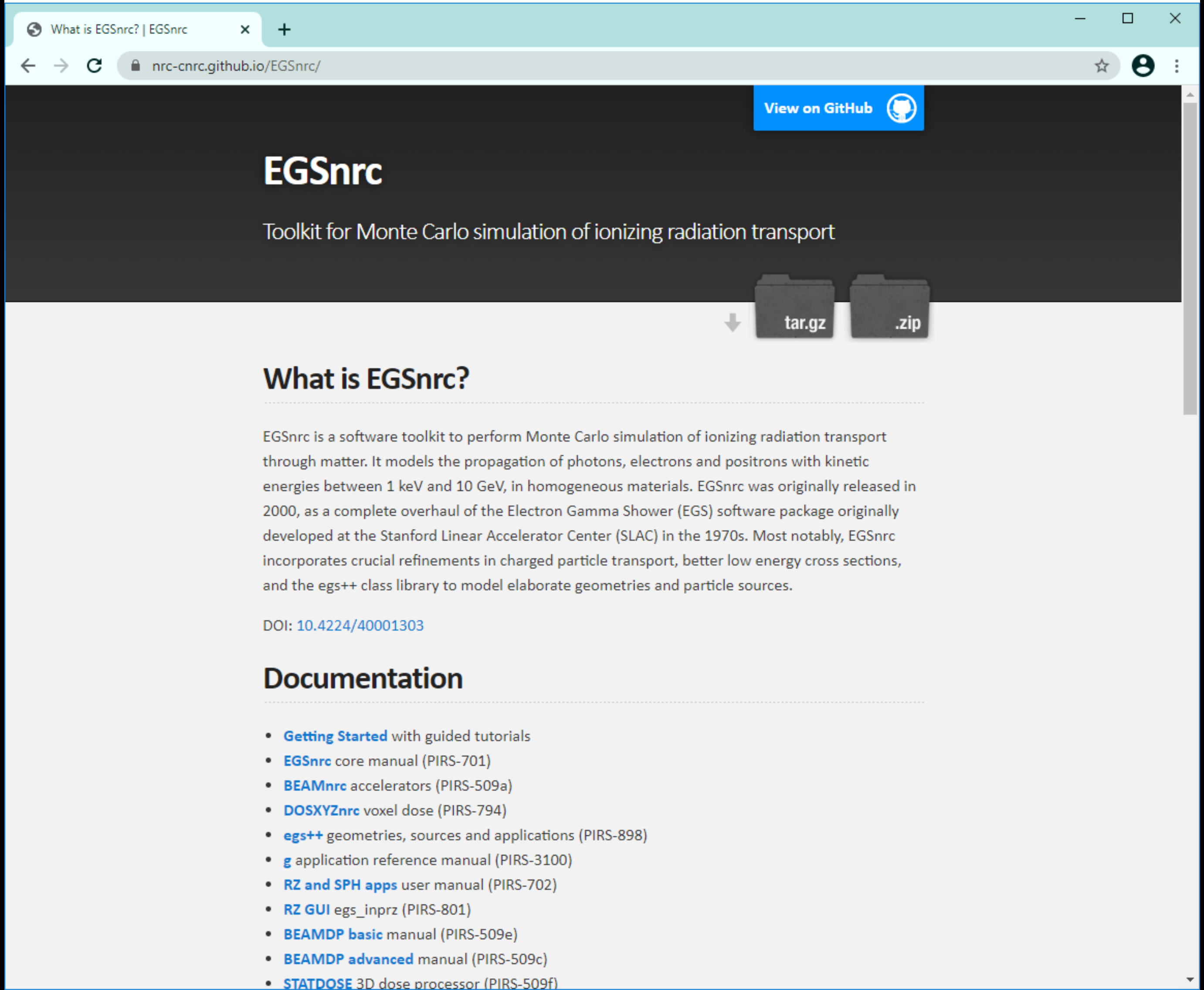
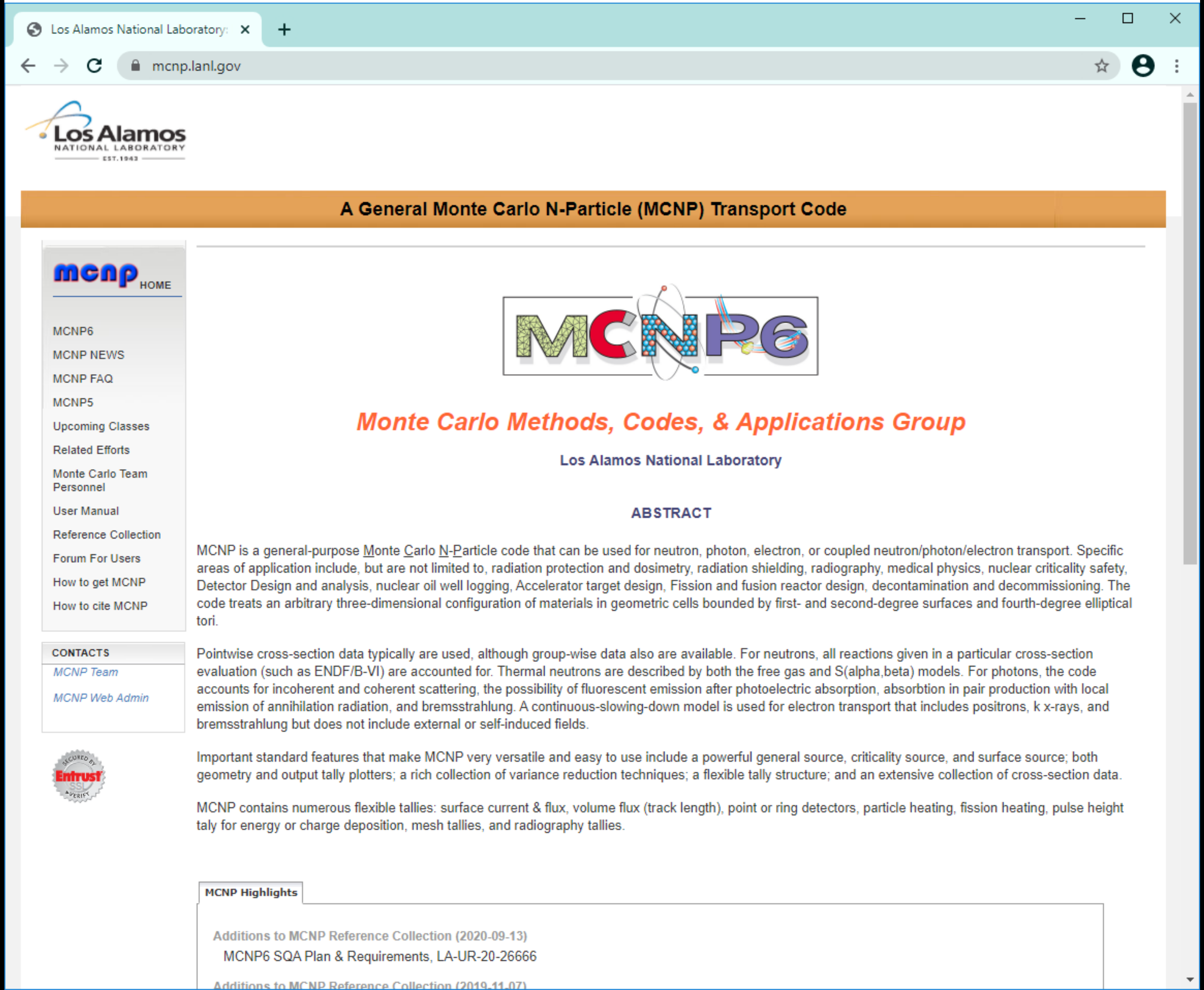
EGSnrc (https://nrc-cnrc.github.io/EGSnrc/)



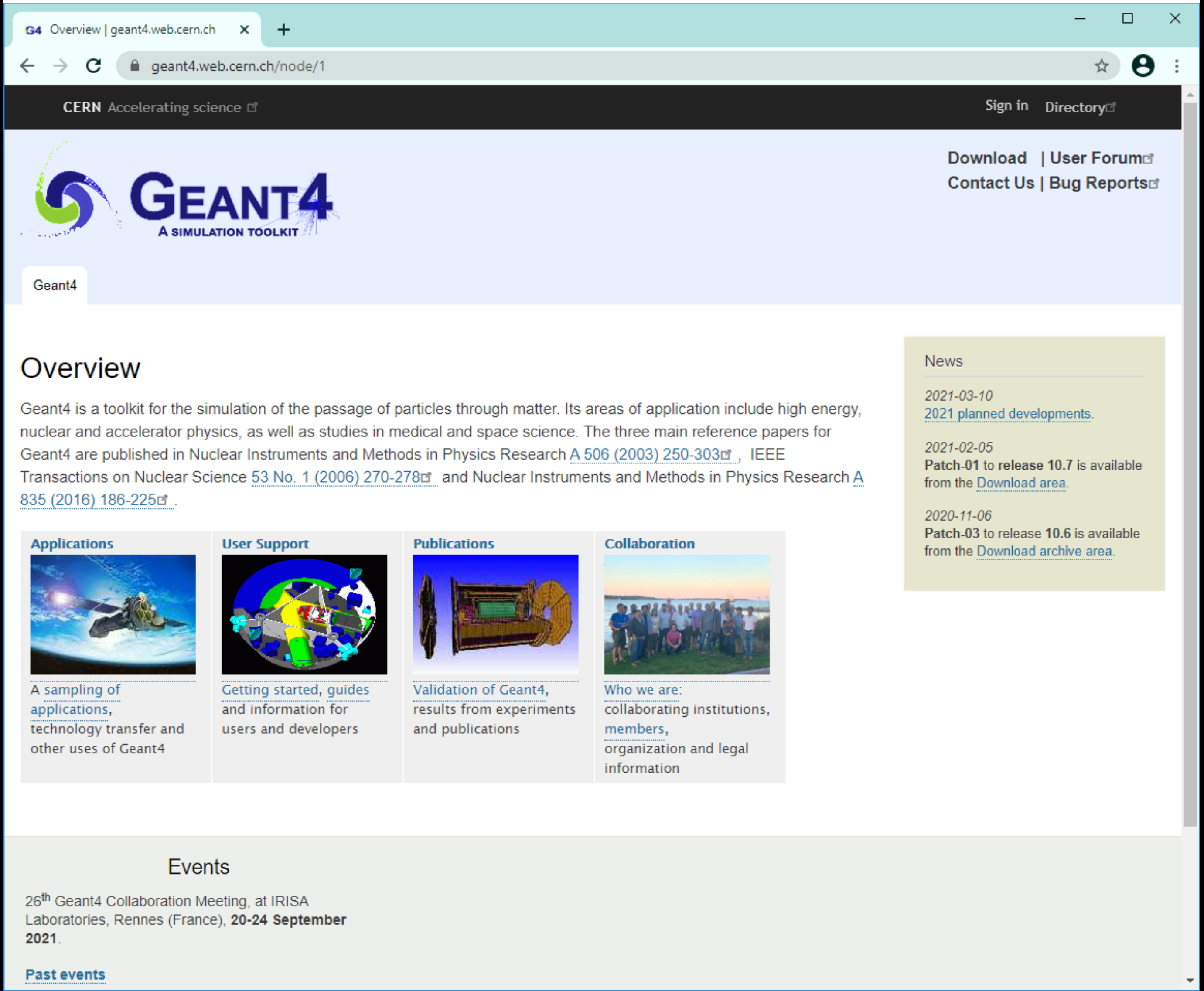
Tools you can use

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



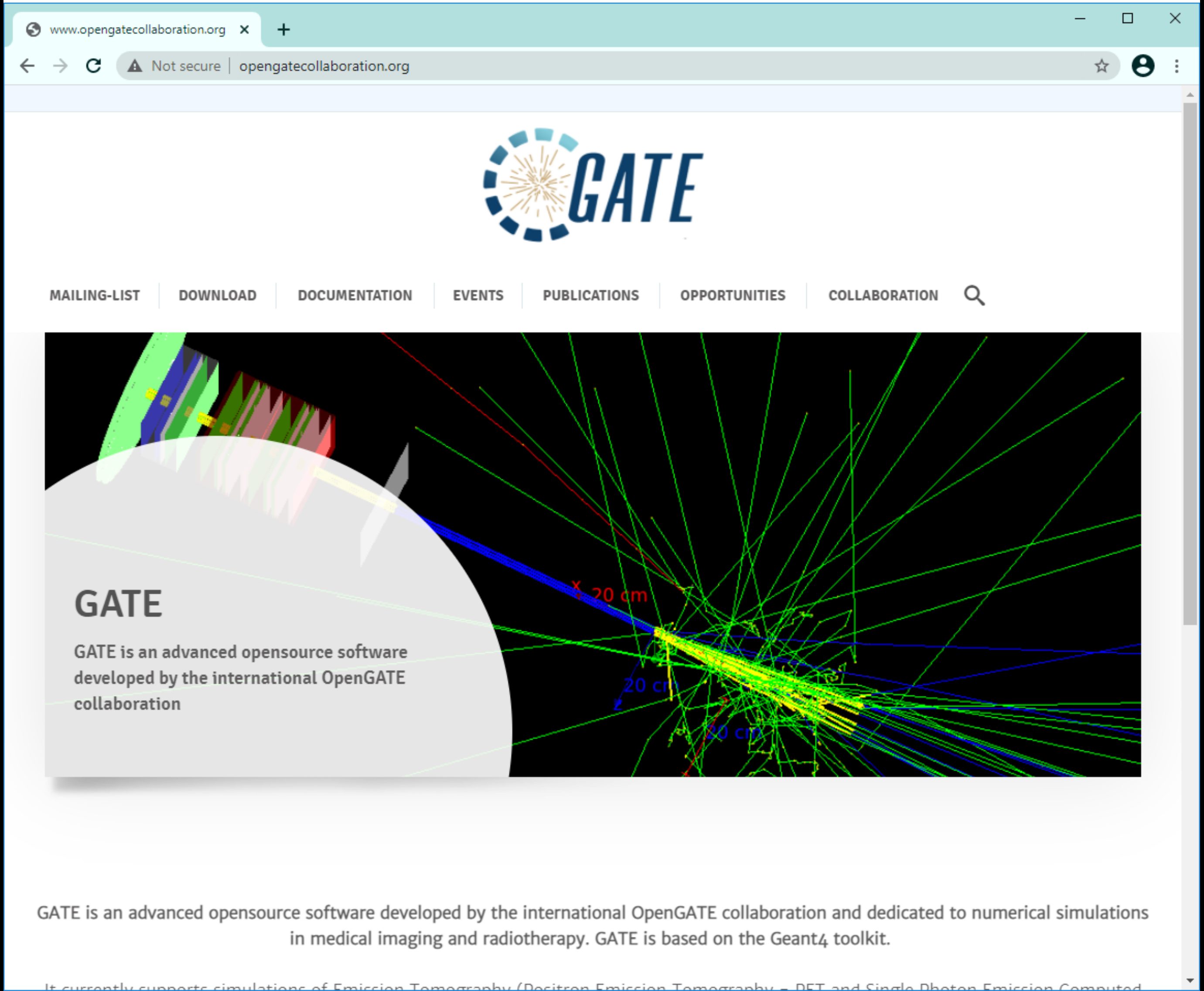
Tools you can use

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



Tools you can use

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



GATE

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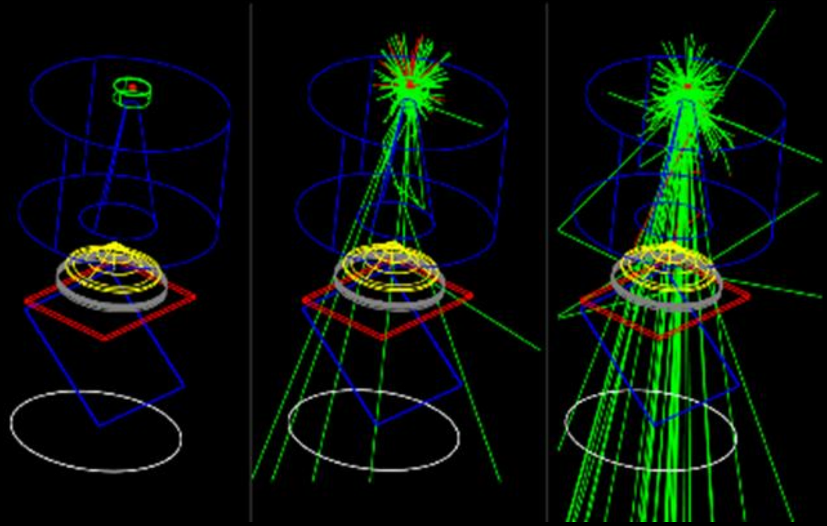

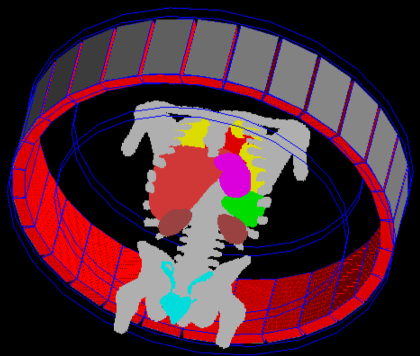

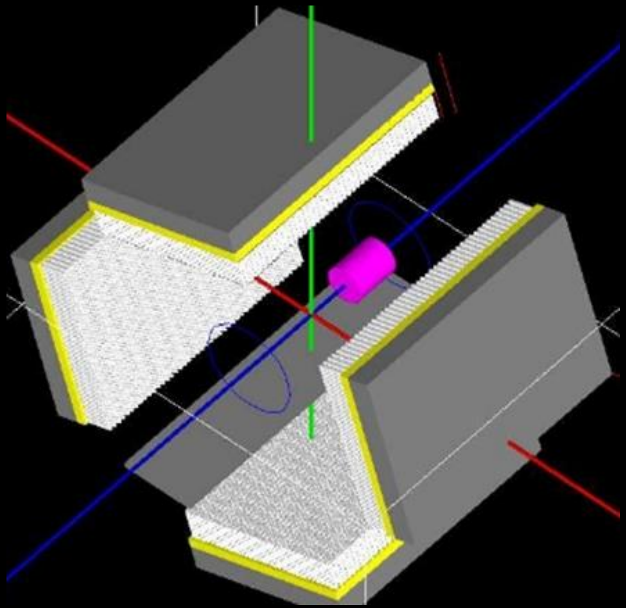

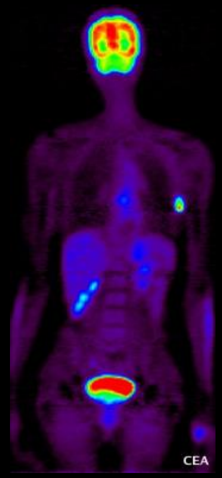

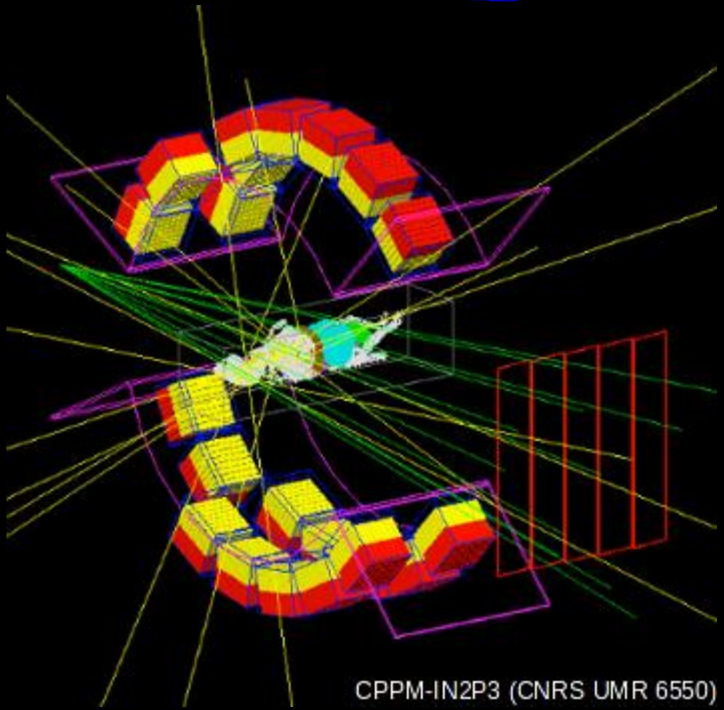

GATE

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 User developed data analysis tools
- χ Undocumented bugs

Monte Carlo Training

http://www.opengatecollaboration.org/

TRAININGS

The OpenGATE collaboration in partnership with CNRS Formation Entreprises are proposing two annual trainings organized in France: one dedicated to beginner users and one dedicated to Python data analysis. Those trainings are provided in english, they are open to 20 users maximum with 3 teachers.

Further, the collaboration can propose special trainings for companies (on site) wishing to use GATE, don't hesitate to contact us for more information.

2022:

- 8-10 March: Python data analysis for GATE simulations, Registration open

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 - **<u>if the simulation has been validated</u>**
  - ✓ Geometry
  - ✓ Detector modelling
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<u>Comparison with experimental data</u>

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Getting Started with GATE

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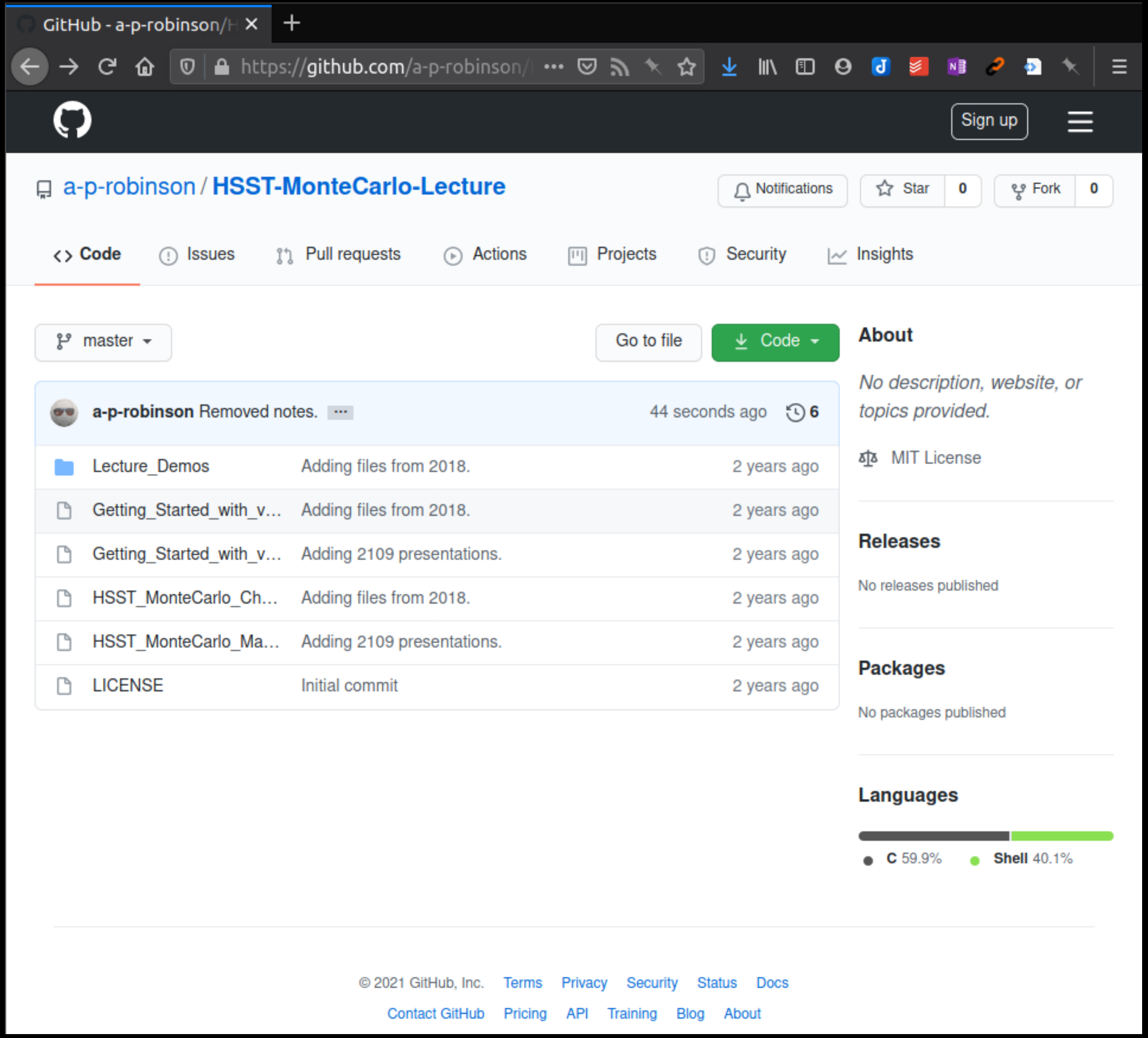

https://github.com/a-p-robinson/HSST-MonteCarlo-Lecture/

http://www.opengatecollaboration.org/

https://gate.uca.fr/download/vgate

https://www.virtualbox.org/