Geant4 physics capability for Heavy Ion Therapy

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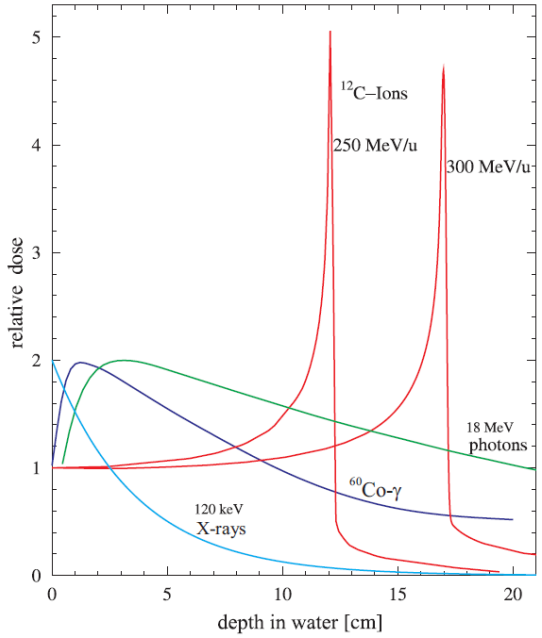
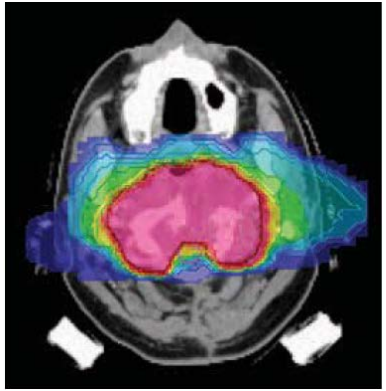
Heavy Ion Therapy

Depth dose distribution in water

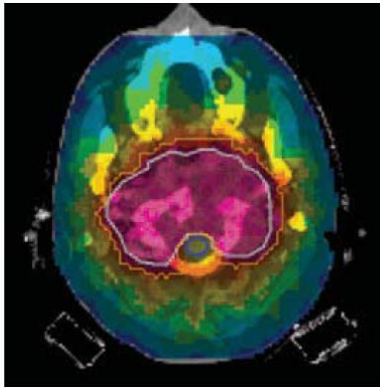


Heavy-Ion Therapy (HIT) demonstrates advantages over conventional photon therapy:

- Highly conformal dose delivery
- **Increased healthy tissue sparing**
- Increased Radiobiological Effectiveness (RBE)



Carbon ion beam irradiation



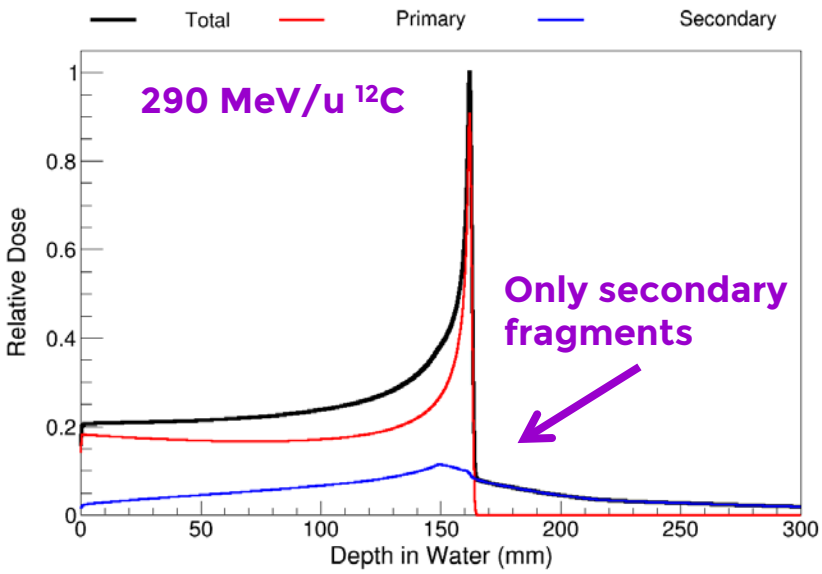
X-ray Intensity Modulated Radiation Therapy

Reference: Tumor Therapy with Heavy Ions, Information for physicians, students, and patients, Association for the Promotion of Tumor Therapy with Heavy Ions

Monte Carlo codes for HIT

- Be able to describe
  - the mixed radiation field of HIT
  - Particle interactions in the human anatomy
- Be able to calculate the spatial energy deposition pattern
- Be accurate!
- Be fast!

HIT mixed radiation field

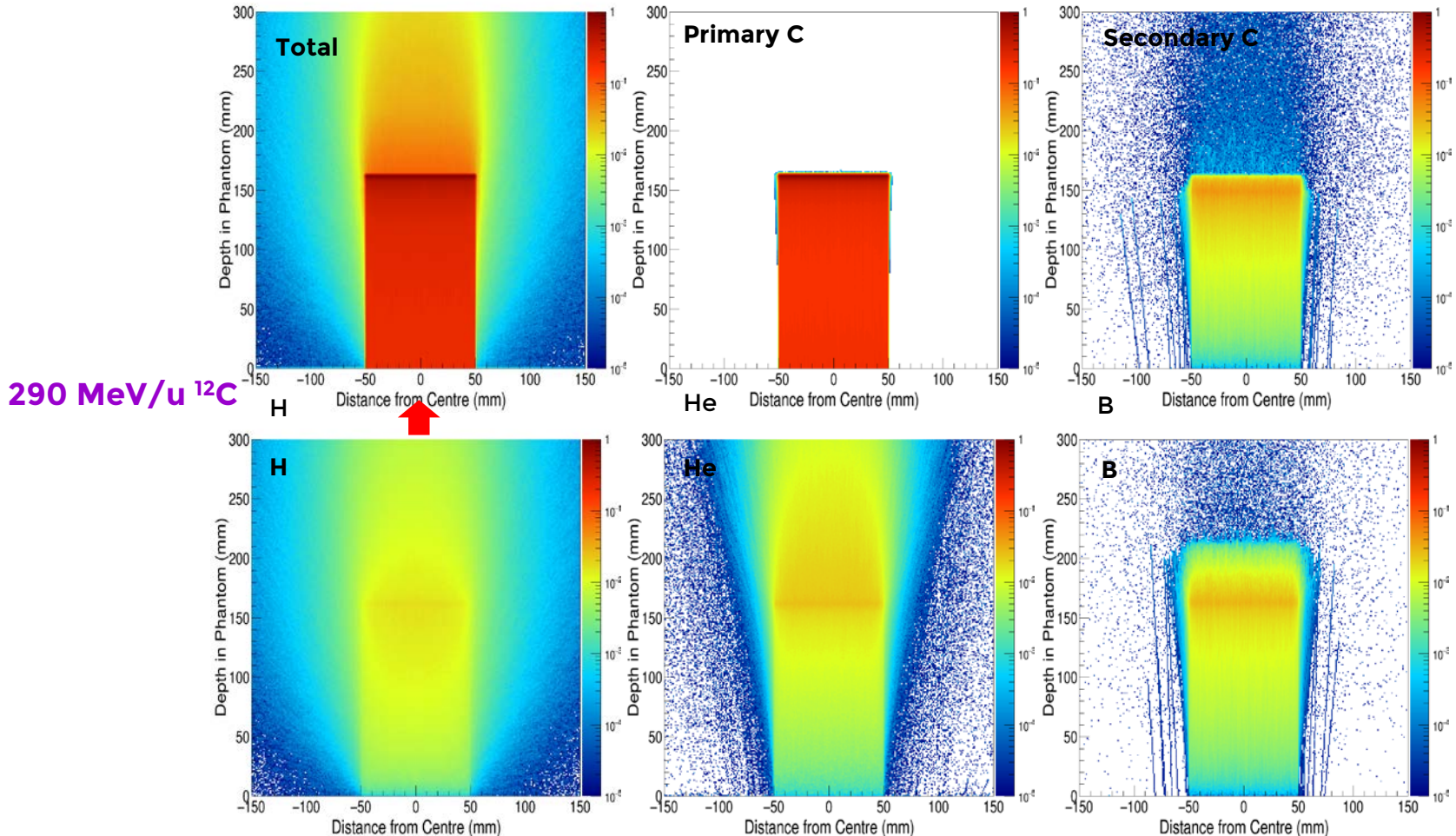


Reference:
Francis et al, PMB, 59 (2014) 7691

Contribution to the **dose**:

- 64% - ^{12}C ions via em interactions
- 36% - produced fragments and their secondaries
    - 14% - protons
    - 13% - alpha particles
    - 4.2 % - B ions
    - 1.7% - Li ions
    - 1.3% - Be ions

Dose in the water phantom



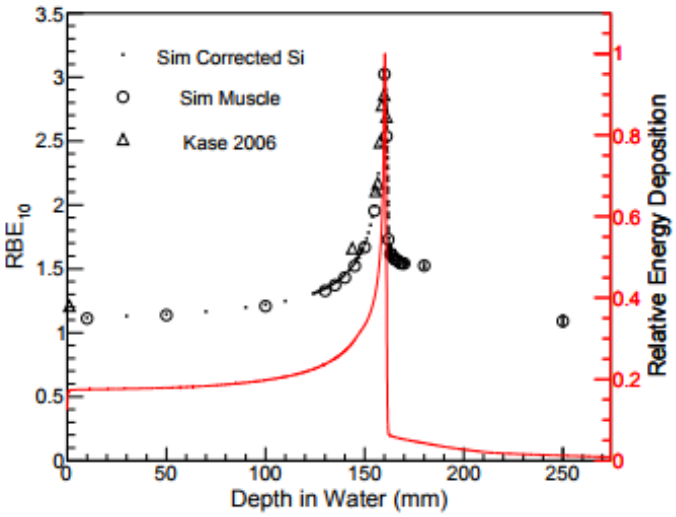
Radiobiological effectiveness (RBE)

$RBE = D_{ref}/D_{ion}$ to produce an identical biological endpoint, input to the TPS

An underlying complication in HIT is that **the RBE varies greatly**

- Especially at the distal edge of the Bragg Peak due to the mixed radiation field.
- As a result, an accurate RBE determination is crucial for the treatment planning and for routine QA

RBE_{10}: RBE at 10% cell surviving fraction in Human Salivary Gland



Correction factors to convert microdosimetry measurements in silicon to tissue in ^{12}C ion therapy

David Bolst[1], Susanna Guatelli[1], Linh T. Tran[1], Lachlan Chartier[1], Michael L. F. Lerch[1], Naruhiro Matsufuji[2], and Anatoly B. Rosenfeld[1]

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PMB 62(6), pp. 2055-2069, 2017

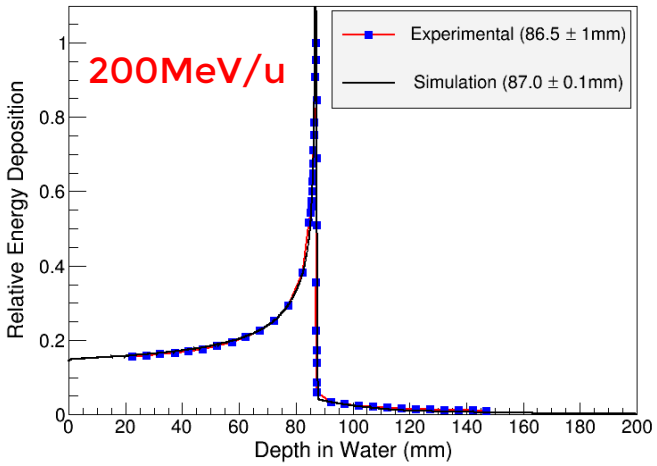
Outline

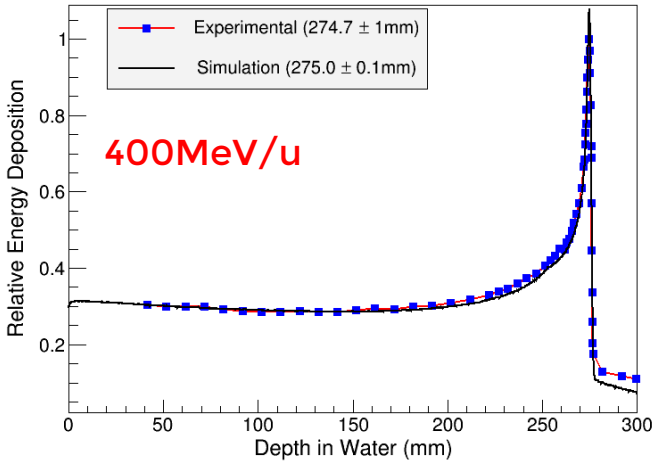
Validation of

- Bragg Peak position
- Bragg Peak shape
- Fragmentation
- β^+ radioisotope production

Bragg Peak validation

- Reference: E. Haettner (2006/2013) for 200MeV/u and 400MeV/u, measurements performed at GSI
- In water
- Step limit 0.05mm
- Cut size 0.1mm
- Standard EM option 3, BIC for hadronic interactions





Bragg Peak Position

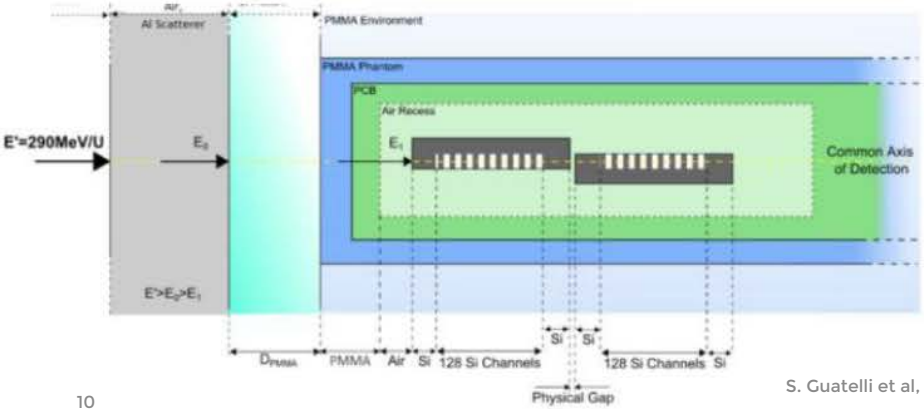
E. Debrot, M. Newall, S. Guatelli, M. Petasecca, A. B. Rosenfeld

Emily Debrot in action

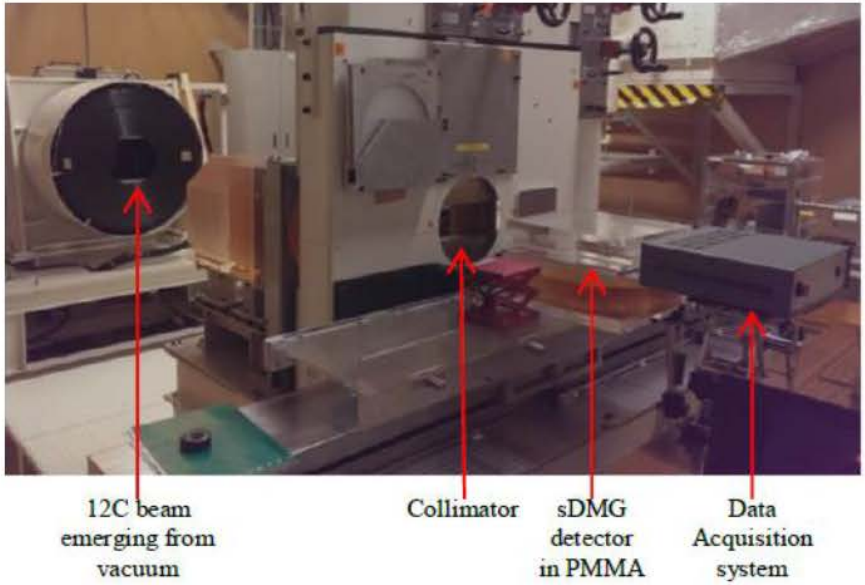
Bragg Peak position– HIMAC beam line

E. Debrot, M. Newall, S. Guatelli, M. Petasecca, A. B. Rosenfeld

The Serial Dose Magnifying Glass



Experimental set-up, HIMAC, NIRS, Japan



S. Guatelli et al, 2017 Geant4 User Workshop, Wollongong, 19-22 September 2017

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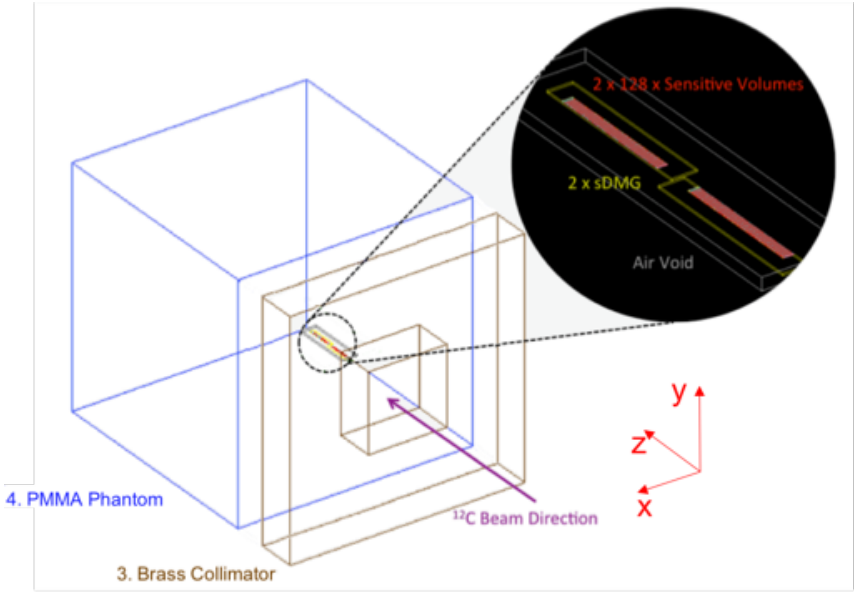
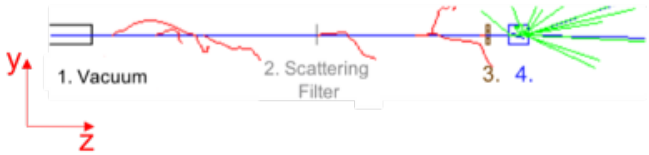
Simulation set-up



Geant4 10.1

Physics Processes	Geant4 Models
Electromagnetic physics	G4EmStandardPhysics_option3
Decay physics	G4DecayPhysics
Radioactive decay physics	G4RadioactiveDecayPhysics
Hadronic physics	G4HadronicPhysicsQGSP_BIC_HP
	G4HadronElasticPhysicsHP
	G4StoppingPhysics
	G4EmExtraPhysics
	G4IonINCLXXPhysics



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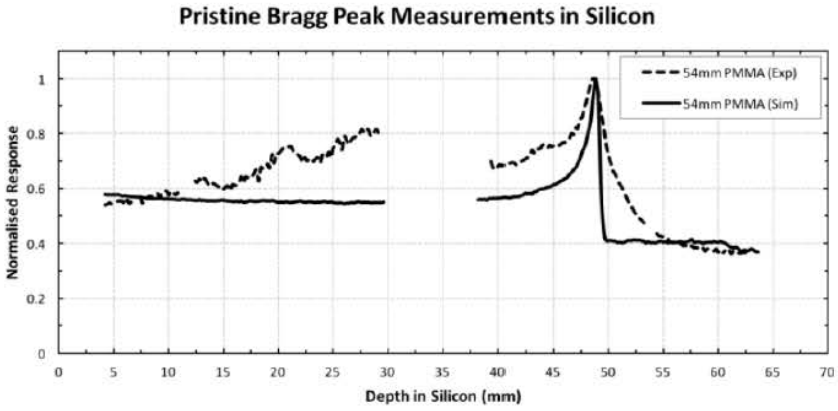
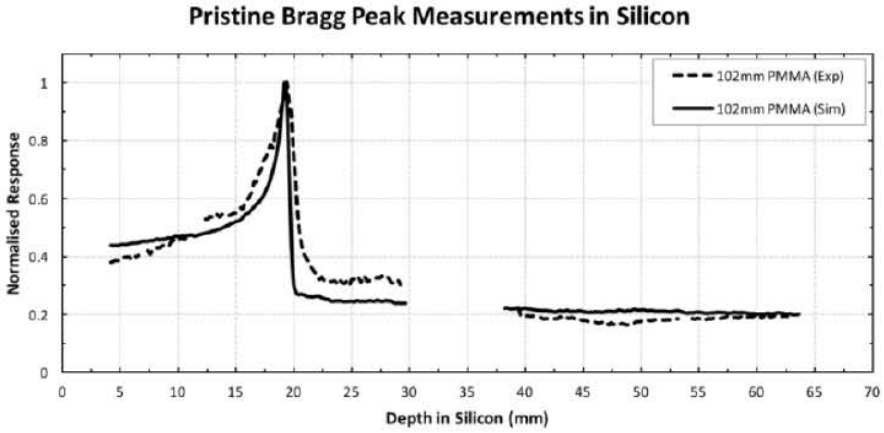
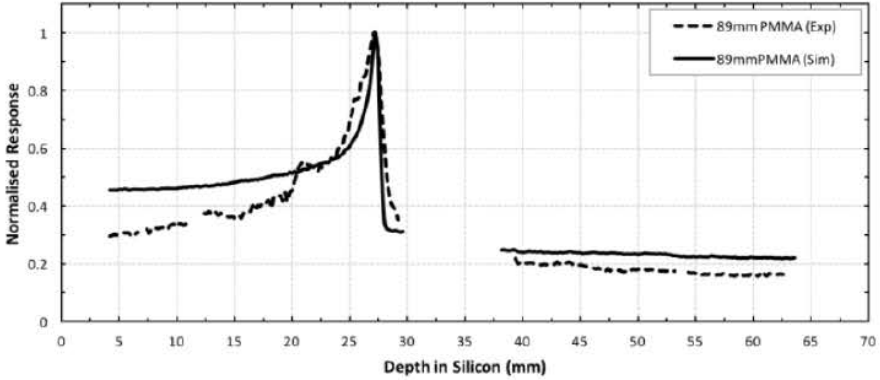
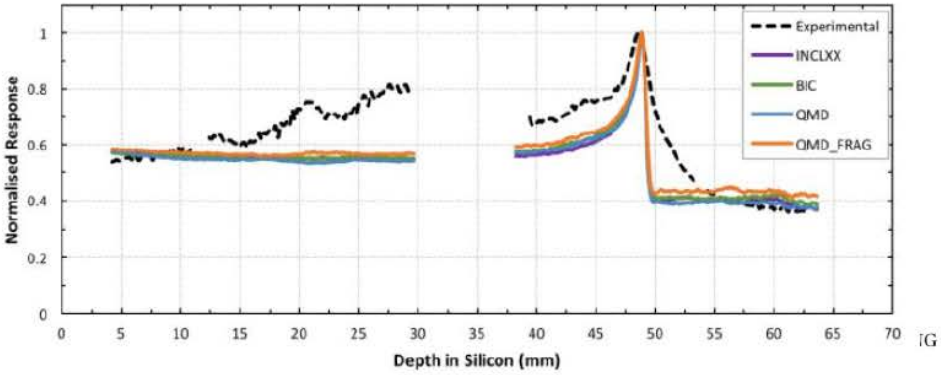
Results

G4EmStandardPhysics_option3









S. Guatelli et al, 2017 Geant4 User Workshop, Wollongong, 19-22 September 2017

Results

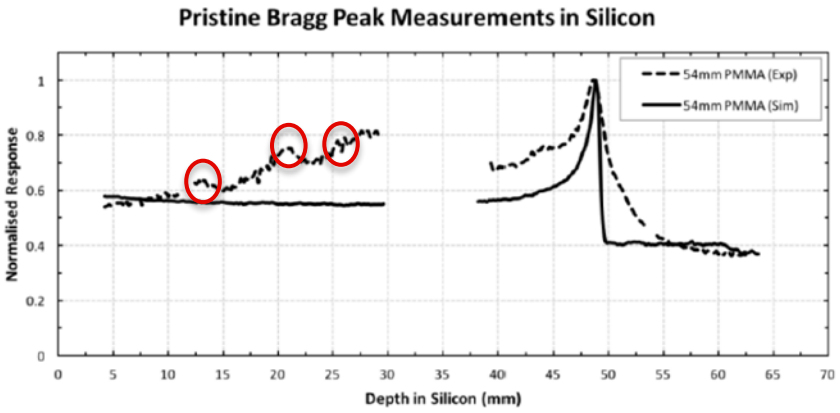
Depth in PMMA (mm)	Depth of Bragg peak in silicon (mm)	
	Experimental	Simulation
(±1)	(±0.4)	(±0.2)
54	48.7	48.8
89	27.2	27.2
102	19.4	19.2

Excellent agreement between experiment and simulation with less than 1.1% difference in the Bragg Peak position.

Within 200 μm spatial resolution

Comments (1)

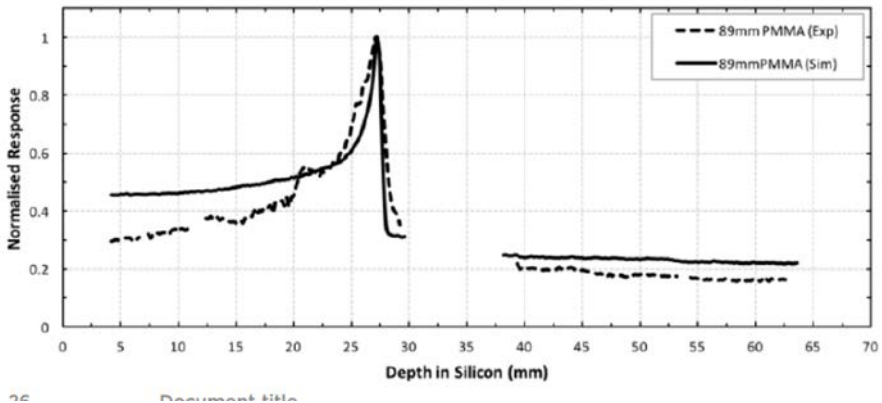
- The peaks observed at depths ~ 13, 21 and 27 mm in silicon in the experimental profiles are due to radiation damage sustained by the detector.



Comments (2)

- Several differences arise in the shape of the experimental and simulated dose profiles.
  - Radiation damage in the detector
  - Variations in the response of individual SVs
  - Dose rate dependence and non-linear response of silicon with changes in particle LET.

- The simulation presents the ideal case where the charge collection efficiency is 100% and cross-talk or charge charging between sensitive volumes does not occur



Validation of Geant4 fragmentation for HIT

Nuclear Inst. and Methods in Physics Research, A 869 (2017) 68–75

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Validation of Geant4 fragmentation for Heavy Ion Therapy

David Bolst [a], Giuseppe A.P. Cirrone [b], Giacomo Cuttone [b], Gunter Folger [c], Sebastien Incerti [d,e], Vladimir Ivanchenko [c,f], Tatsumi Koi [g], Davide Mancusi [h], Luciano Pandola [b], Francesco Romano [b,i], Anatoly B. Rosenfeld [a], Susanna Guatelli [a,*]

[a] Centre for Medical Radiation Physics, University of Wollongong, Australia
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[d] CNRS/IN2P3, Centre d'Etudes Nucléaires de Bordeaux-Gradignan, France
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[h] French Alternative Energies and Atomic Energy Commission (CEA), Saclay, France
[i] National Physical Laboratory, Acoustic and Ionizing Radiation Division, Teddington TW11 0LW, Middlesex, UK

V10.2.p2

Summary of Fragment yields

- Models agreed ~5-35% with exp
- QMD-F performed best for lighter fragments

Mean %Error

Z	BIC	QMD	QMD-F	INCL
1	19 ± 2	14 ± 2	5 ± 2	8 ± 2
2	6 ± 1	17 ± 1	5 ± 1	10 ± 1
3	4 ± 7	25 ± 7	31 ± 7	21 ± 7
4	32 ± 10	14 ± 10	22 ± 10	15 ± 10
5	19 ± 8	20 ± 8	26 ± 8	33 ± 8

Angular Distribution Summary

- INCL performed significantly better than the other models, particularly for higher Z
- QMD performed best for protons
- BIC and QMD produced broader distributions

Mean %Error

Z	BIC	QMD	INCL
1	14 ± 4	7 ± 4	15 ± 4
2	24 ± 2	16 ± 2	7 ± 2
3	29 ± 8	26 ± 8	16 ± 8
4	47 ± 14	42 ± 14	18 ± 14
5	132 ± 12	135 ± 12	28 ± 13

Energy Distribution Summary

- BIC and QMD perform similar to one another with INCL performing noticeably more poor

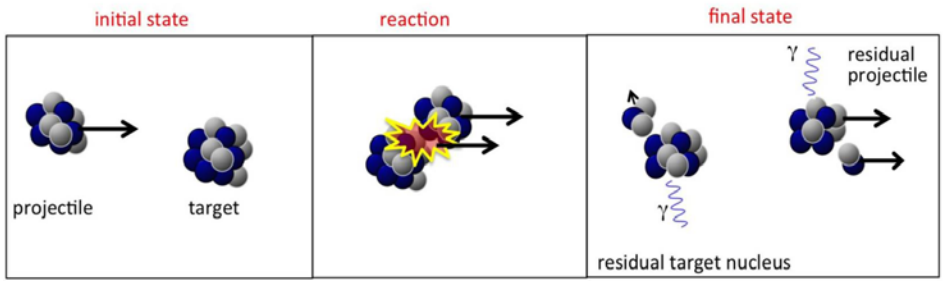
- INCL commonly produces lower energy distributions

Mean %Error

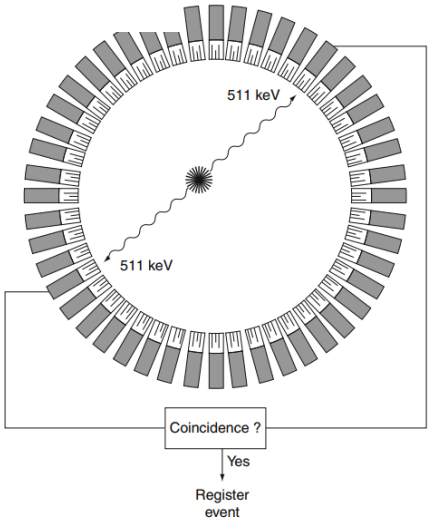
Z	BIC	QMD	INCL
1	26 ± 6	22 ± 6	46 ± 6
2	30 ± 7	33 ± 7	73 ± 7
3	41 ± 8	42 ± 8	93 ± 8
4	61 ± 9	52 ± 9	116 ± 9
5	221 ± 11	194 ± 10	398 ± 10

Verification of Bragg Peak Position

- Positron Emission Tomography (PET)
  - Coincidence detection of 511 KeV annihilation photons



Nuclear Fragmentation of a Carbon-12 Atom [1]



[1] Kraan, A. C. (2015). Range Verification Methods in Particle Therapy: Underlying Physics and Monte Carlo Modeling. *Frontiers in Oncology*, *5*, 150. http://doi.org/10.3389/fonc.2015.00150

Evaluation of Geant4 for in-vivo range verification in Heavy Ion Therapy

[1,2]Andrew Chacon, [2,1]Mitra Safavi-Naeini[1,3], Susanna Guatelli, [2]Marie-Claude Gregoire, [1,3]Anatoly Rozenfeld

Experiment and PET Imaging Collaborators

[4]Akram Mohammadi, [4]Muneka Nitta, [4]Fuminiko Nishikido, [4]Yuma Iwao, [4]Hideki Tashima, [4]Eiji Yoshida, [4]Taiga Yamaya

[1] University of Wollongong, Centre for Medical Radiation Physics, Wollongong, NSW, Australia
[2] Australian Nuclear Science and Technology Organisation, Human Health, Lucas Heights, NSW, Australia
[3] University of Wollongong, Illawarra Health and Medical Research Institute, Wollongong, NSW, Australia
[4] National Institutes for Quantum and Radiological Science and Technology, National Institute of Radiological Sciences (NIRS), Inage-ku, Chiba, Japan

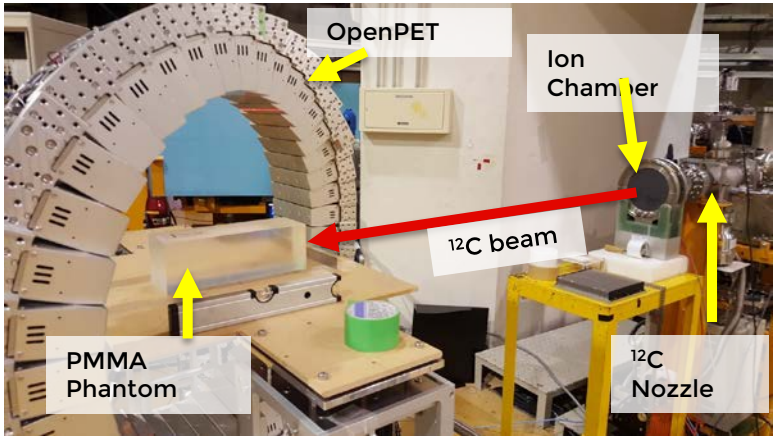
Aim

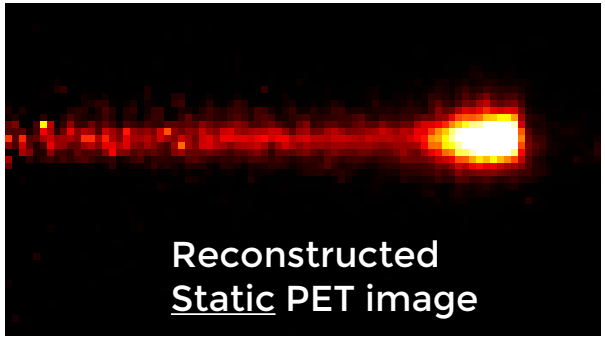
- To identify which hadronic ion physics model best describes the production of β^+ emitters for ^{12}C therapy
  - Binary Ion Cascade (BIC),
  - Quantum Molecular Dynamics (QMD)
  - Liege Intranuclear Cascade model (INCL)

- See the talk of Andrew Chacon

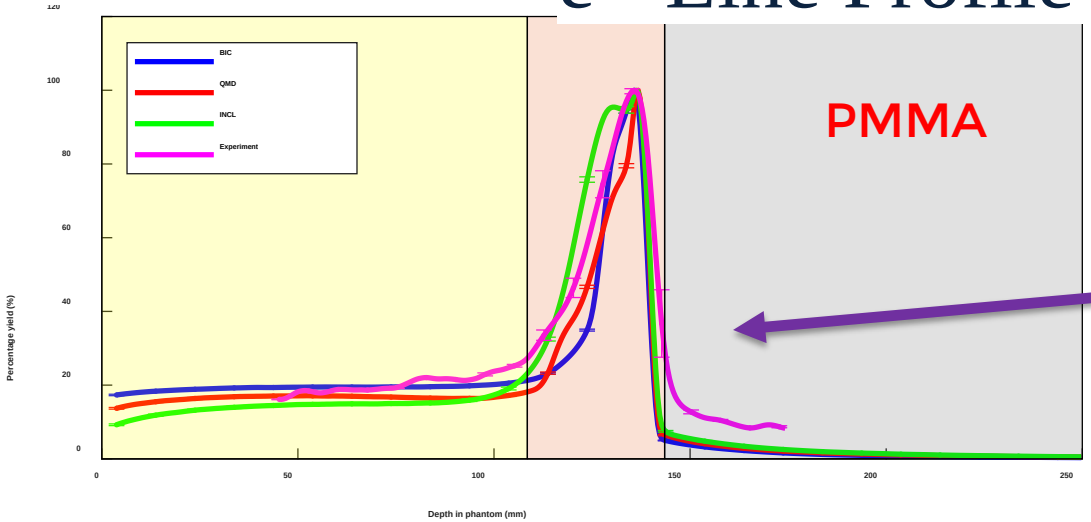
Experiment

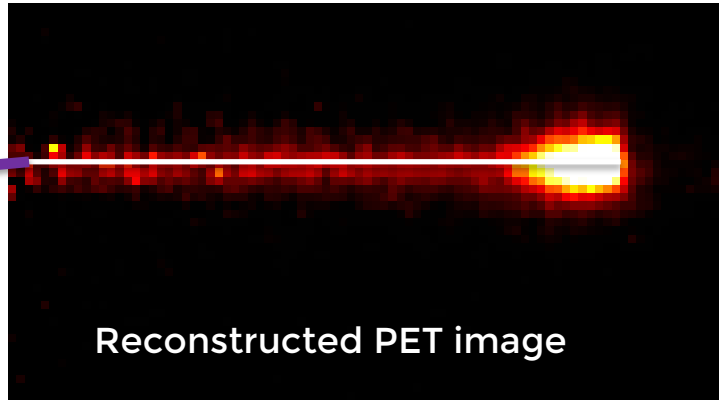
1. Carbon ion energies
   - 290, 230, 350 MeV/u
2. Incident on a phantom
   - Gelatin (Water), PMMA, Polyethylene
     - 10 x 10 x 30 cm^3
3. PET Scanner measured activity
   - 36 minutes post irradiation
4. Image reconstructed using Ordered Subset Expectation Maximisation Model (3D-OSEM)
   - Voxel size: 0.5 mm^3
   - Resolution: 2.6 mm

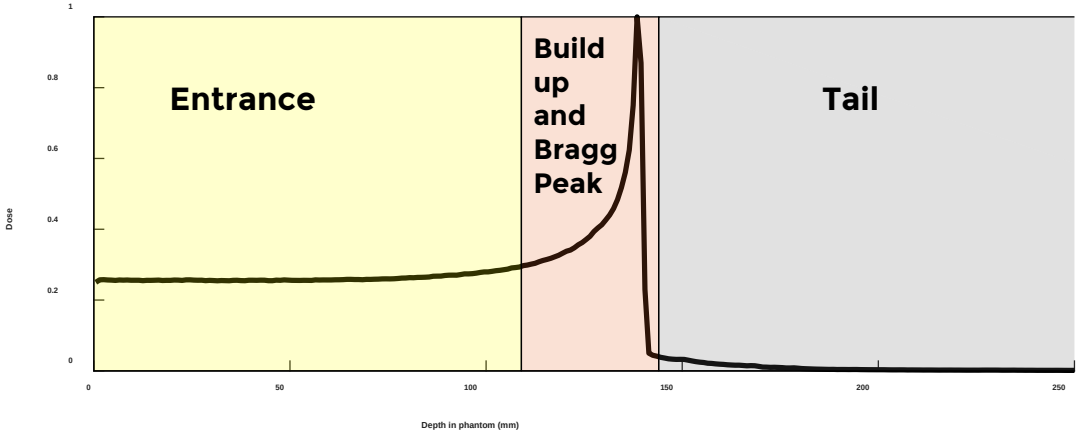




e+ Line Profile







Conclusion

- Geant4 is more and more used for HIT

- Validation of Bragg Peak and its position
  - In the MedPhys Benchmarking suite
  - Currently internal regression test at CMRP

- Validation of fragmentation and β^+ production
  - In the MedPhys Benchmarking suite (frag)
  - Currently internal regression testing at CMRP (frag and and β+ production)
  - Regression tests: G4 9.6-> 10.3

- We do validation w.r.t. data available in the literature and our own detectors