Validation of Geant4 fragmentation for Heavy Ion Therapy

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¹²C Therapy

- Conformal treatment
 - Sparing Organs at Risk (eg. spinal chord) close to the target tumour

High LET/RBE

- Ideal for hypoxic/fast proliferating tumours (eg. head, neck)
- Complex radiation field
 - Fragmentation of primary beam produces diverse secondary field
 - Vital to take into account for treatment planning



Energy Deposition in the water phantom

Energy Deposition by incident ¹²C ions Total Energy Deposition



Project Summary

- The accuracy of different fragmentation models in Geant4 were benchmarked for a 400MeV/u ¹²C beam
- Alternative approaches investigated
 - BIC (Binary Intranuclear Cascade)
 - QMD (Quantum Molecular Dynamics)
 - INCL (Liege Intranuclear Cascade)
- Work to be part of system testing of Geant4 releases



Previous Work

 Bohlen Studied BIC and QMD in Geant4 v9.3 and FLUKA



IOP PUBLISHING

Phys. Med. Biol. 55 (2010) 5833-5847

doi:10.1088/0031-9155/55/19/014

Benchmarking nuclear models of FLUKA and GEANT4 for carbon ion therapy

T T Böhlen^{1,2}, F Cerutti¹, M Dosanjh¹, A Ferrari¹, I Gudowska², A Mairani³ and J M Quesada⁴



Figure 5. Fragment build-up curves in water of a 400 MeV/u carbon beam as a fraction of primary carbon ions N/N_0 . Experimental data are shown as points (Haettner *et al* 2006). Simulations done for FLUKA (solid) and for GEANT4 using the BIC LI (dashed) and the G4QMD (dotted) model are displayed as lines. The dashed vertical line indicates the position of the Bragg peak.

Experimental Data

- Fragmentation study of a 400MeV/u ¹²C pencil beam (FWHM 5mm) studied at GSI
- Bragg Curve, fragment yields, angular and energy distribution of fragments

OP PUBLISHING

PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. 58 (2013) 8265-8279

doi:10.1088/0031-9155/58/23/8265

Experimental study of nuclear fragmentation of 200 and 400 MeV/u ¹²C ions in water for applications in particle therapy

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Experimental Method



Simulation Setup (1)

- Versions: 9.6p4, 10.0, 10.1, 10.2p1 and 10.2p2 of Geant4 were benchmarked using
 - $\,^\circ\,$ BIC, QMD and INCL
 - EM Std Opt3
- Fragment yields, angular and energy distributions measured

400MeV/u ¹²C pencil beam was fired onto a variable thickness of water and fragments with Z=1-5 were recorded in a 2.94m radius hemisphere

400MeV ¹²C

Simulation Setup (2)

- Total fragment yields were calculated within a 10° cone (θ₁=10°) for different water thicknesses
- Angular distributions were recorded within 0.4° spans ($\theta_2 \theta_1 = 0.4^\circ$)





Simulation Setup (3)

- Energy distributions were measured based on the time to reach the collection hemisphere
- Assumptions made:
 - All fragments are created at the centre of the phantom
 - Recorded fragments are due to the only most abundant isotope (¹H, ⁴He, ⁷Li, ⁹Be, ¹¹B



Bragg Peak

- All three models tested agreed well with experimental measurements
- BIC and INCL performed slightly better QMD

	BIC	\mathbf{QMD}	INCL
p-value	0.317	0.215	0.325





Fragment Yields

Version 10.2p2









\mathbf{Z}	BIC	$\mathbf{Q}\mathbf{M}\mathbf{D}$	INCL
1	6.42 E- 52	1.09E-32	4.78 E- 12
2	0.00281567	1.28E-19	2.23E-09
3	0.81582	1.91E-10	$5.05 \text{E}{-}07$
4	1.35 E-05	0.452742	0.355545
5	0.0595837	5.52E-05	1.04E-08



Angular Distribution



Angular Distributions are normalised to the total experiment counts In total 32 distributions compared Version 10.2p2









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

Energy Distribution

L/2

Energy Distributions are normalised to the total experiment counts In total 159 distributions compared Version 10.2p2







Energy Distribution Summary

- BIC and QMD perform similar to one another with INCL performing noticeably more poor
- Possible energy miscalibration of experiment may be the reason for such disagreement for the energy distributions
 - Measurements done over two session one calibration shifted from (358±23)MeV/u to (402±26)MeV/u, with the first measurement being what was expected

Mean %Error								
	\mathbf{Z}	BIC	QMD	INCL				
	1	26	22	46	-			
	2	30	33	73				
	3	41	42	93				
	4	61	52	116				
	5	221	194	398				
					-			
		1	0.2р2 • в	IC • QMD				
P-value								

0.9

0.8

0.7

Leduency 0.6

0.3

0.2

0.1

Regression Testing



BIC changes







INCL changes



Fragment Yields

- Protons performed best in 9.6p4
- Versions 10.1-10.2p2 do not vary significantly from one another

Mean %Error

Version	Z	BIC	$\mathbf{Q}\mathbf{M}\mathbf{D}$	INCL	Version	Z	BIC	$\mathbf{Q}\mathbf{M}\mathbf{D}$	INCL
9.6p4	1	3	10	4	10.1	1	19	14	8
	2	15	31	15		2	6	17	10
	3	13	12	31		3	4	25	21
	4	45	5	28		4	33	14	15
	5	19	12	9		5	19	20	33
10.0	1	11	18	5	10.2 p2	1	19	14	8
	2	17	31	18		2	6	17	10
	3	10	14	13		3	4	25	21
	4	38	9	15		4	32	14	15
	5	19	20	33		5	19	20	33

P-value

Version	\mathbf{Z}	BIC	QMD	INCL	Version	Z	BIC	QMD	INCL
9.6p4	1	0.164125	9.56E-15	0.00454177	10.1	1	1.77E-55	1.82E-32	4.36E-12
	2	6.60E-19	6.39E-66	8.75E-16		2	0.00390083	3.39E-19	5.18E-09
	3	0.00142822	0.0304257	1.55E-17		3	0.801321	1.92E-10	4.67E-07
	4	6.07E-11	0.989617	0.00110671		4	1.50E-05	0.476251	0.360502
	5	0.0429735	0.233434	0.161929		5	0.0549038	5.79E-05	9.45E-09
10.0	1	2.55E-17	1.77E-49	3.19E-05	10.2p2	1	6.11E-52	1.31E-32	4.97E-12
	2	3.40E-21	2.79E-67	4.82E-24		2	0.00282421	1.08E-19	2.19E-09
	3	0.096467	0.0025111	0.00474973		3	0.806699	1.91E-10	4.09E-07
	4	1.34E-07	0.845022	0.325135		4	1.42E-05	0.477444	0.358123
	5	0.0563761	5.89E-05	7.52E-09		5	0.0568256	6.03E-05	1.04E-08



Angular Distribution

 INCL improved greatly, going from ~10% of distributions having a p-value ≥ 0.05 in v9.6p4 to ~30% in 10.0 and ~40% in 10.1+



INCL changes



Energy Dist

- BIC was seen not to vary much for each different version
- QMD and INCL performed best in v9.6p4



INCL frequently seen to produce energy distributions shifted to lower energies compared to BIC and QMD (and exp) in version 10 and up 9.6p4 distributions were higher energy than in 10.X for the most part except for



Summary

- Fragment data from a 400MeV/u ¹²C beam in water was used to benchmark Geant4
- Fragment yield values agreed within ~20% of experimental values
- Angular Distributions agreed ~30% with the exception of B. INCL performs much better than BIC and QMD in versions 10.0 and higher
- Energy distributions agreed noticeably poorer (possible experimental calibration error)
- For different versions of Geant4, each model can vary significantly from one another
- This work will be part of regression testing for future releases of Geant4



Thank you

