Validation of Geant4 fragmentation for Heavy Ion Therapy

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Geant4 Users Workshop 2017, Wollongong

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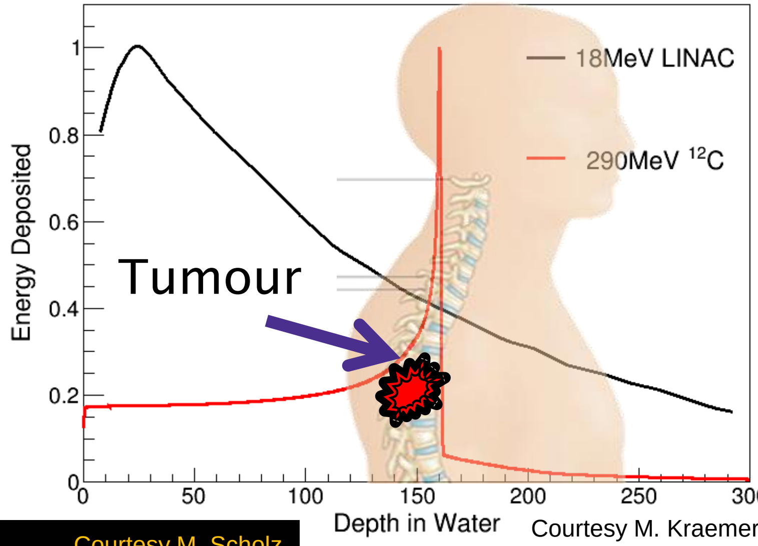
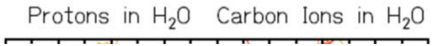
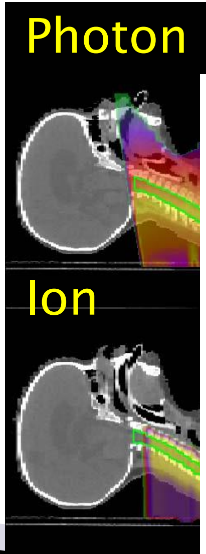
Carbon Therapy

- Conformal treatment
  - Sparing Organs at Risk (eg. spinal chord) close to the target tumour
- High LET
  - Ideal for hypoxic/fast proliferating tumours
- Complex radiation field
  - Fragmentation of primary beam produces diverse secondary field
  - Vital to take into account for treatment planning

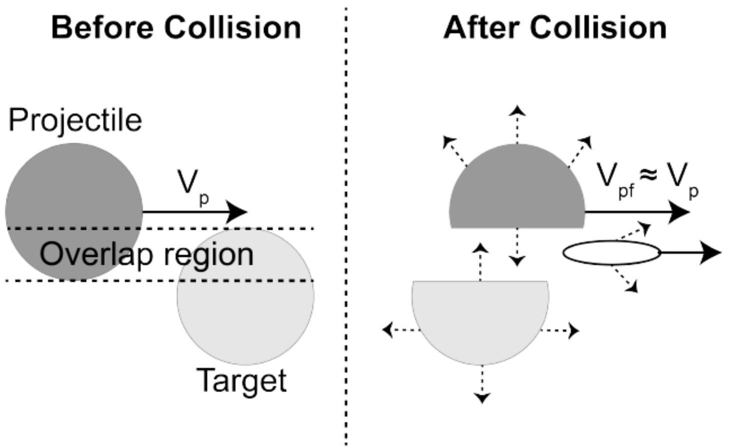


Courtesy M. Kraemer GSI



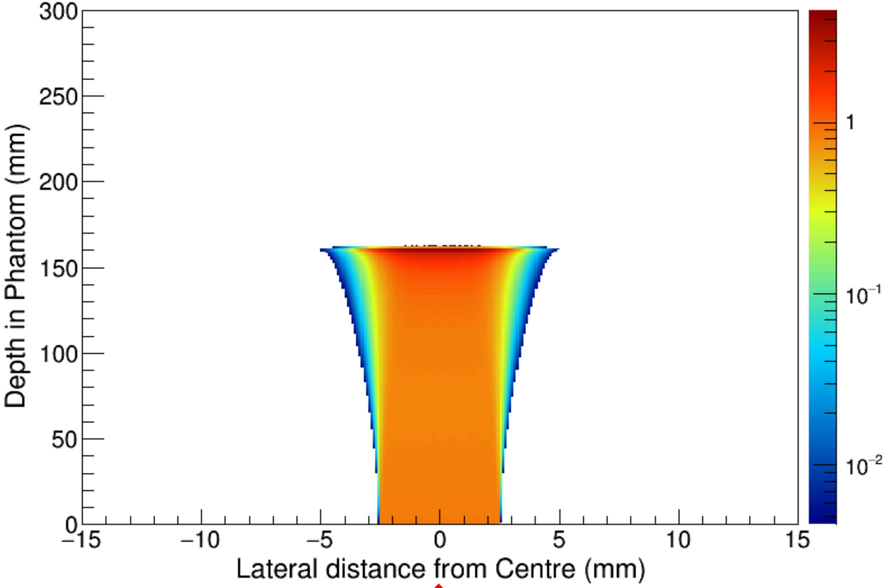


Courtesy M. Scholz, GSI Darmstadt, Germany



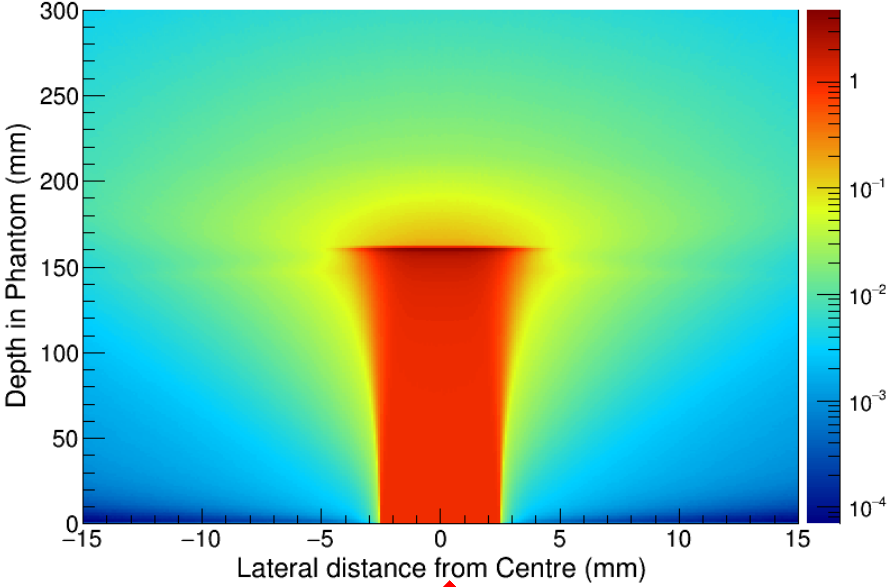
Energy Deposition in the water phantom

Energy Deposition by incident ^{12}C ions



^{12}C ion beam

Total Energy Deposition



^{12}C ion beam

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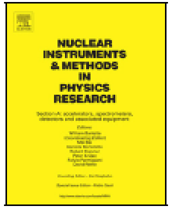

Validation of Geant4 fragmentation for Heavy Ion Therapy

CrossMark

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[d] CNRS/IN2P3, Centre d'Etudes Nucléaires de Bordeaux-Gradignan, France
[e] Université Bordeaux, Centre d'Etudes Nucléaires de Bordeaux-Gradignan, France
[f] Tomsk State University, Tomsk, Russia
[g] SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, CA, 94025, USA
[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

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Experimental Data

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

IOP 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* ^{12}C ions in water for applications in particle therapy

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GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

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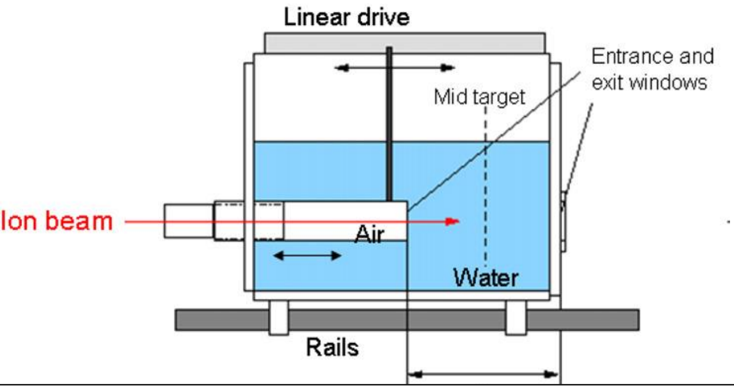
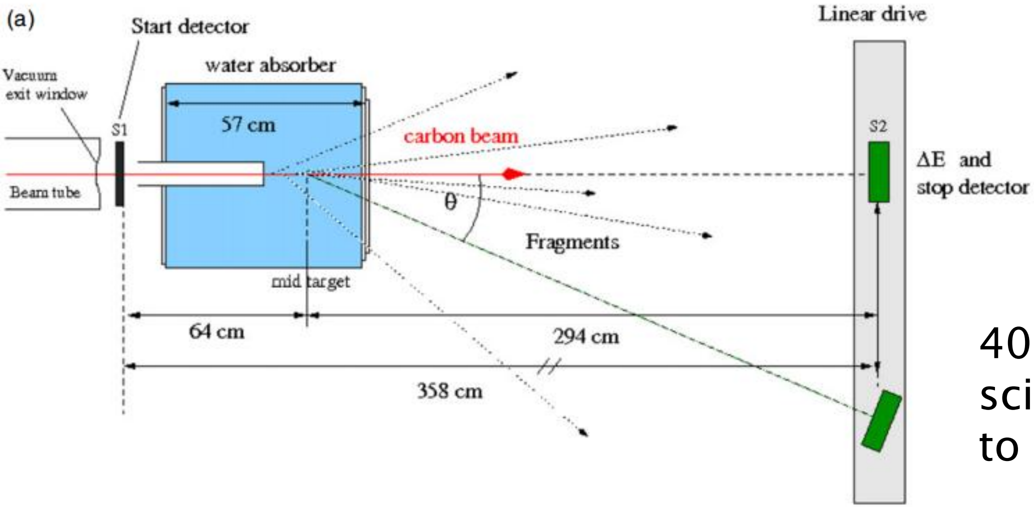
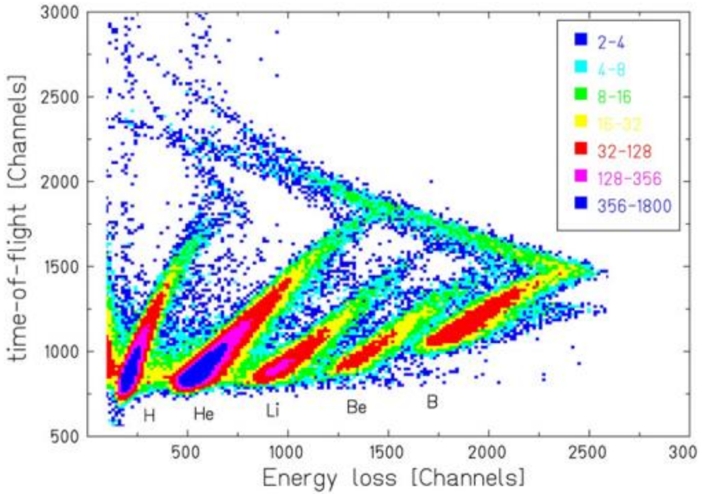
Experimental Method







40x40mm^2 plastic scintillator coupled to Hamamatsu PMT

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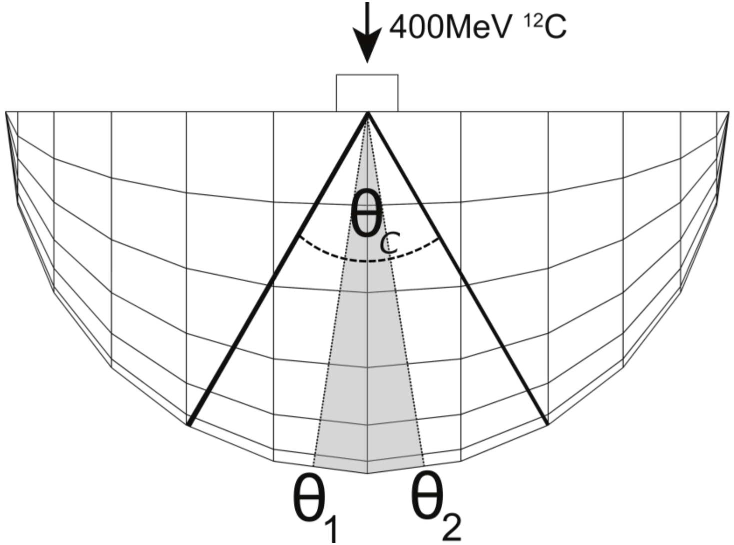
Simulation Setup (1)

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

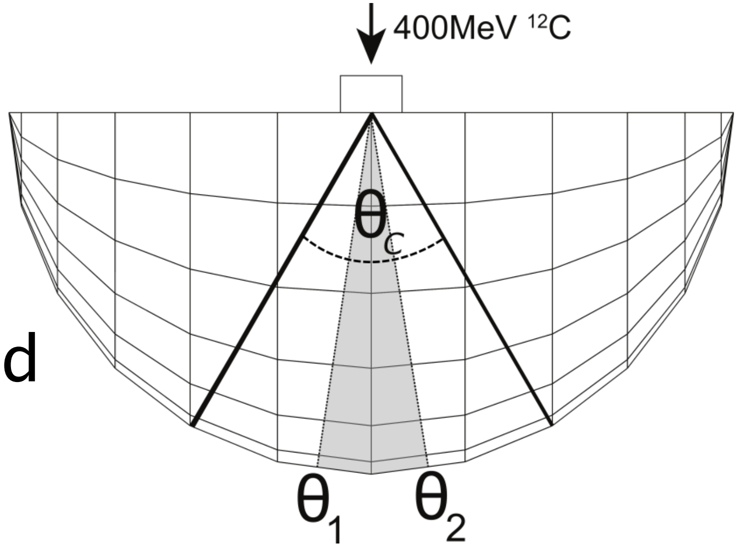
- Geant4 10.2p2
  - BIC, QMD, QMD-F and INCL
  - EM Std Opt3

    (QMD-F (frag) changes the interaction criterion and only changes the fragment yield)
- Fragment yields, angular and energy distributions measured



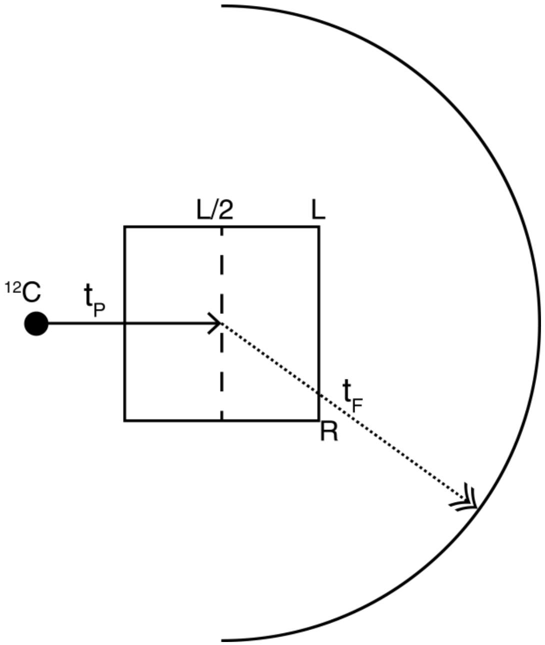
Simulation Setup (2)

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



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 (^{1}H, ^{4}He, ^{7}Li, ^{9}Be, ^{11}B



$$KE_F = \left(\frac{1}{\sqrt{1-\beta^2}} - 1\right) m_0 c^2$$

$$\beta = \frac{R}{ct_F}$$

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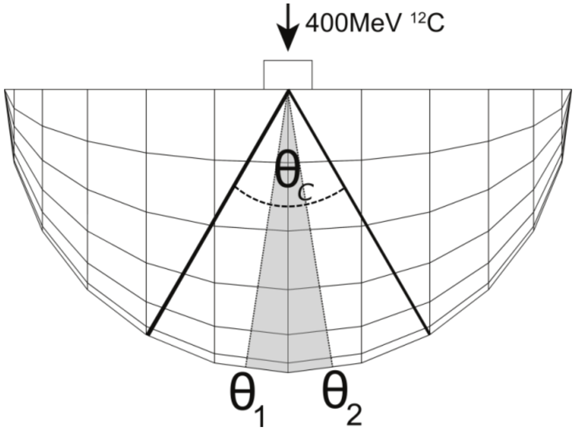
Ranking Models

- To quantify how well each model performs they were ranked using a combination of:
  - <PE> the mean percentage error
  - X^2 (analogous to Chi2 value except no p-value is calculated)



$$\langle PE \rangle = \frac{100}{n}\left(\sum_{i=1}^{n}\left|\frac{Sim_i - Exp_i}{Exp_i}\right|\right)$$

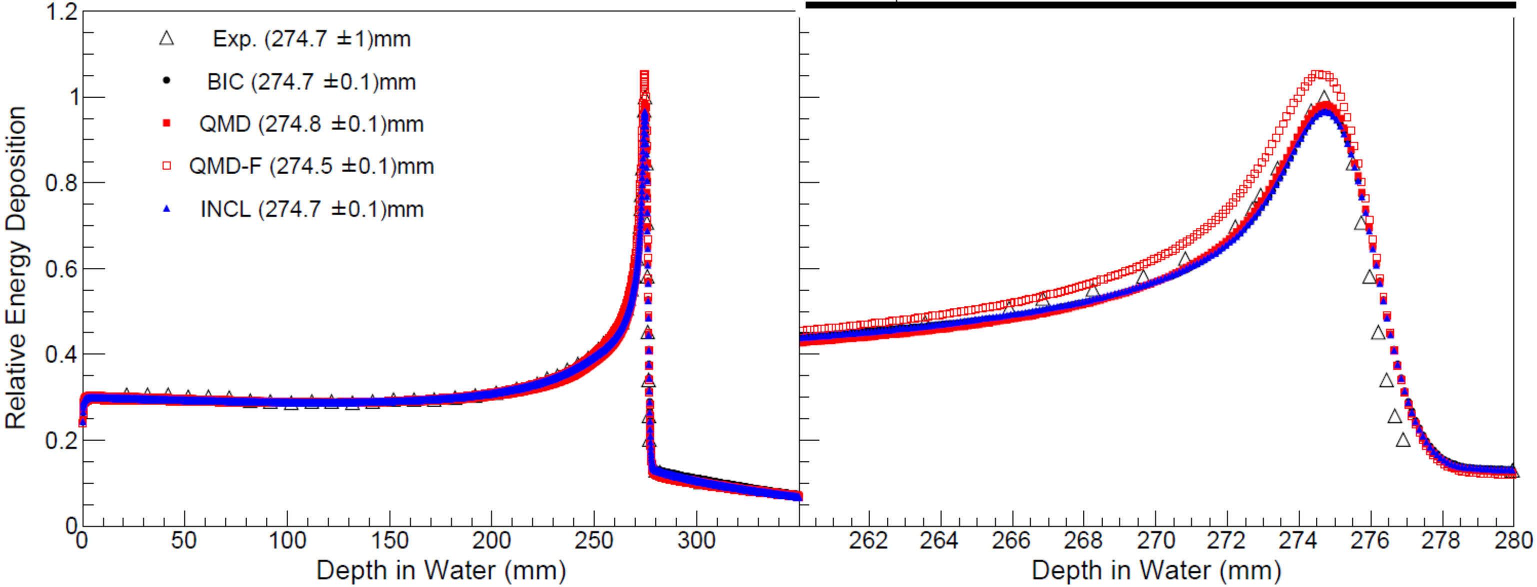
$$X^2 = \sum_{i=1}^{n}\frac{(Sim_i - Exp_i)^2}{Exp_i}$$

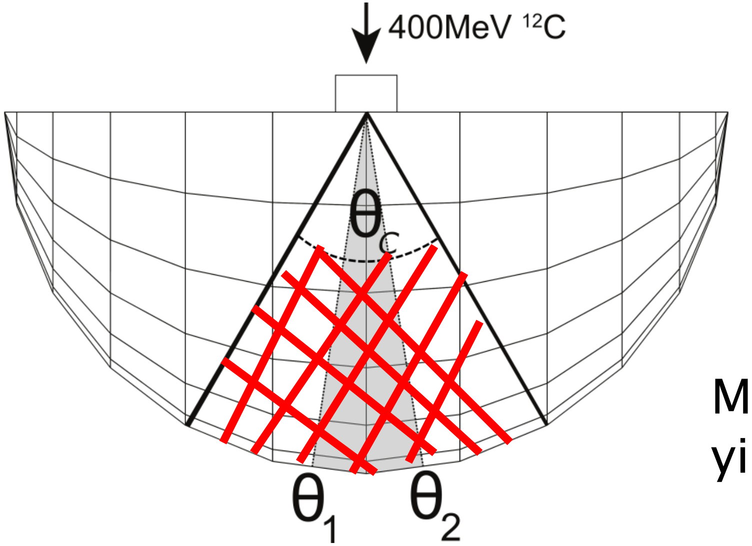
Results

Bragg Peak

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

	BIC	QMD	QMD-F	INCL
X^2	53.098	54.335	46.720	52.021

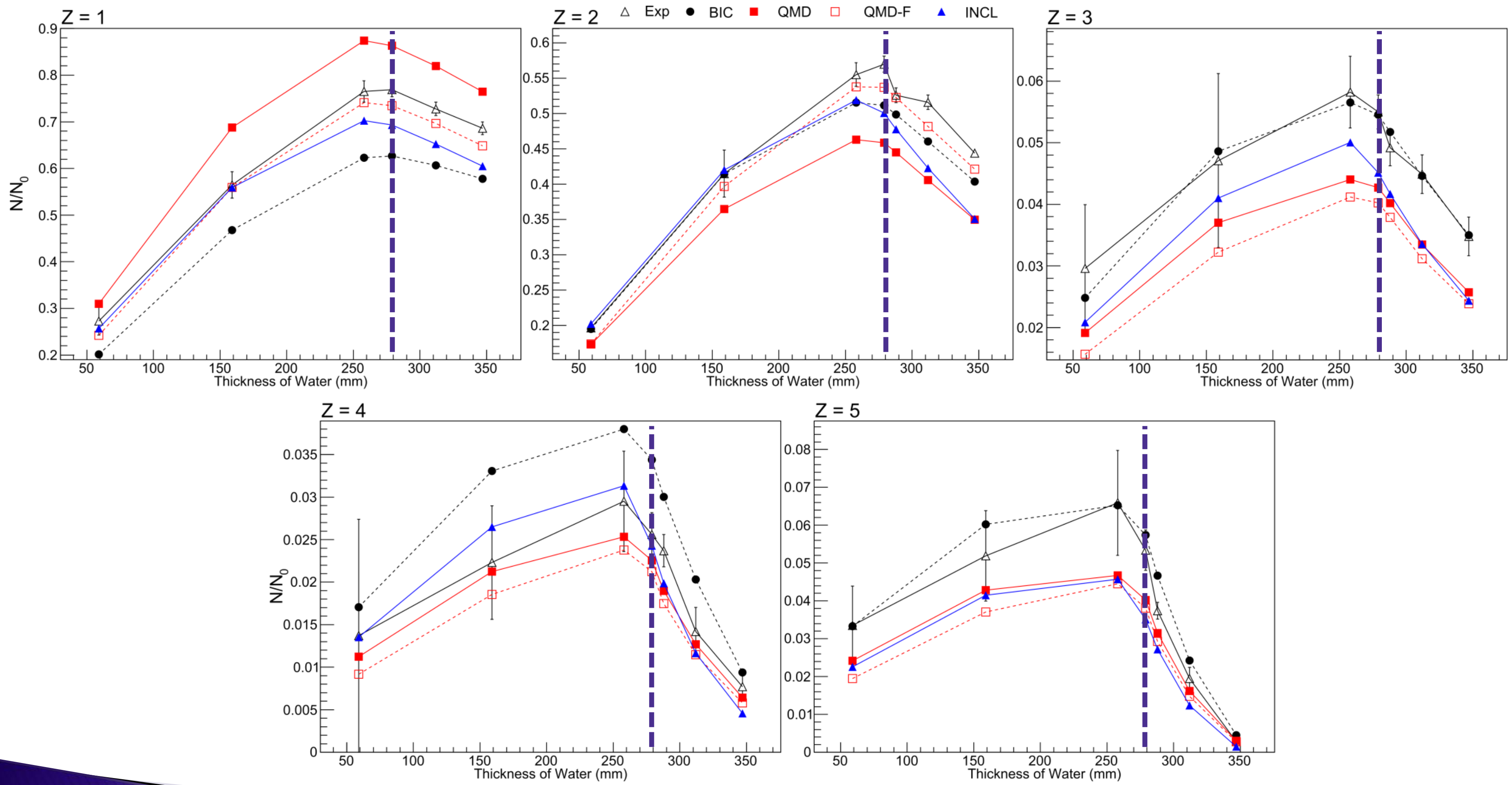




Fragment Yields

Version 10.2p2

Measuring Fragment yield in 10° cone (θ_C)


Z = 1
Z = 2
Z = 3
Z = 4
Z = 5
Exp
BIC
QMD
QMD-F
INCL
N/N0
Thickness of Water (mm)

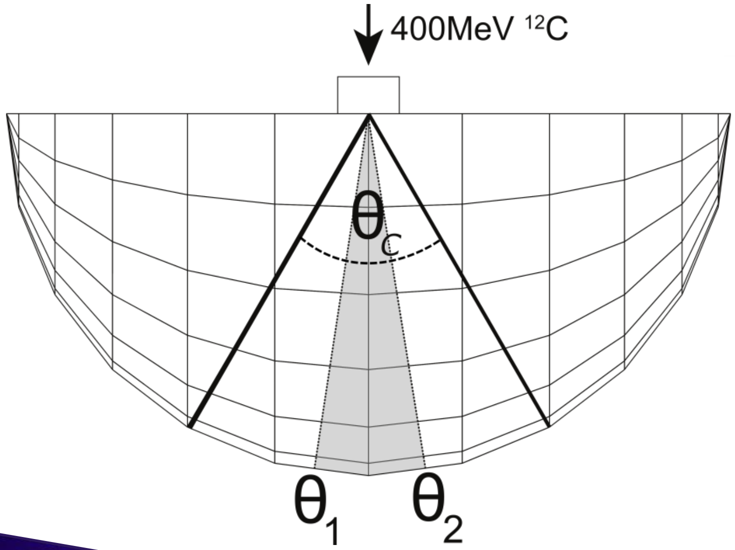
Summary of Fragment yields

- Models agreed ~5–35% with exp
- QMD–F performed best for lighter fragments
- Larger Z exp results for infield were characterised by larger errors due to primary ^{12}C masking events
  - Comparison more important for out–of–field

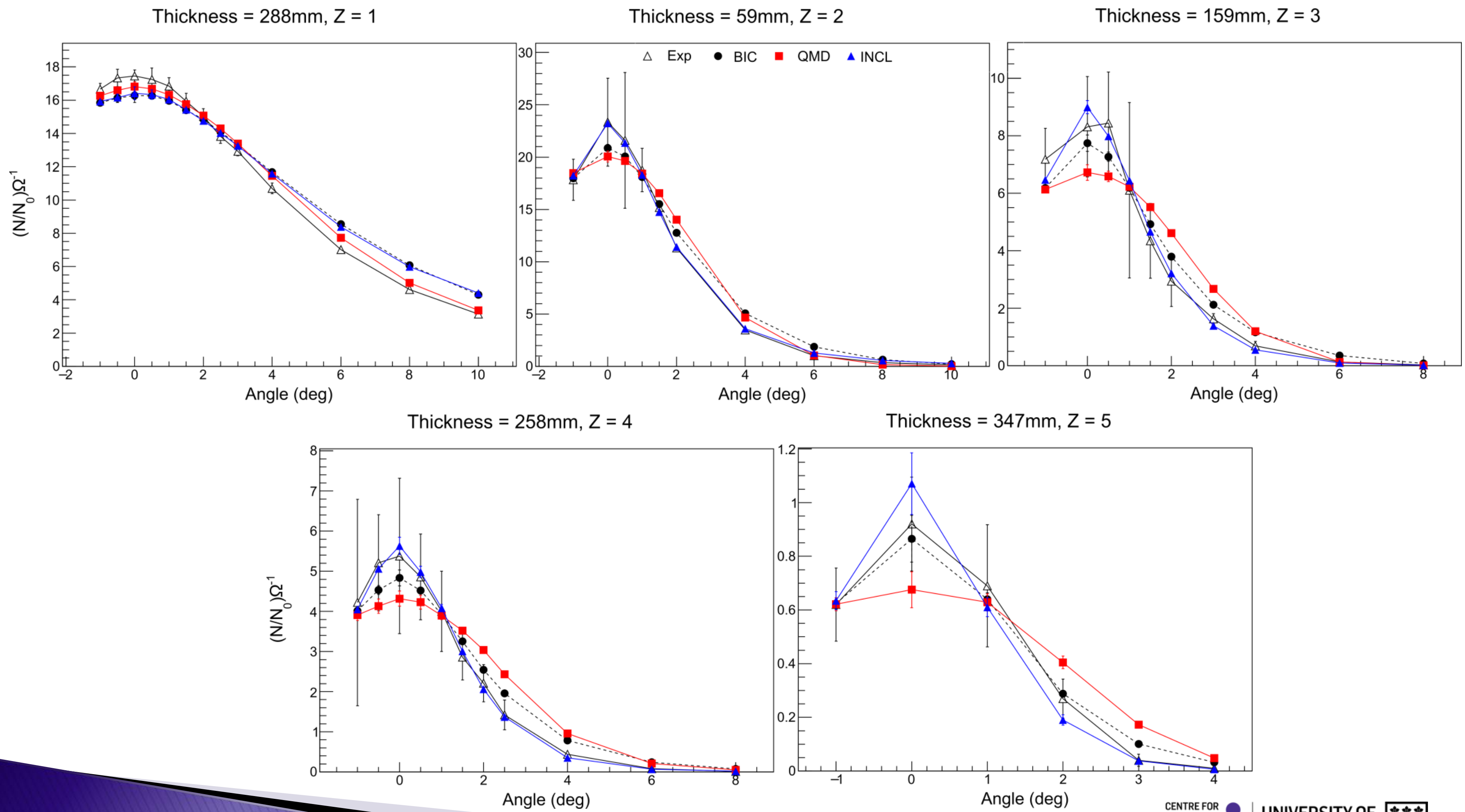
Mean %Error

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



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



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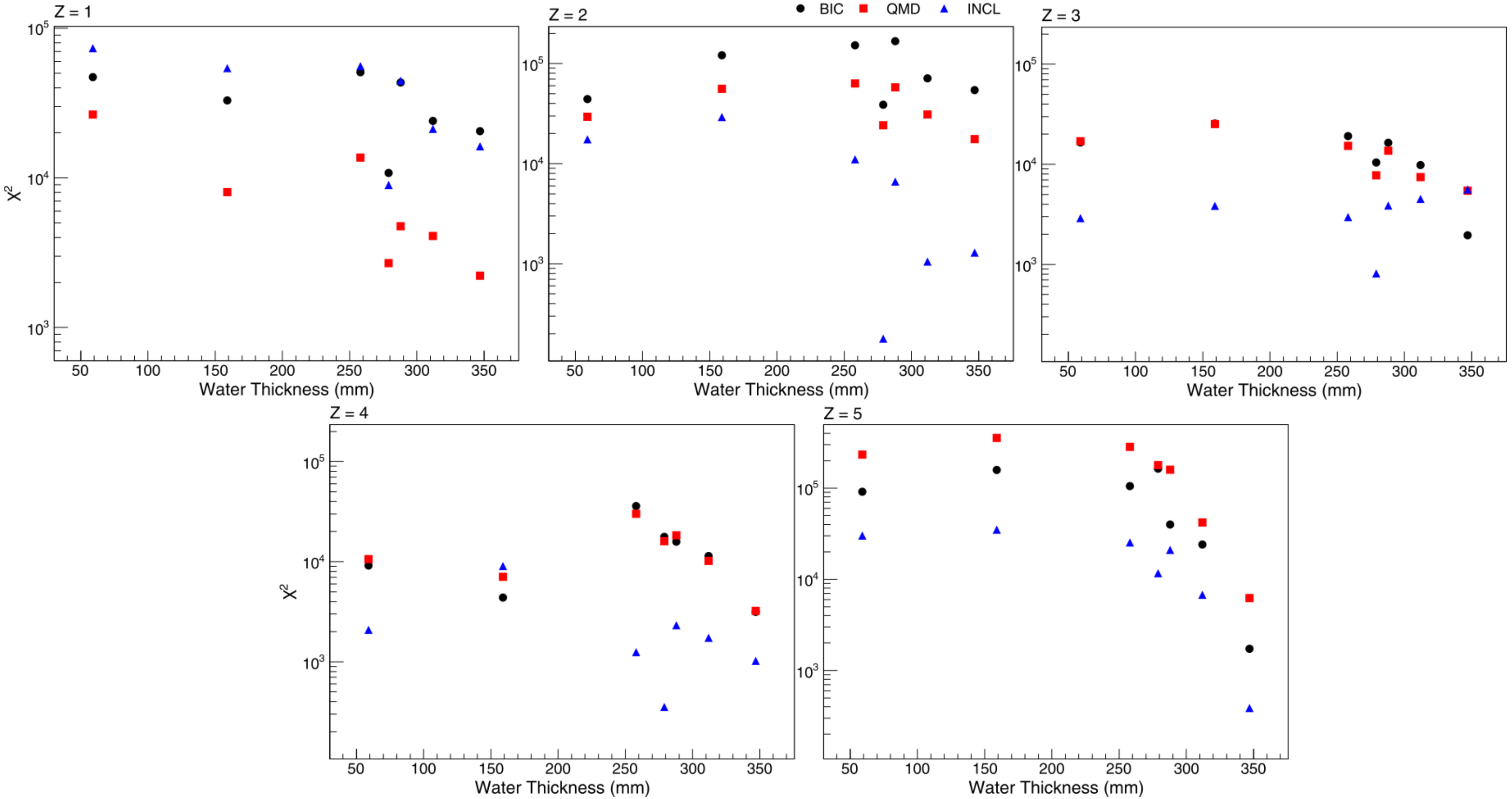
X^2 values


BIC
QMD
INCL
Z = 1
Z = 2
Z = 3
Z = 4
Z = 5
X^2
10^3
10^4
10^5
50
100
150
200
250
300
350
Water Thickness (mm)

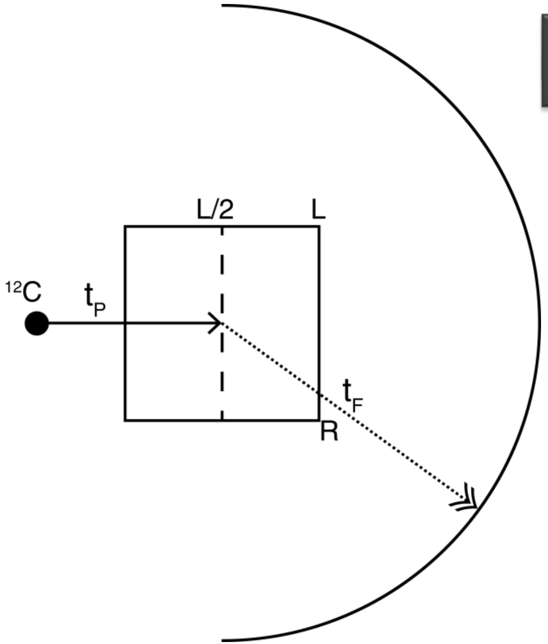
Angular Distribution Summary

- 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

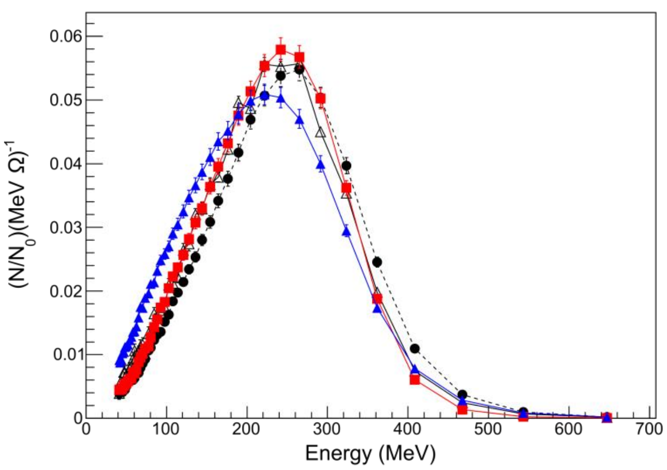
Z	BIC	QMD	INCL
1	14 ± 4	7 ± 4	15 ± 4
2	24 ± 2	16 ± 2	7 ± 2
3	29 ± 8	26 ± 8	16 ± 8
4	47 ± 14	42 ± 14	18 ± 14
5	132 ± 12	135 ± 12	28 ± 13

Energy Distribution

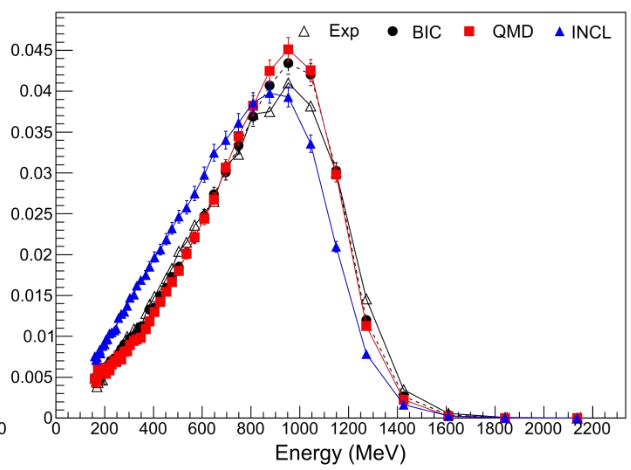


- Energy Distributions are normalised to the total experiment counts
- In total 159 distributions compared
- Version 10.2p2

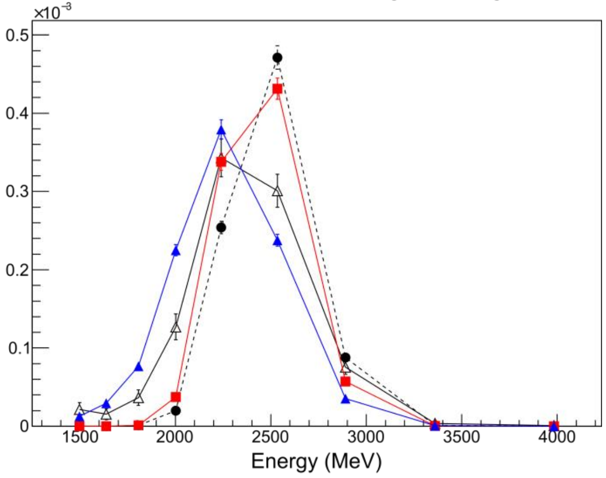
Thickness = 258mm, Z = 1, Angle = 4deg



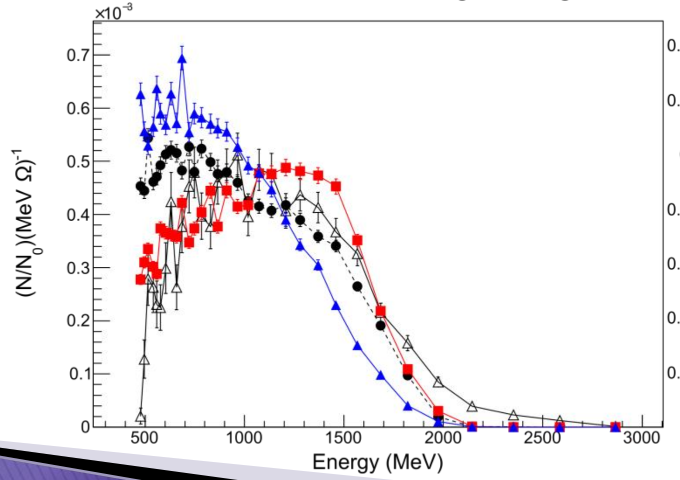
Thickness = 312mm, Z = 2, Angle = 1deg



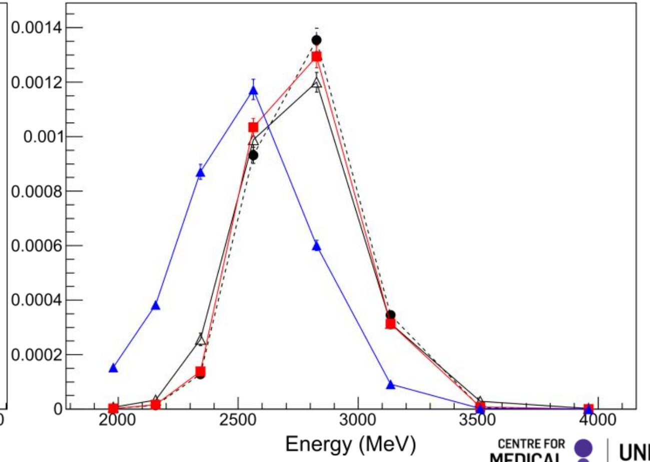
Thickness = 59mm, Z = 3, Angle = 4deg



Thickness = 347mm, Z = 4, Angle = 2deg



Thickness = 159mm, Z = 5, Angle = 3deg



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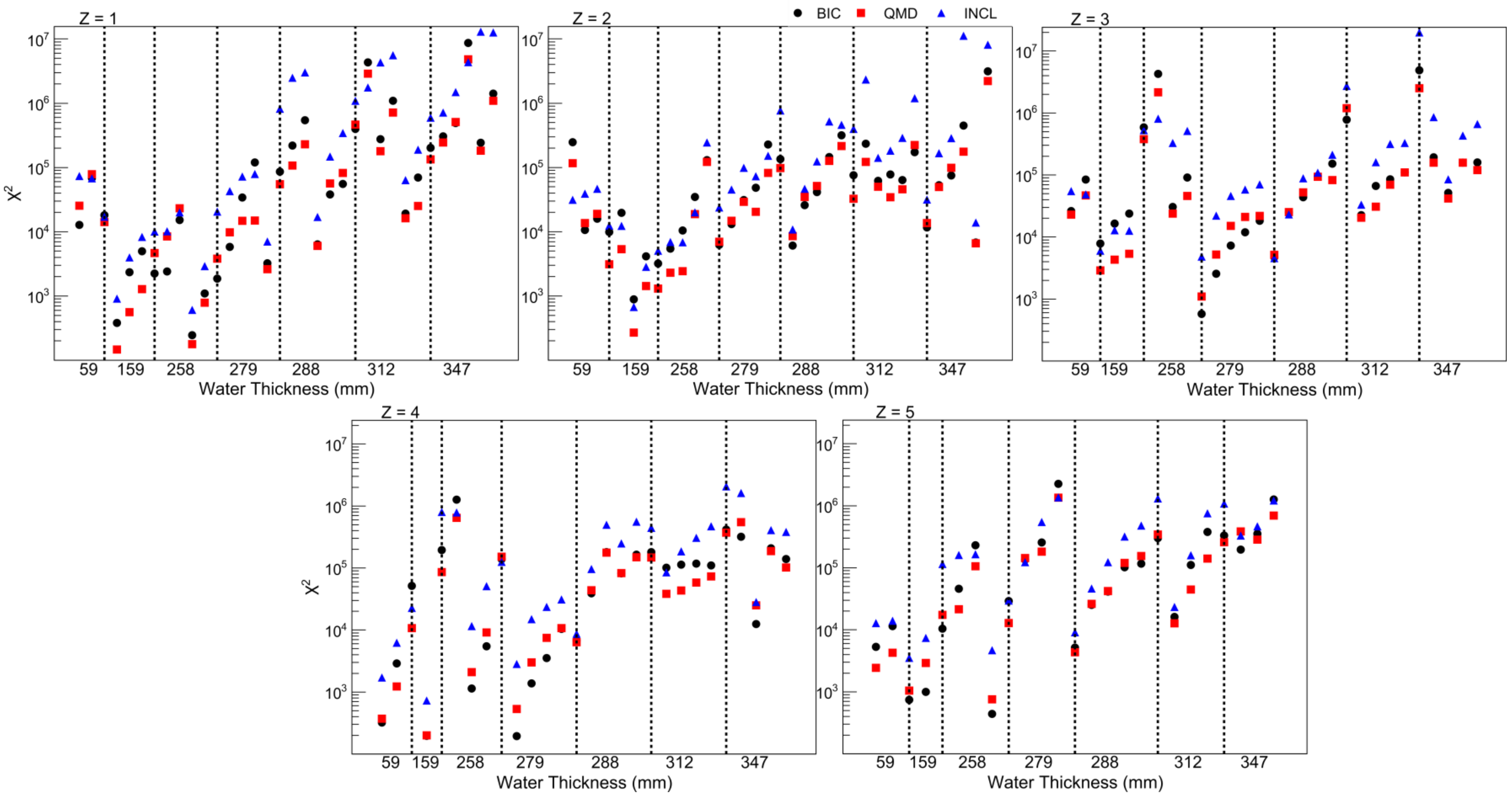
X^2 values


Z = 1
Z = 2
Z = 3
Z = 4
Z = 5
BIC
QMD
INCL
χ^2
Water Thickness (mm)
59
159
258
279
288
312
347

Energy Distribution Summary

- BIC and QMD perform similar to one another with INCL performing noticeably more poor
- INCL commonly produces lower energy distributions
- Possible energy miscalibration of experiment may be contribute to poor agreement
  - Measurements done over two session one calibration shifted from (358±23)MeV/u to (402±26)MeV/u

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

Comparison of Runtime

- Compared runtimes of 10^5 primary particles for each model using an Intel Xeon E5-2650v3 @2.30GHz
- QMD/QMD-F was a considerably more computationally intensive for thinner targets
- BIC and INCL had similar runtimes apart from thinner targets

Thickness	BIC (seconds)	QMD/BIC	QMD-F/BIC	INCL/BIC
59	97.5 ± 3.3	10.83 ± 0.45	7.73 ± 0.29	0.79 ± 0.05
159	569 ± 18.2	5.40 ± 0.18	3.94 ± 0.14	0.97 ± 0.03
258	1382.9 ± 90.7	3.67 ± 0.25	2.85 ± 0.24	1.04 ± 0.06
279	1643.4 ± 57.9	3.41 ± 0.15	2.46 ± 0.31	1.03 ± 0.12
288	1765 ± 63.6	3.29 ± 0.13	2.11 ± 0.22	1.01 ± 0.10
312	1979.1 ± 73.9	3.16 ± 0.13	2.26 ± 0.13	1.03 ± 0.05
347	2380.3 ± 47.6	2.86 ± 0.06	2.17 ± 0.08	1.00 ± 0.04

Summary

- Fragment data from a 400MeV/u ^{12}C beam in water was used to benchmark Geant4 using version 10.2p2
- Fragment yield values agreed within ~5-35% of experimental values
  - QMD-F best for H and He, BIC/QMD for heavier fragments
- Angular Distributions agreed ~5-35% for INCL, which performed much better than BIC and QMD in versions
- Energy distributions agreed noticeably poorer (possible experimental calibration error)
  - BIC and QMD performed similar for Angular and Energy distributions (both treat interaction as Gaussian wave functions)- INCL produced lower energies
- Computation times showed QMD considerably more intensive, BIC and INCL were similar

Thank you