Simulation of light ion transport in a water phantom using Geant4.

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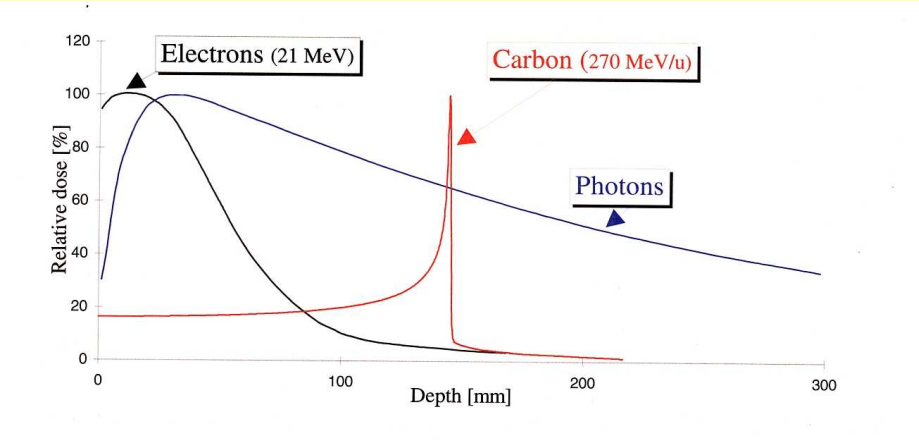
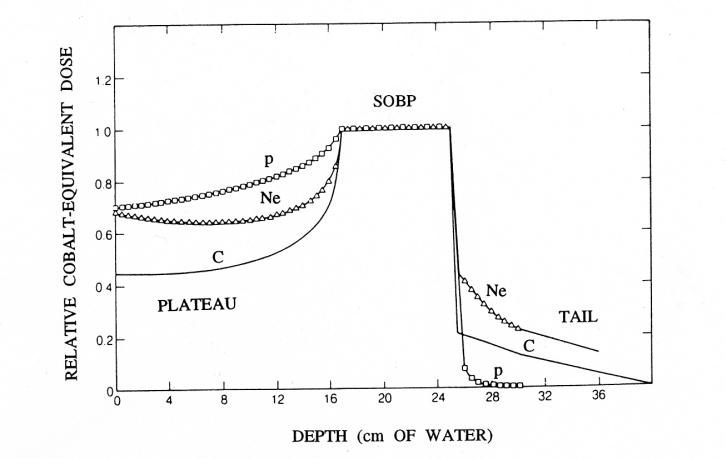
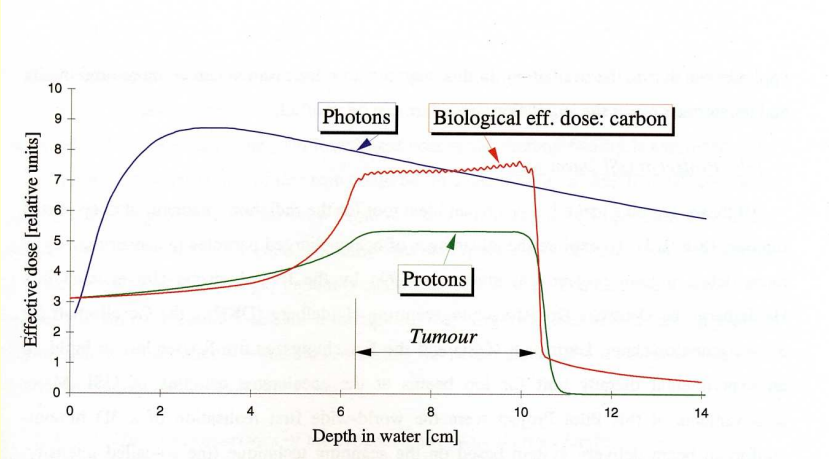
Outline

- Monte Carlo codes for hadron therapy
- Stopping power data; ICRU 73 vs Geant4
- Ion transport in water: ^{1}H, ^{4}He, ^{12}C and ^{20}Ne in the energy range 100 - 400 MeV/u
- Results Geant4 vs experiment and other MC codes
- Conclusions

Light ion therapy







Ion Transport Monte Carlo codes possible for application in hadron therapy.

- **SHIELD/SHIELD-HIT** (Heavy Ion Transport (Sobolevsky et al, Inst. of Nucl. Res., Moscow)
- **MCNPX** (Los Alamos NL)
- **FLUKA** (CERN)
- **GEANT3** (CERN, Italy-Milan, Turin)
- **GEANT4** (CERN)
- **PHITS** (Iwase et al 2002, Tohoku Univ.)

- Only proton transport
- **PTRAN** (Berger)
- **PETRA** (Medin,Andreo)
- **PEREGRINE** (Hartmann Siantar et al, LLNL)

Application for light ion therapy

Requirements:

- to transport protons, light ions (up to oxygen), heavy ions (A > 16)
- media : the tissue equivalent and constructional materials of the accelerator
- energy region of interest for medical applications from few up to 500 MeV/u
- production and transport of secondary particles (fragments)
- scoring of the energy deposition from primary and secondary particles
- particle spectra differential in energy (for primary and secondary particles)
- production of secondary electrons

MC codes used in this comparison

- **GEANT4** ver. 7.1
- **SHIELD-HIT** ver.1 2004, ver.2 2005
- **MCNPX** ver. 2.5.e
- **PETRA** (Medin&Andreo 1997)
- **PTRAN** (Berger 1993a)

Experimental data

Light ion clinical facilities: HIMAC in Chiba, Japan and GSI in Darmstadt, Germany, TRIUMF, Vancouver, Canada.

GEANT4 ver. 7.1

- Electromagnetic interact standard, 0.2 mm cut off (default)
- Hadron/ion interactions – Binary Cascade
- Development of the IION code based on the Geant4 toolkit
- Tests:

  Standard, Low Energy,

  different step limits,

  different cut off values

  chemical effect on/off

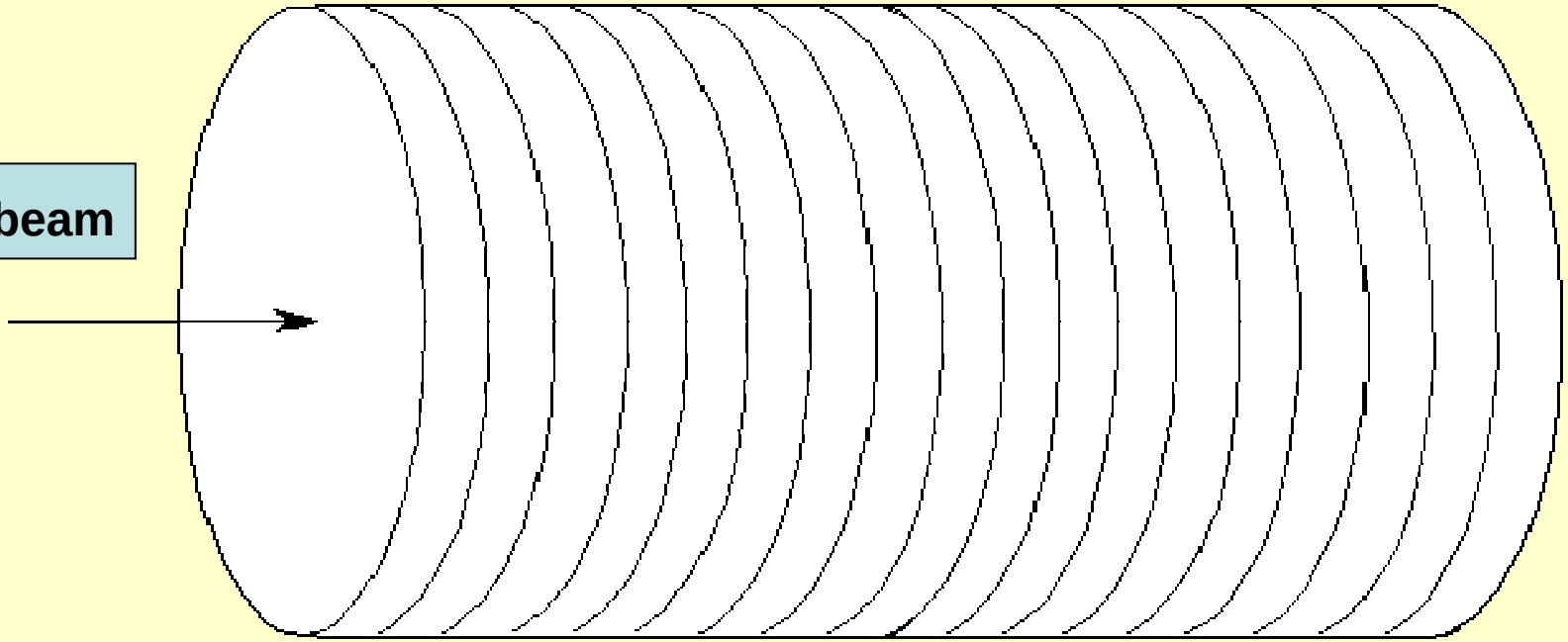
SCHEMATIC GEOMETRY FOR SIMULATION OF ION TRANSPORT

CYLINDRICAL PHANTOM : Length 30 cm, Radius 10 cm,

Layers of 1, 0.5, 0.1 mm

MATERIAL: Water

Pencil beam



PROJECTILES:

^{1}H, ^{4}He, ^{12}C, ^{20}Ne ions of energies in the range up to 500 MeV/u.

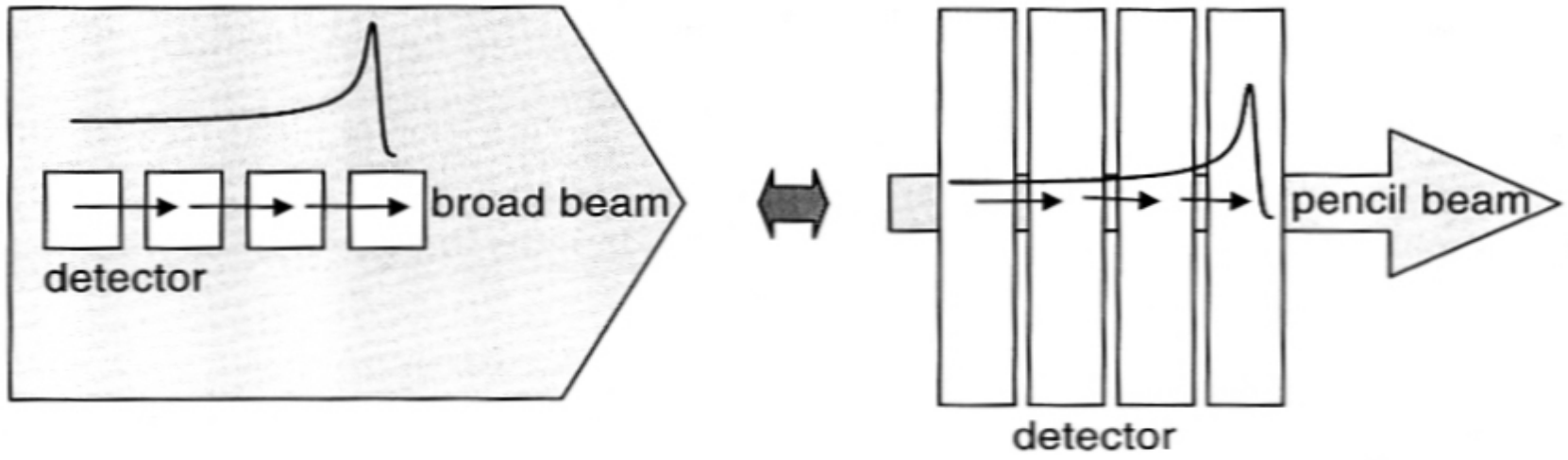
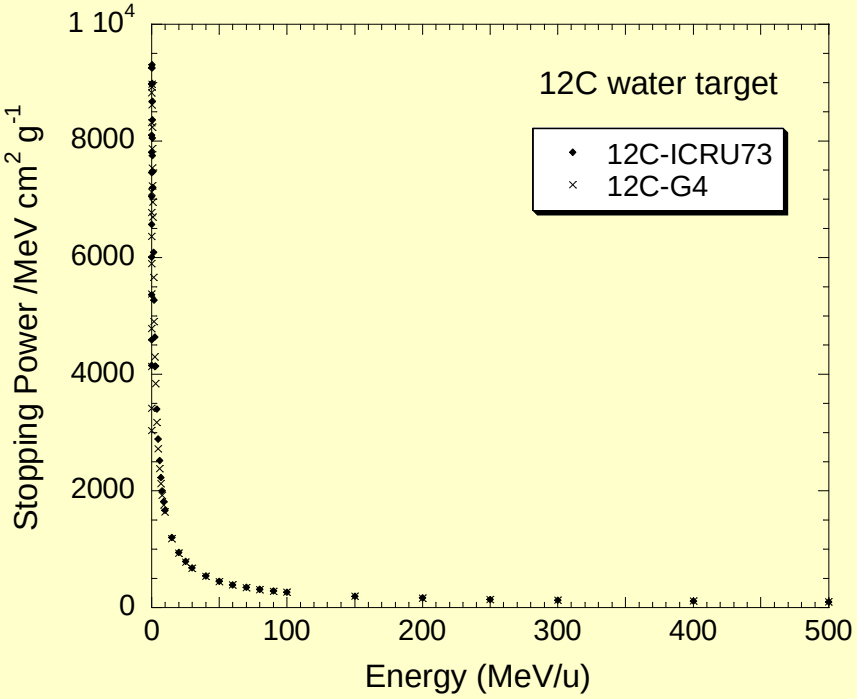
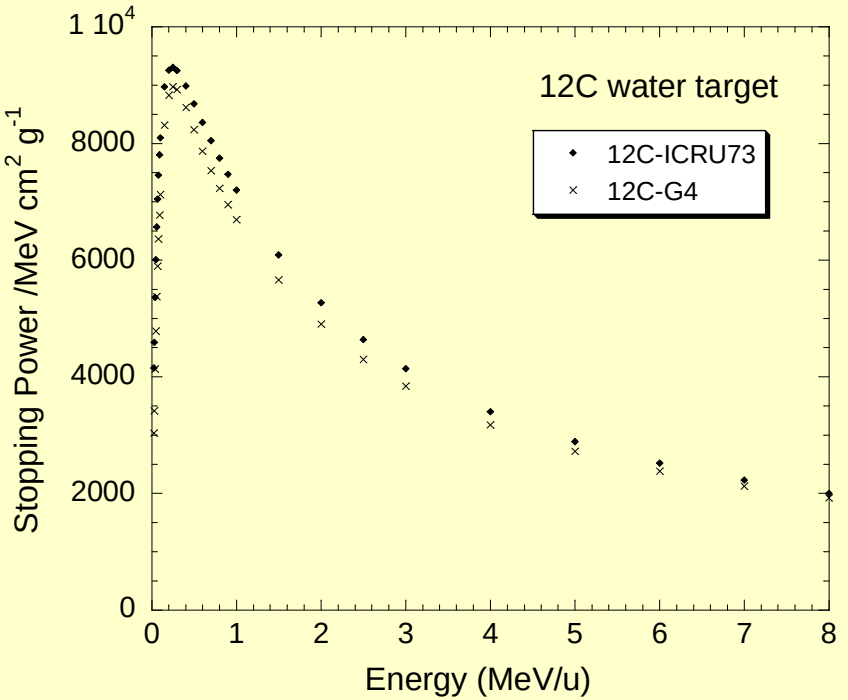


Figure 3.7: *The equivalence of a small detector in a broad beam and a broad detector in a pencil beam.*

Stopping power data for ion transport Geant4 vs ICRU73

^{12}C

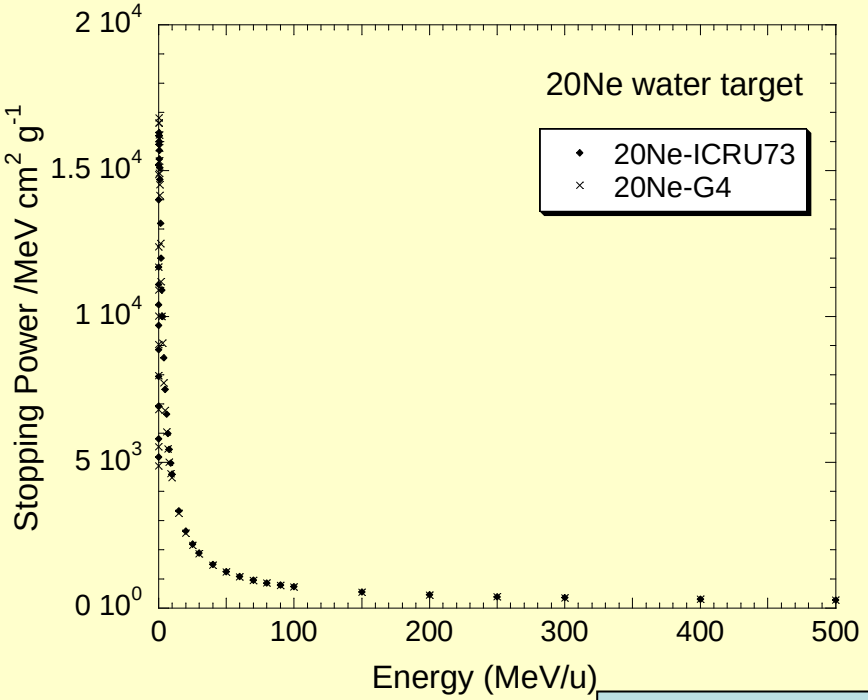


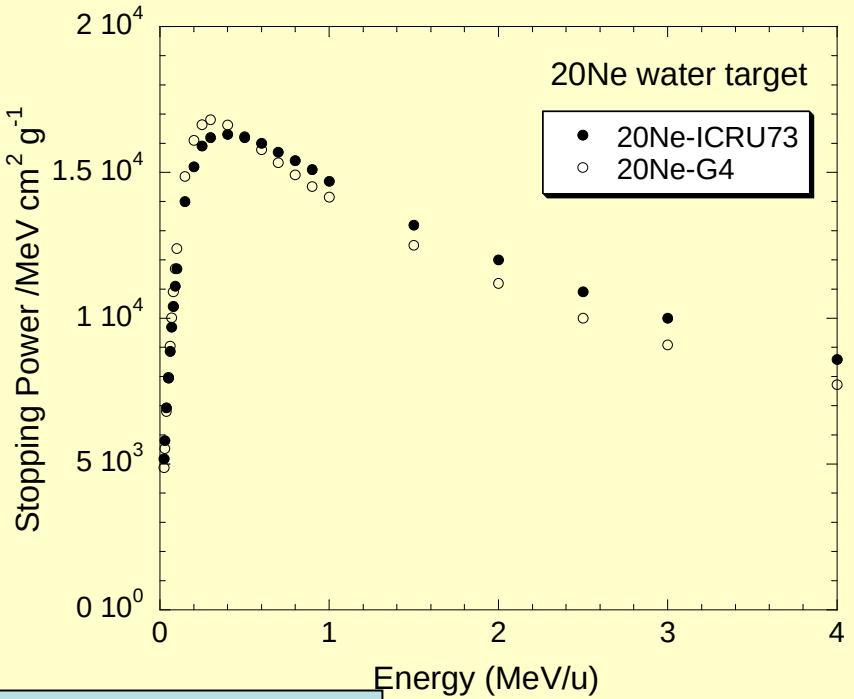


ICRU73 vs G4
^{12}C

Energy: 0.25 MeV/u diff. 3.8%
1 MeV/u diff. 7.5%
7 MeV/u diff. 4.8%
50 MeV/u diff. 1.6%

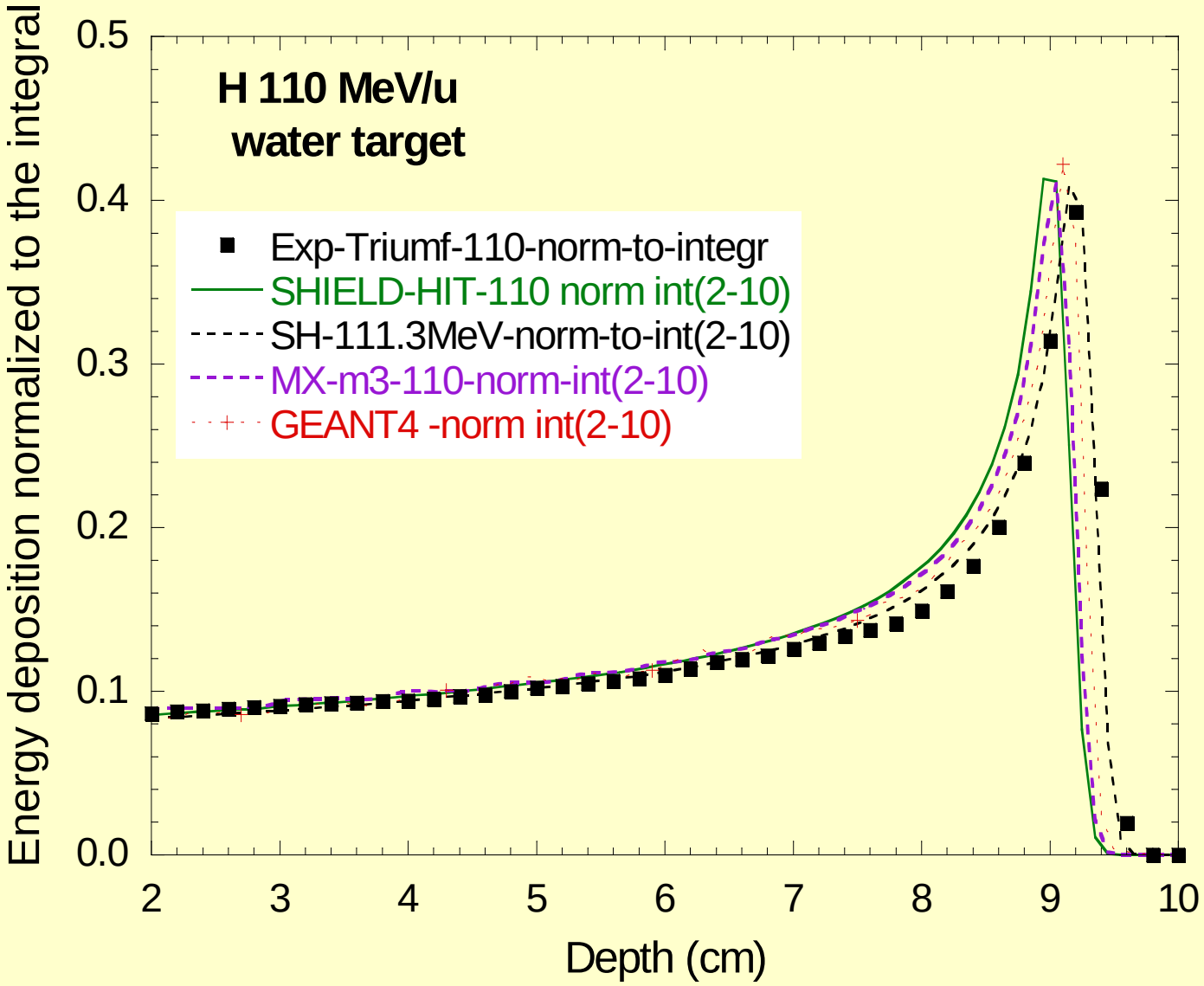
^{20}Ne

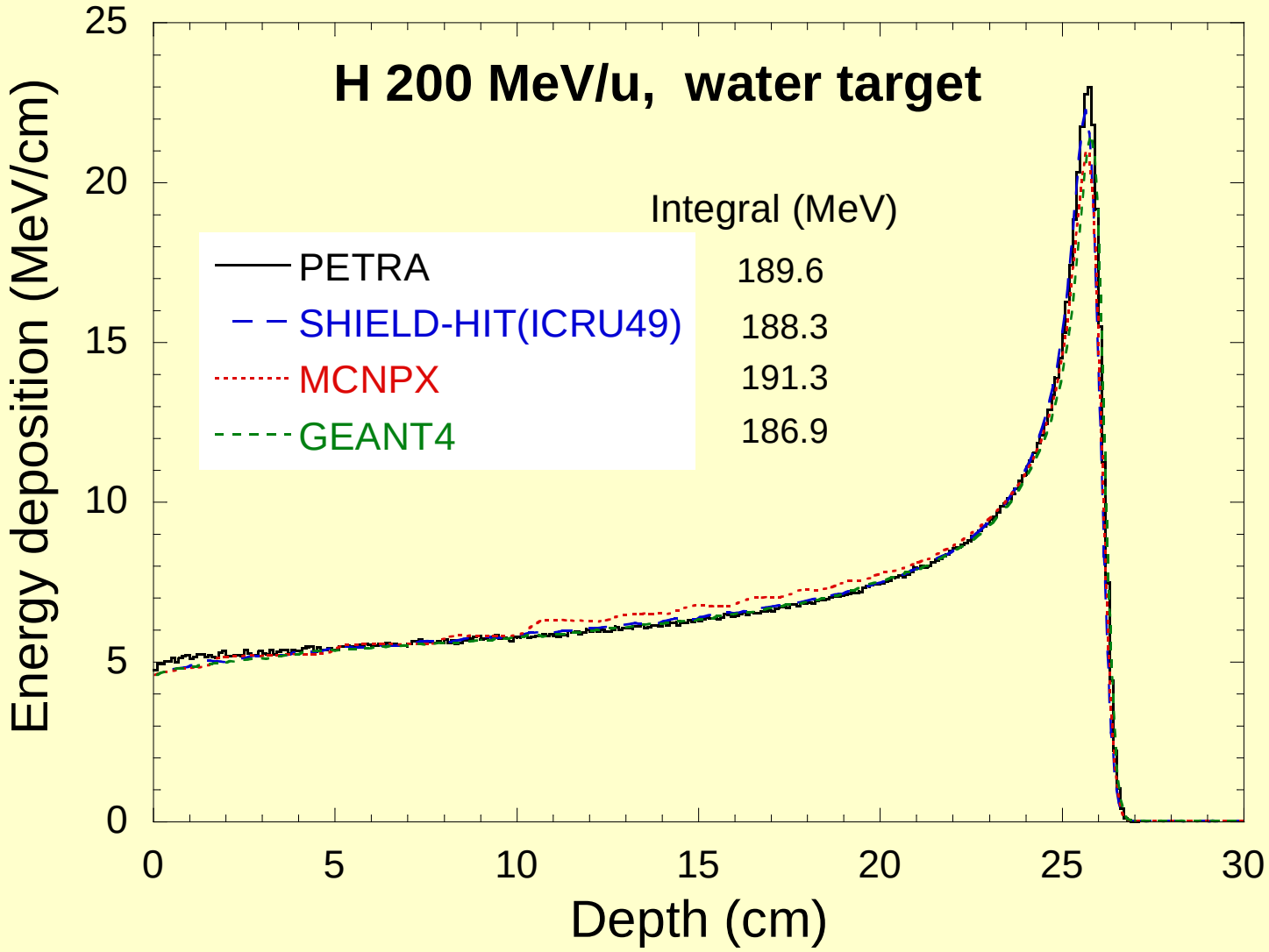


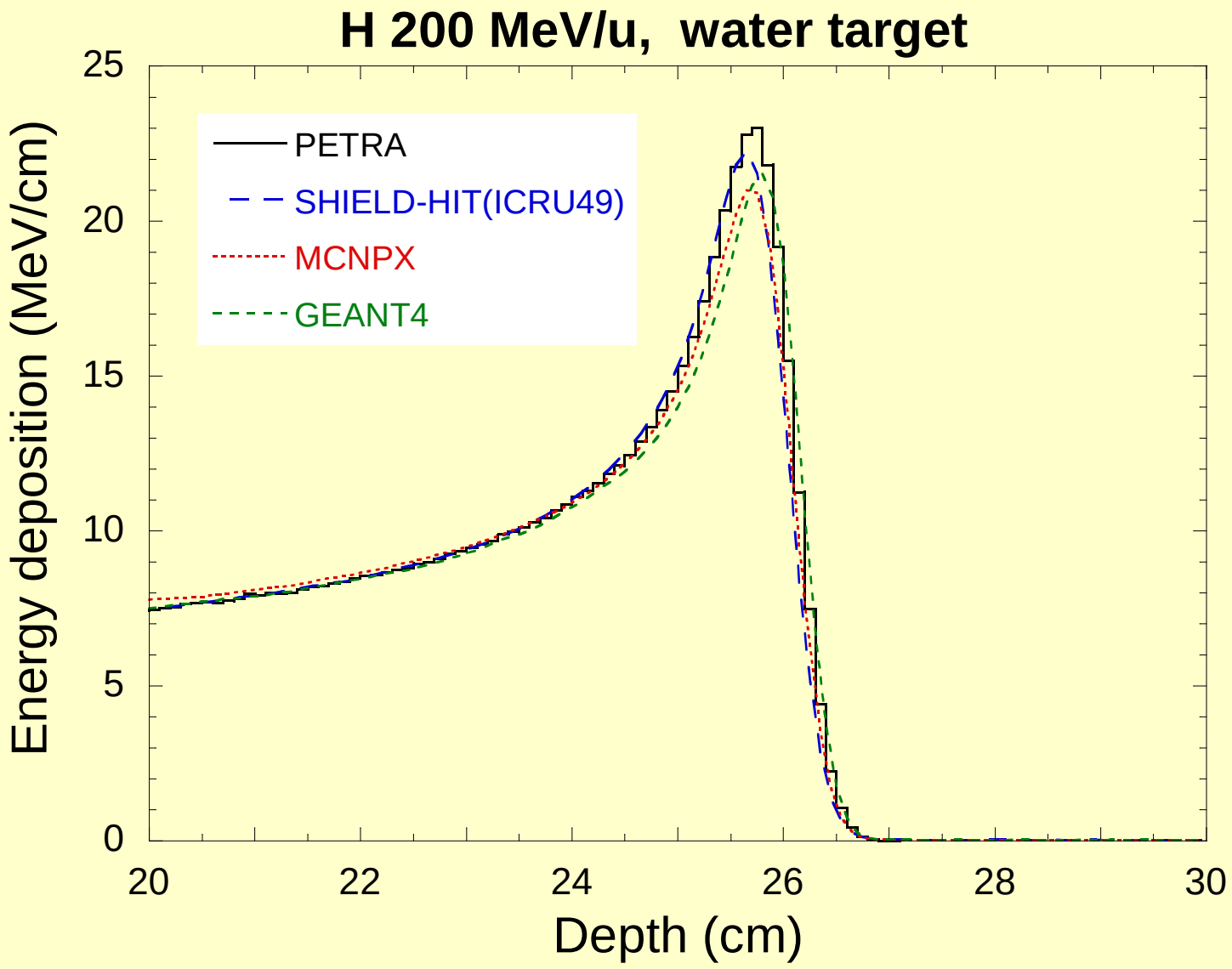


ICRU73 vs G4
^{20}Ne

Energy:	0.3 MeV/u	diff.	3.7 %
	1 MeV/u	diff.	3.9 %
	4 MeV/u	diff.	11.0 %
	10 MeV/u	diff.	2.6 %
	50 MeV/u	diff.	1.7 %


H 110 MeV/u
water target
Exp-Triumf-110-norm-to-integr
SHIELD-HIT-110 norm int(2-10)
SH-111.3MeV-norm-to-int(2-10)
MX-m3-110-norm-int(2-10)
GEANT4 -norm int(2-10)
Energy deposition normalized to the integral
Depth (cm)
0.0
0.1
0.2
0.3
0.4
0.5
2
3
4
5
6
7
8
9
10


H 200 MeV/u, water target
Integral (MeV)
PETRA 189.6
SHIELD-HIT(ICRU49) 188.3
MCNPX 191.3
GEANT4 186.9
Energy deposition (MeV/cm)
Depth (cm)
0
5
10
15
20
25
30

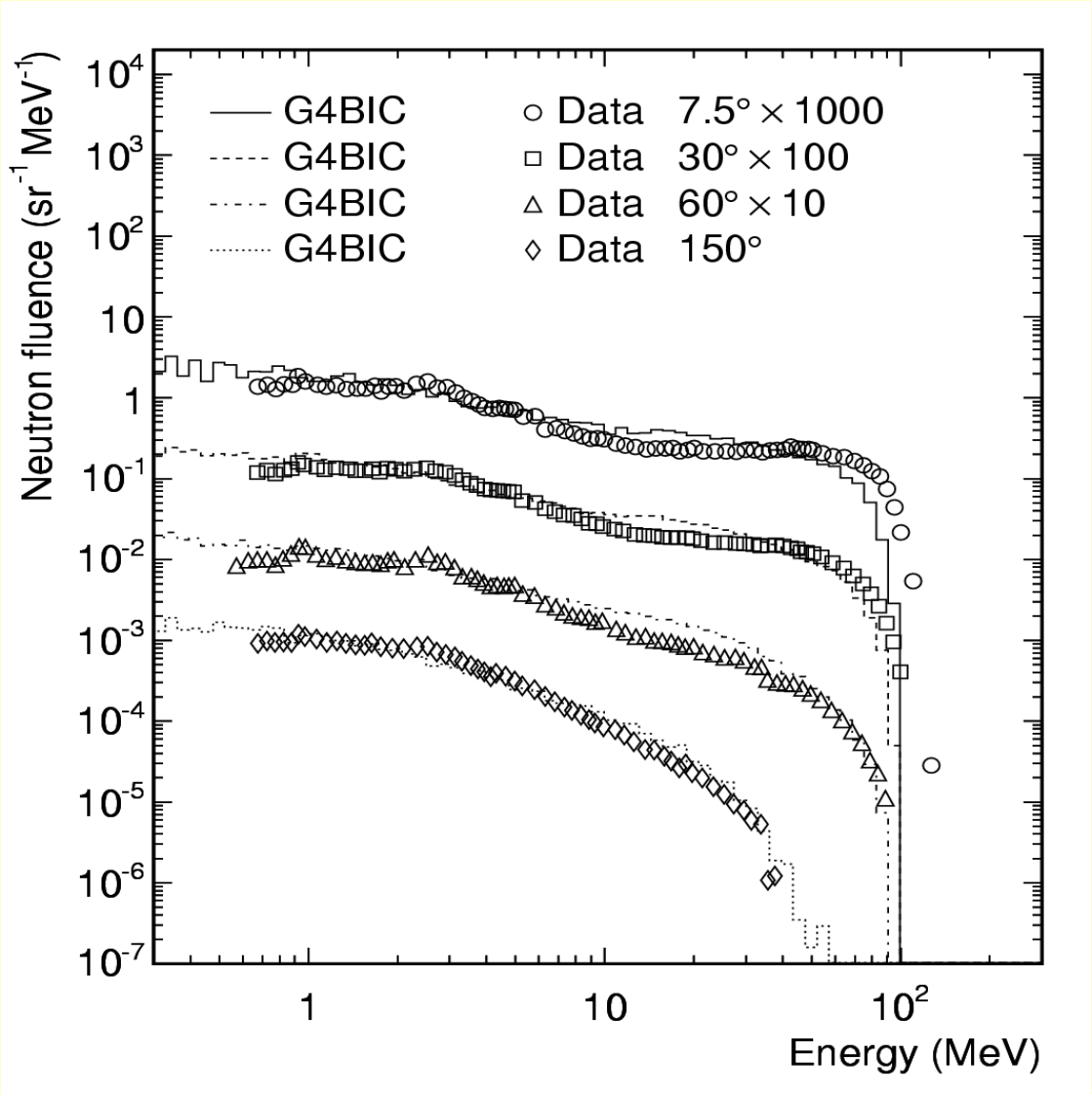

H 200 MeV/u, water target
PETRA
SHIELD-HIT(ICRU49)
MCNPX
GEANT4
Energy deposition (MeV/cm)
Depth (cm)
0
5
10
15
20
25
20
22
24
26
28
30

GEANT4

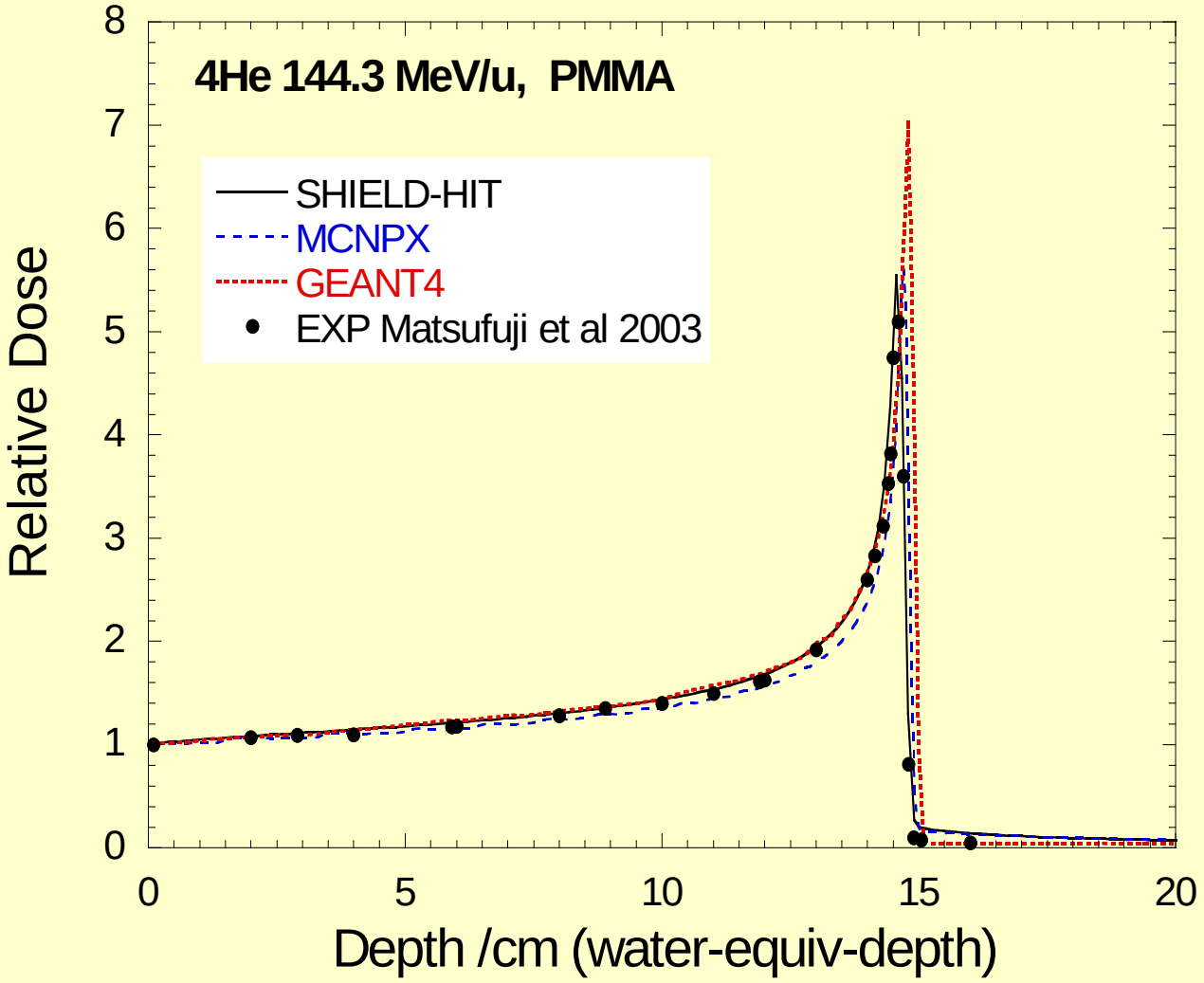
113 MeV protons on Al target

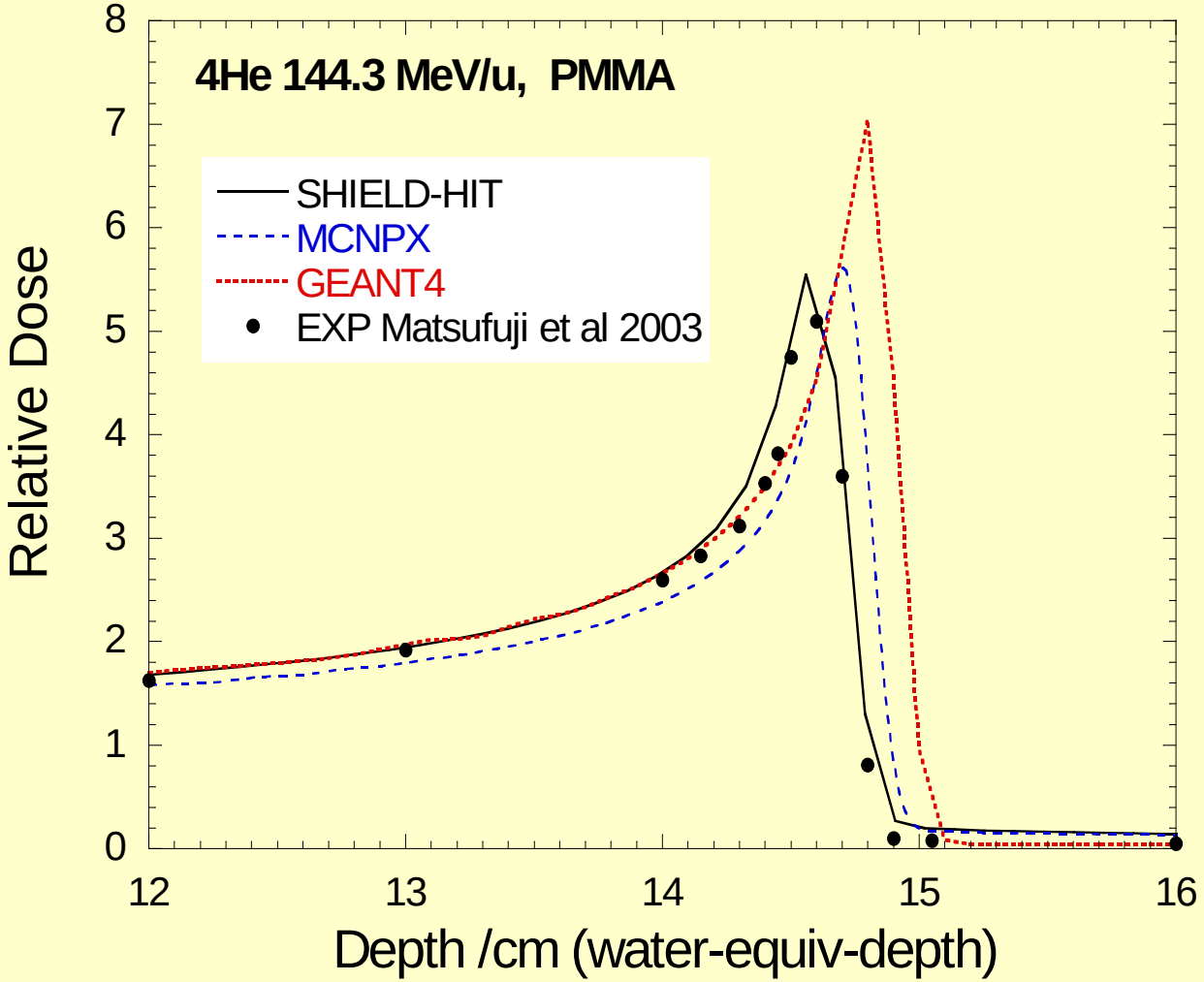
Neutron spectra differential in energy and angle.

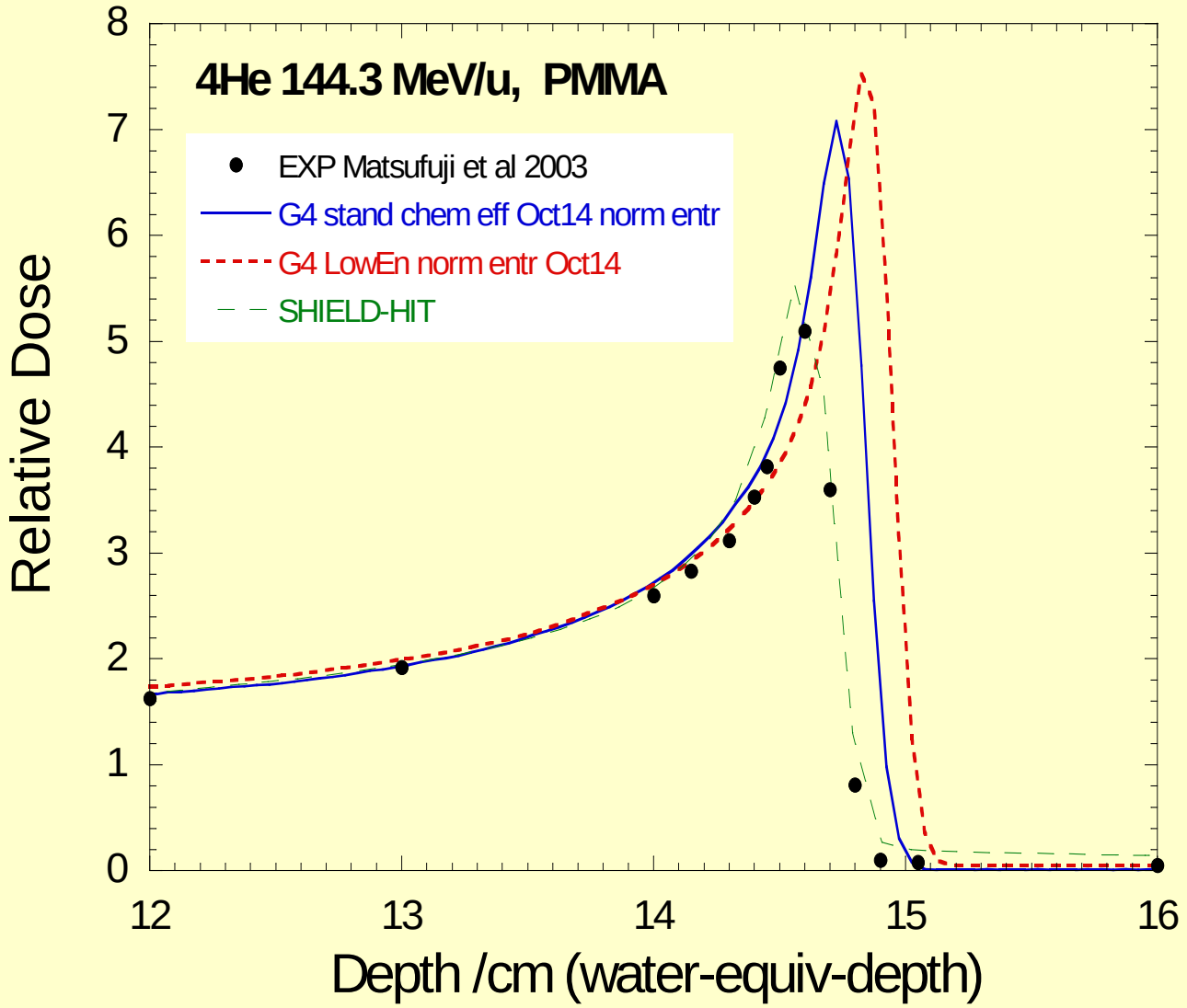
Exp Meier et al 1989



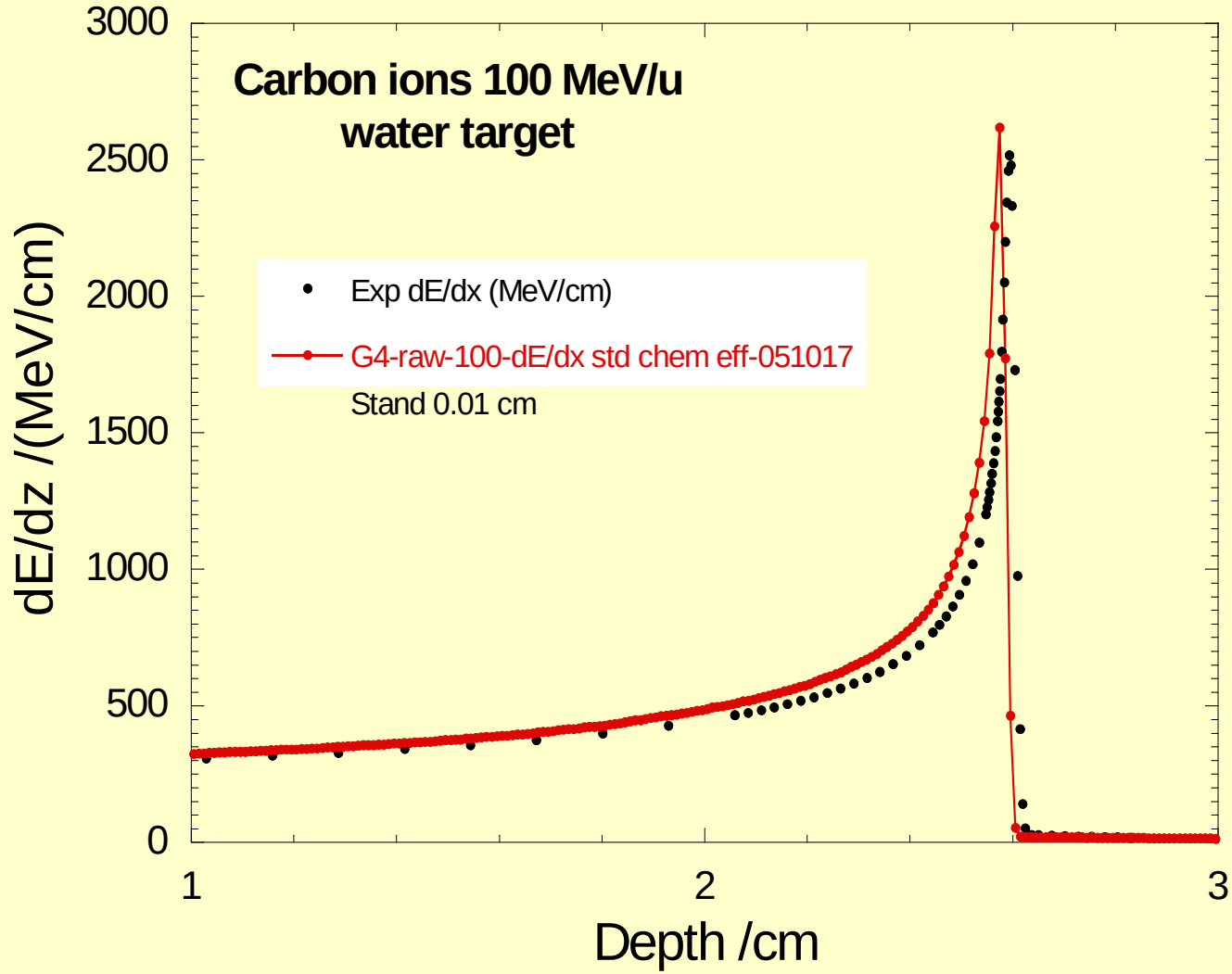
Courtesy of T. Ersmark, KTH, Stockholm

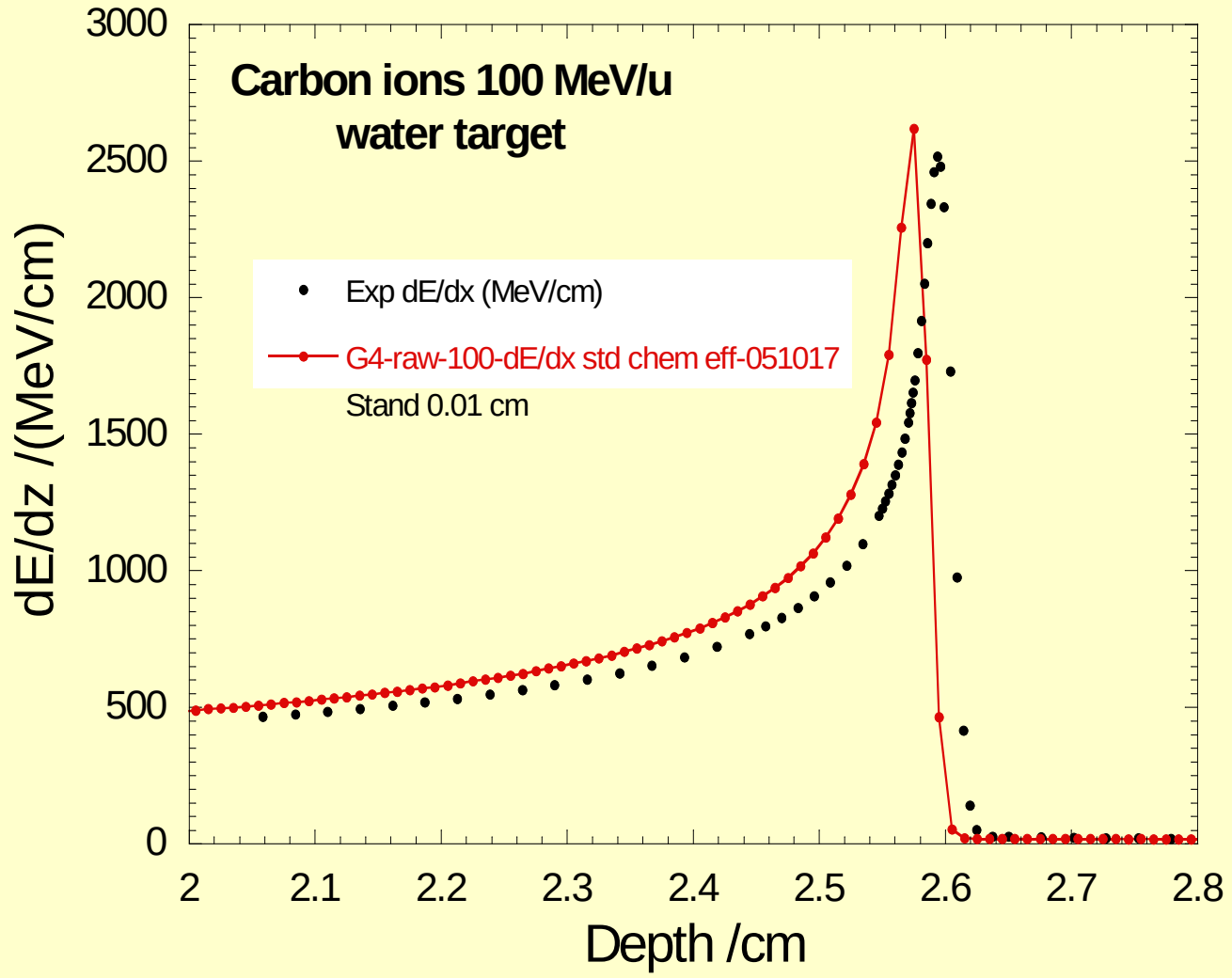

4He 144.3 MeV/u, PMMA
SHIELD-HIT
MCNPX
GEANT4
EXP Matsufuji et al 2003
Relative Dose
Depth /cm (water-equiv-depth)
0
1
2
3
4
5
6
7
8
0
5
10
15
20

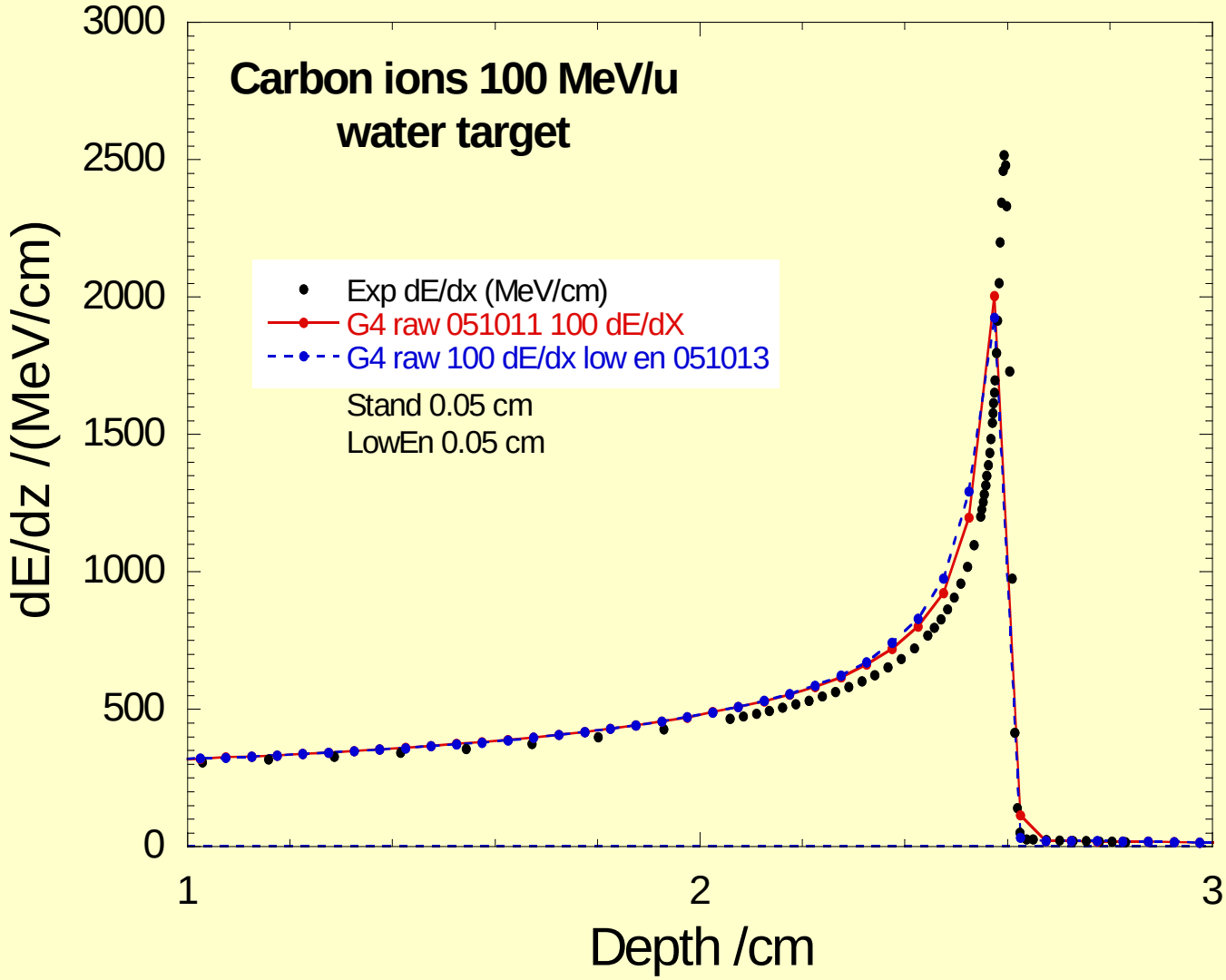

4He 144.3 MeV/u, PMMA
SHIELD-HIT
MCNPX
GEANT4
EXP Matsufuji et al 2003
Relative Dose
Depth /cm (water-equiv-depth)
0
1
2
3
4
5
6
7
8
12
13
14
15
16

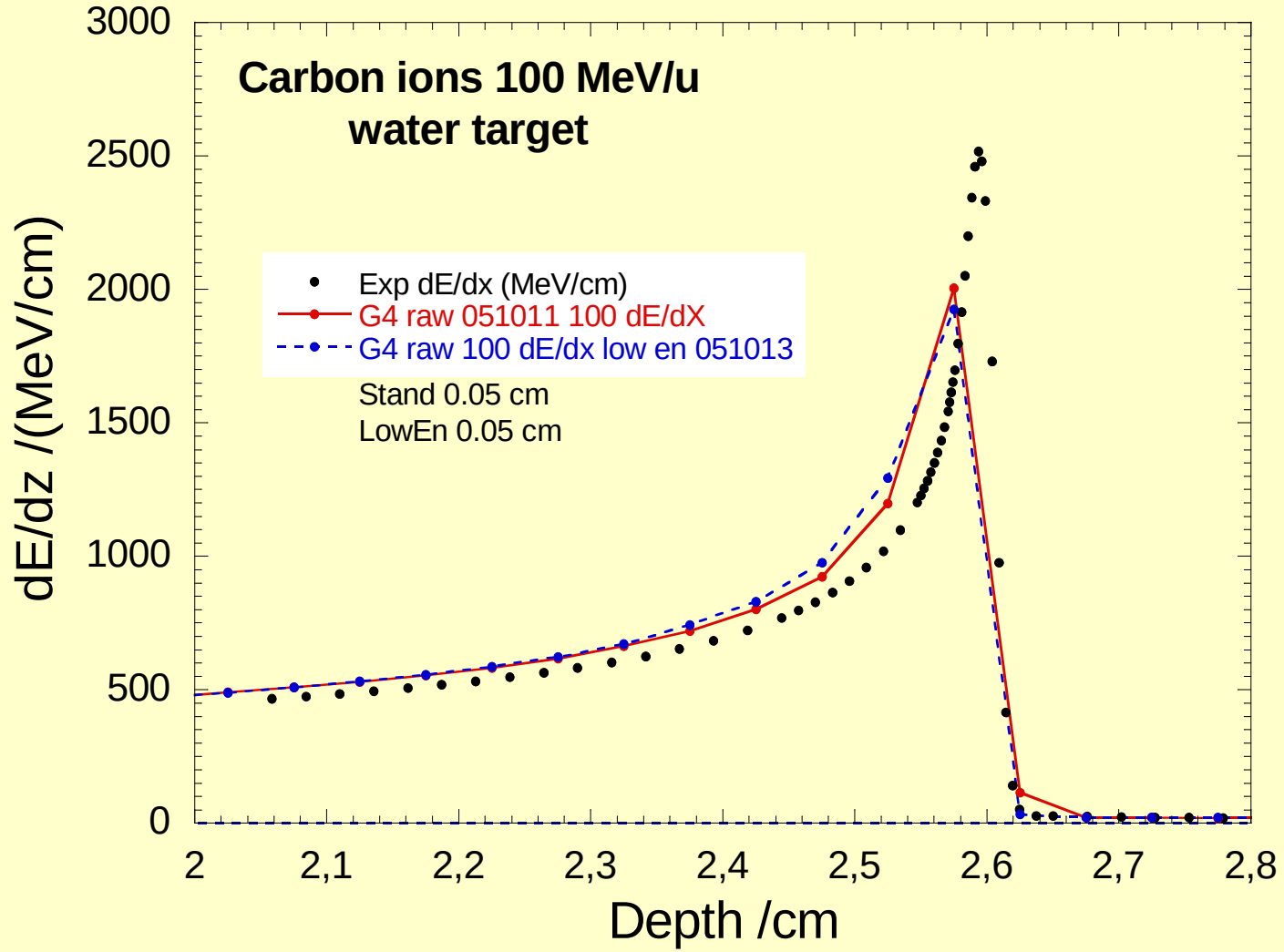

4He 144.3 MeV/u, PMMA
EXP Matsufuji et al 2003
G4 stand chem eff Oct14 norm entr
G4 LowEn norm entr Oct14
SHIELD-HIT
Relative Dose
Depth /cm (water-equiv-depth)
0
1
2
3
4
5
6
7
8
12
13
14
15
16

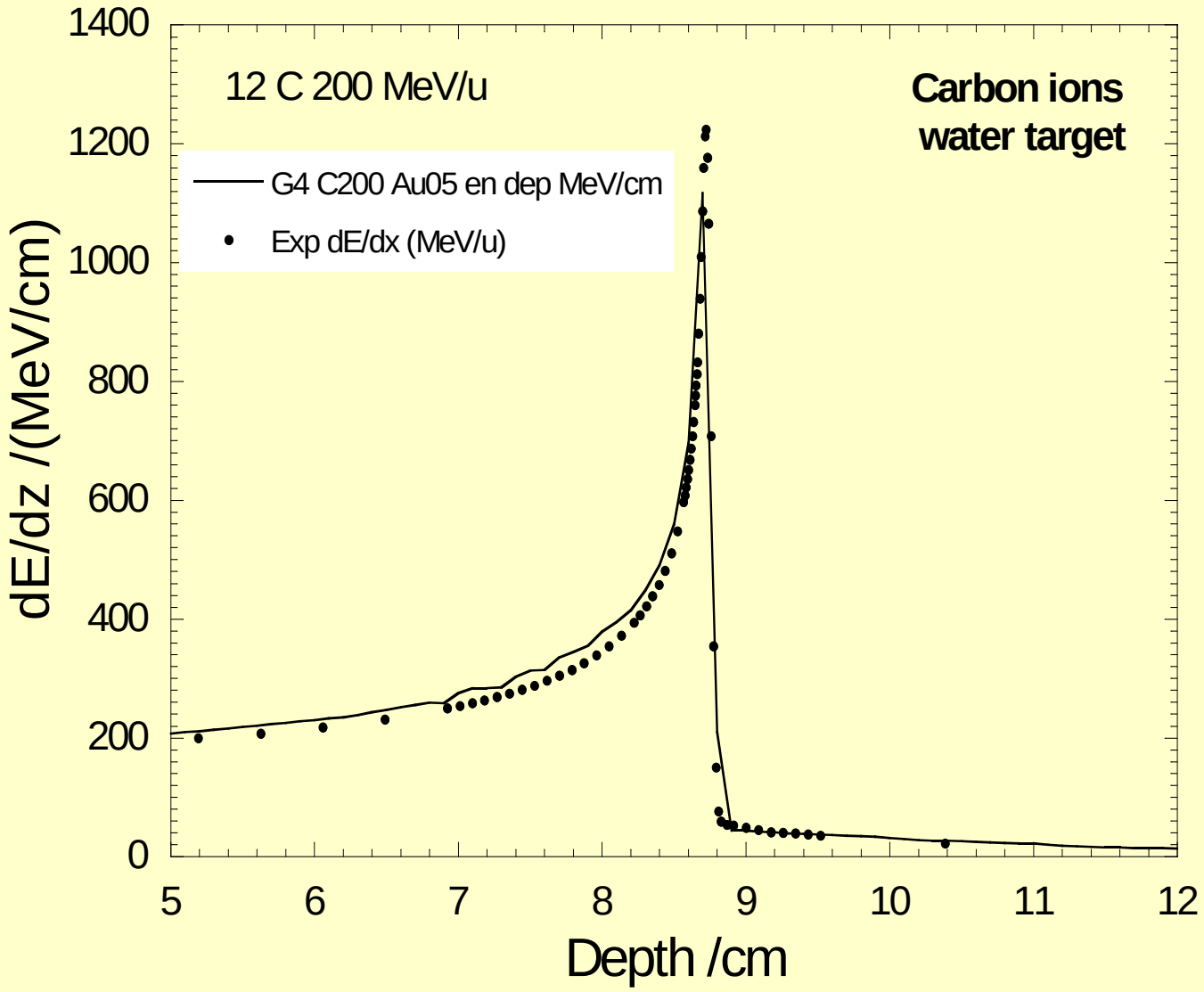
Experiment ^{12}C 100-400 MeV/u, GSI Jäkel et at 2000

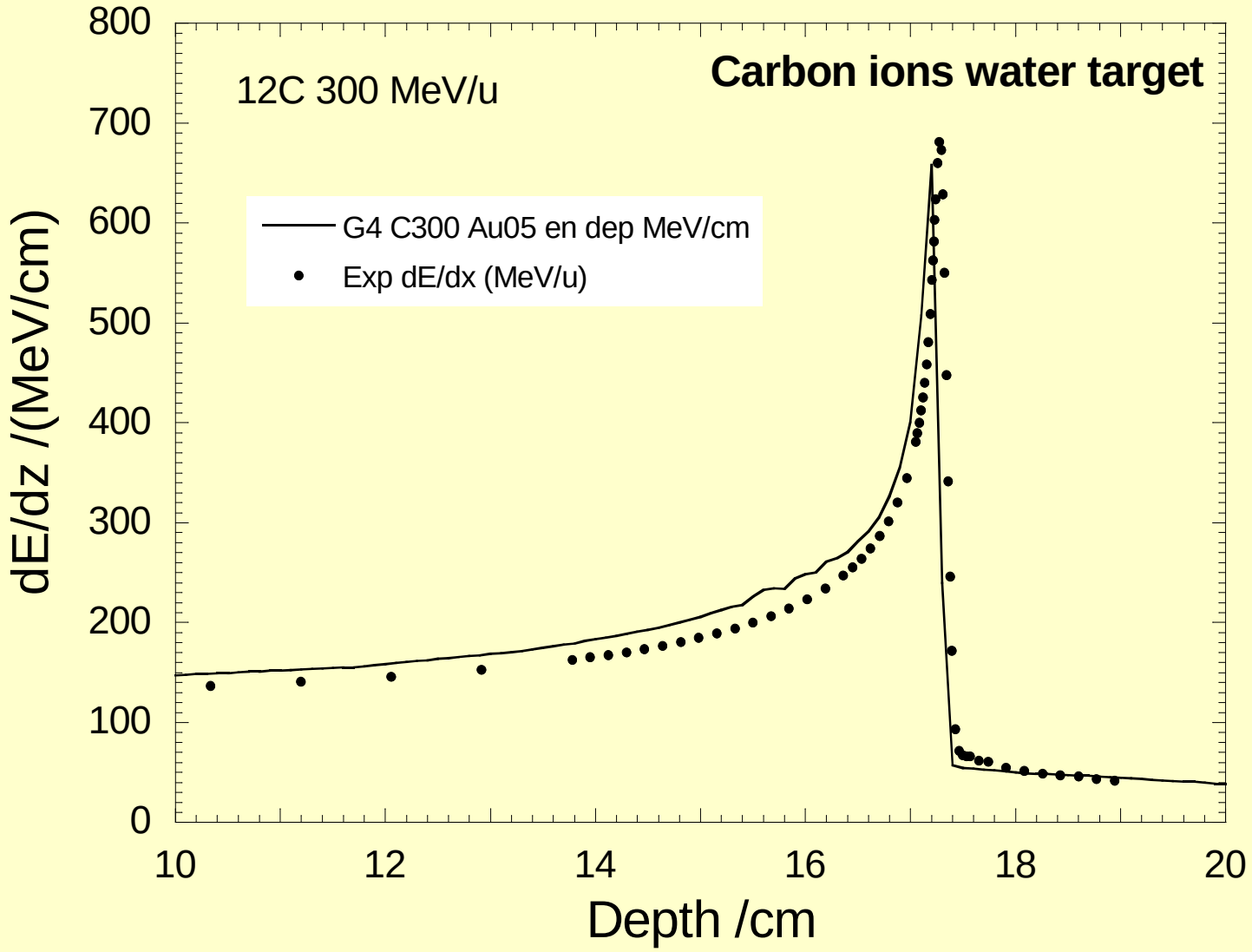


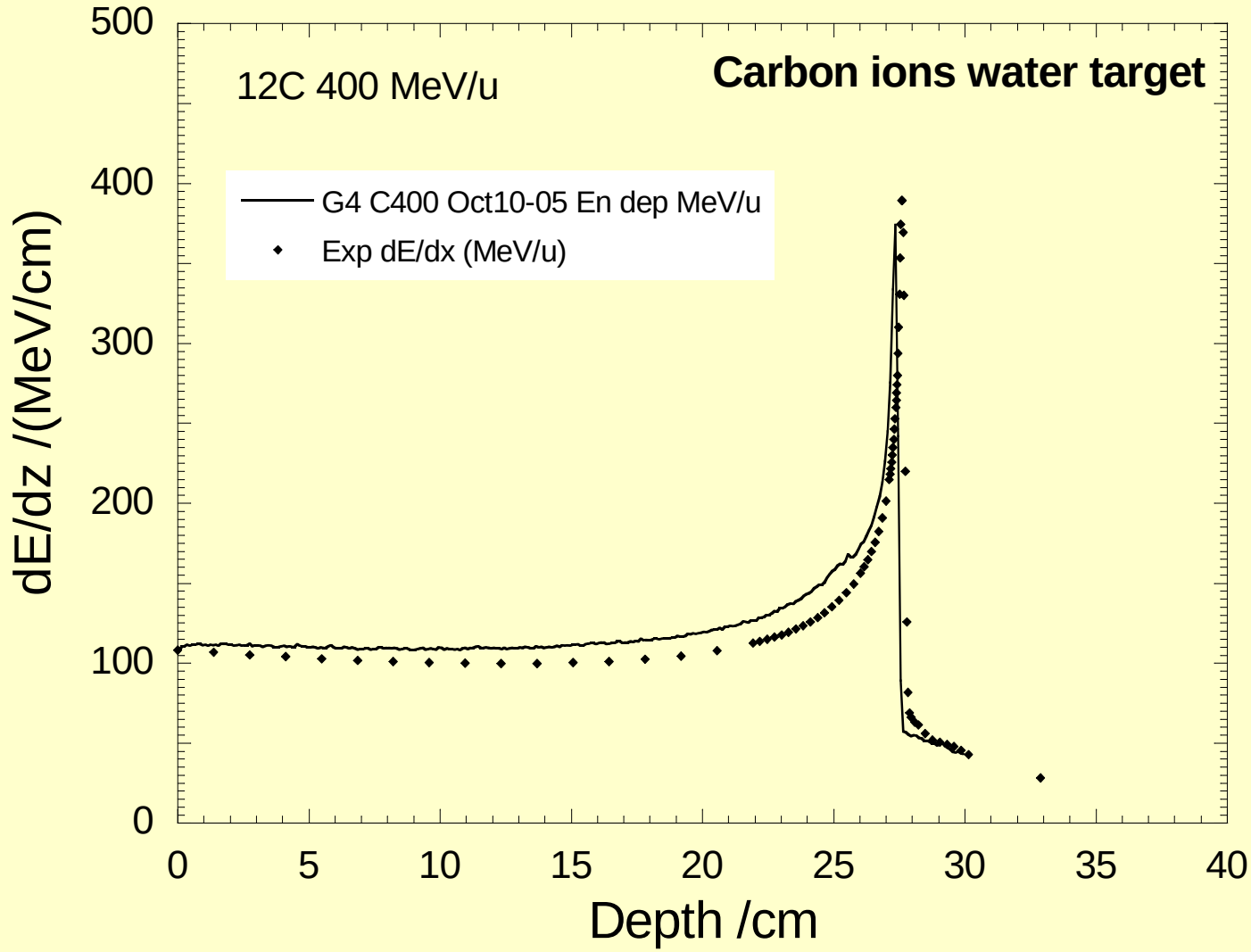

Carbon ions 100 MeV/u
water target
Exp dE/dx (MeV/cm)
G4-raw-100-dE/dx std chem eff-051017
Stand 0.01 cm
dE/dz /(MeV/cm)
Depth /cm
3000
2500
2000
1500
1000
500
0
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8

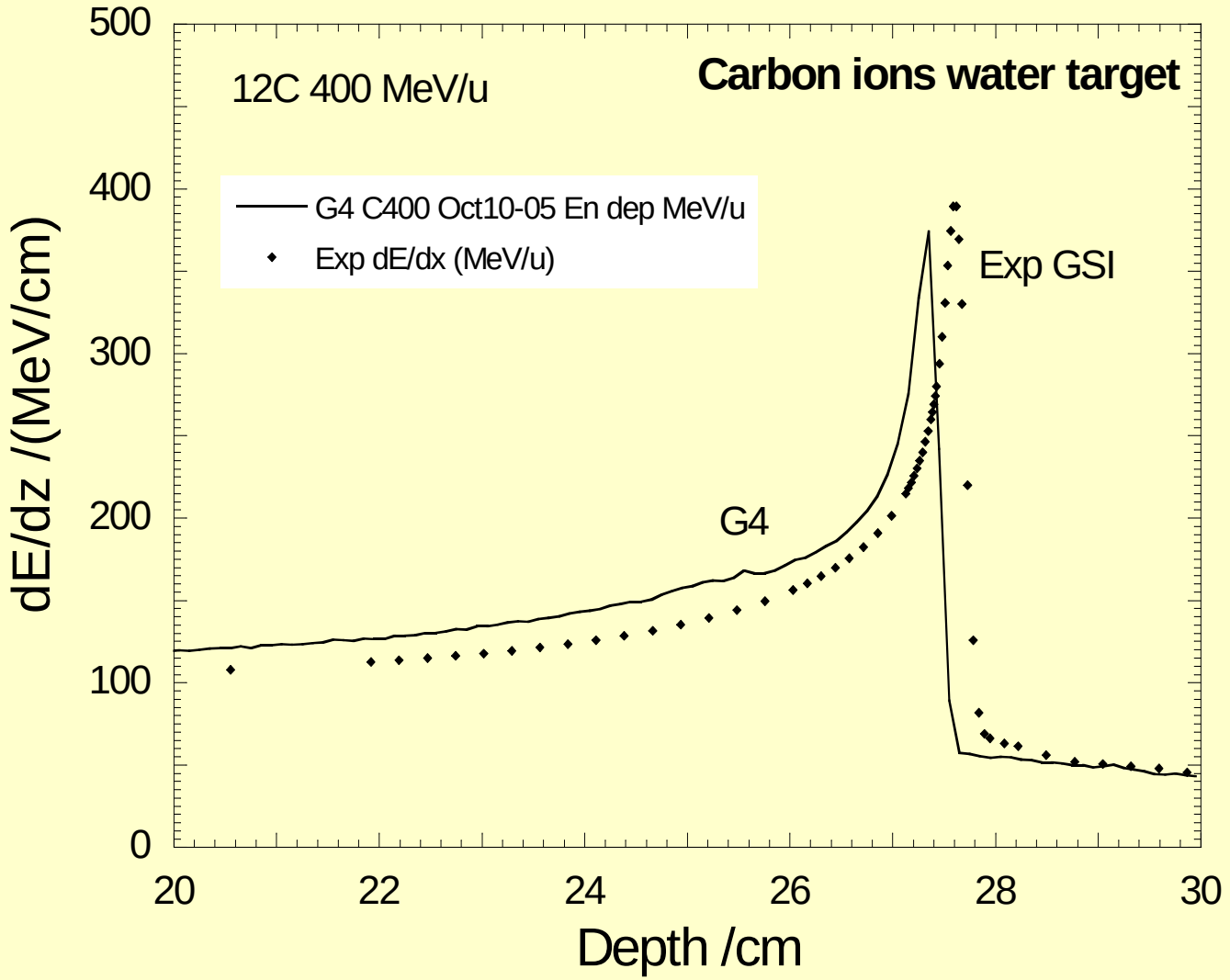

Carbon ions 100 MeV/u
water target
Exp dE/dx (MeV/cm)
G4 raw 051011 100 dE/dX
G4 raw 100 dE/dx low en 051013
Stand 0.05 cm
LowEn 0.05 cm
dE/dz /(MeV/cm)
Depth /cm
3000
2500
2000
1500
1000
500
0
1
2
3

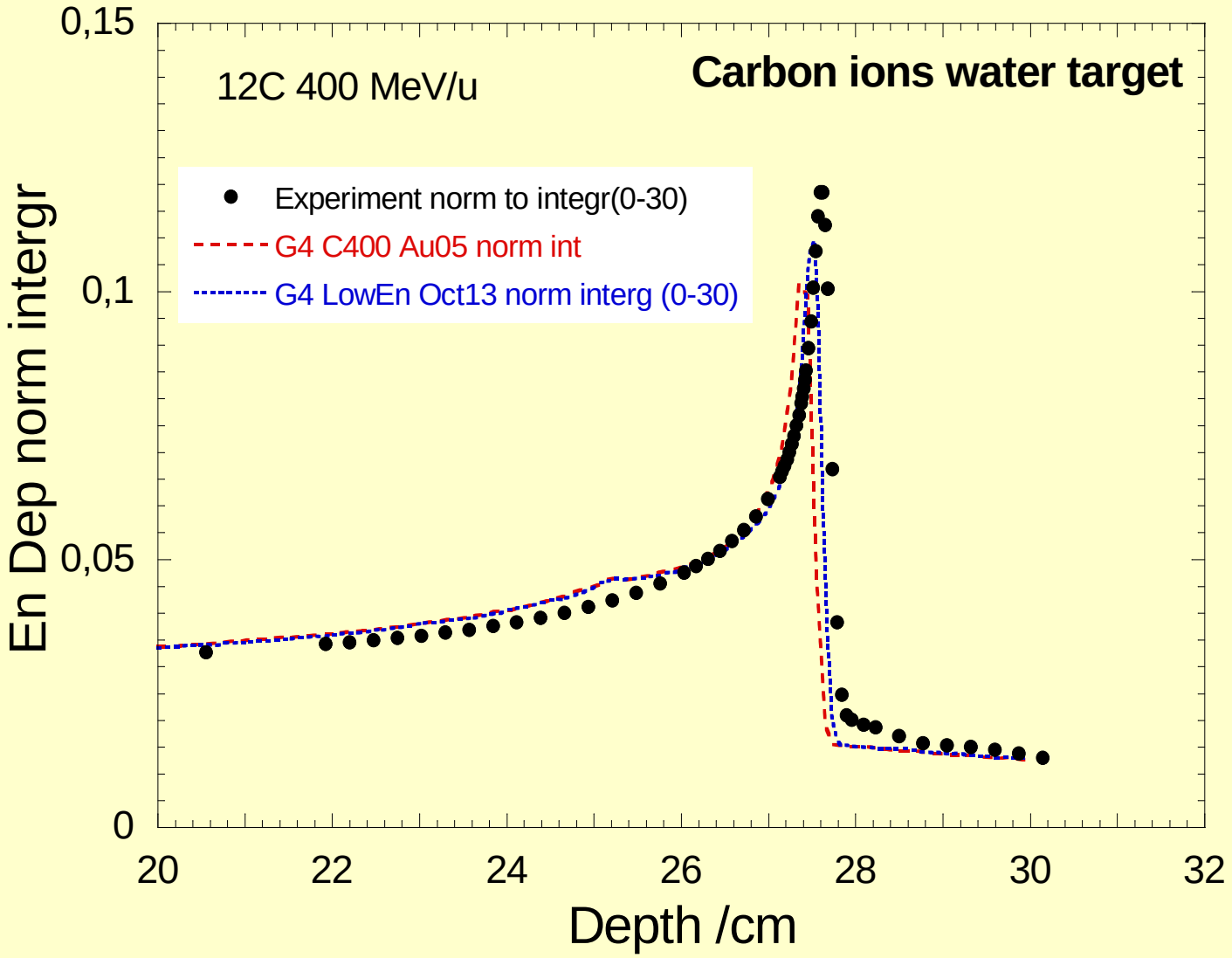

Carbon ions 100 MeV/u
water target
Exp dE/dx (MeV/cm)
G4 raw 051011 100 dE/dX
G4 raw 100 dE/dx low en 051013
Stand 0.05 cm
LowEn 0.05 cm
dE/dz /(MeV/cm)
Depth /cm
3000
2500
2000
1500
1000
500
0
2
2,1
2,2
2,3
2,4
2,5
2,6
2,7
2,8

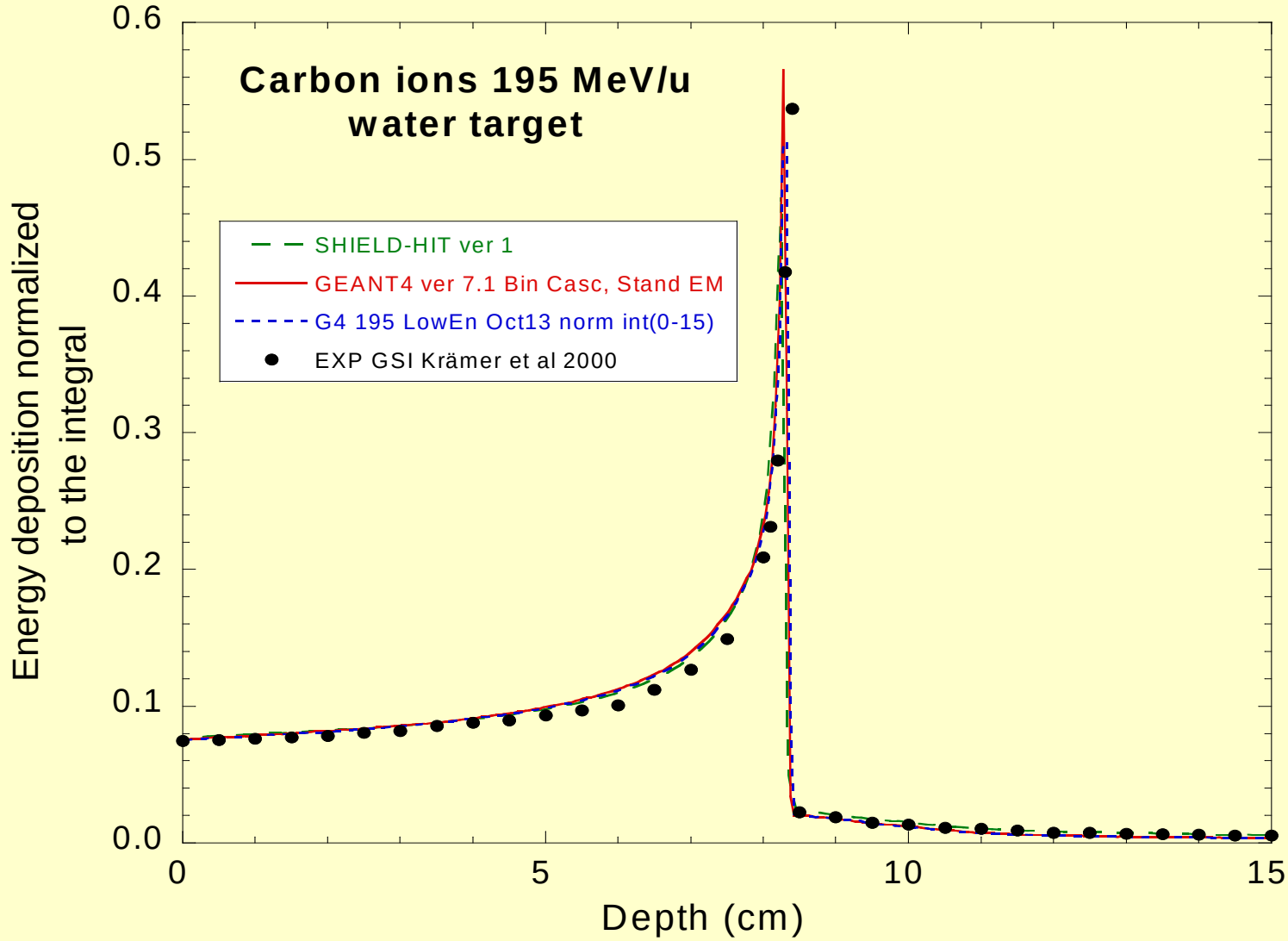

12 C 200 MeV/u
Carbon ions
water target
G4 C200 Au05 en dep MeV/cm
Exp dE/dx (MeV/u)
dE/dz /(MeV/cm)
Depth /cm
0
200
400
600
800
1000
1200
1400
5
6
7
8
9
10
11
12

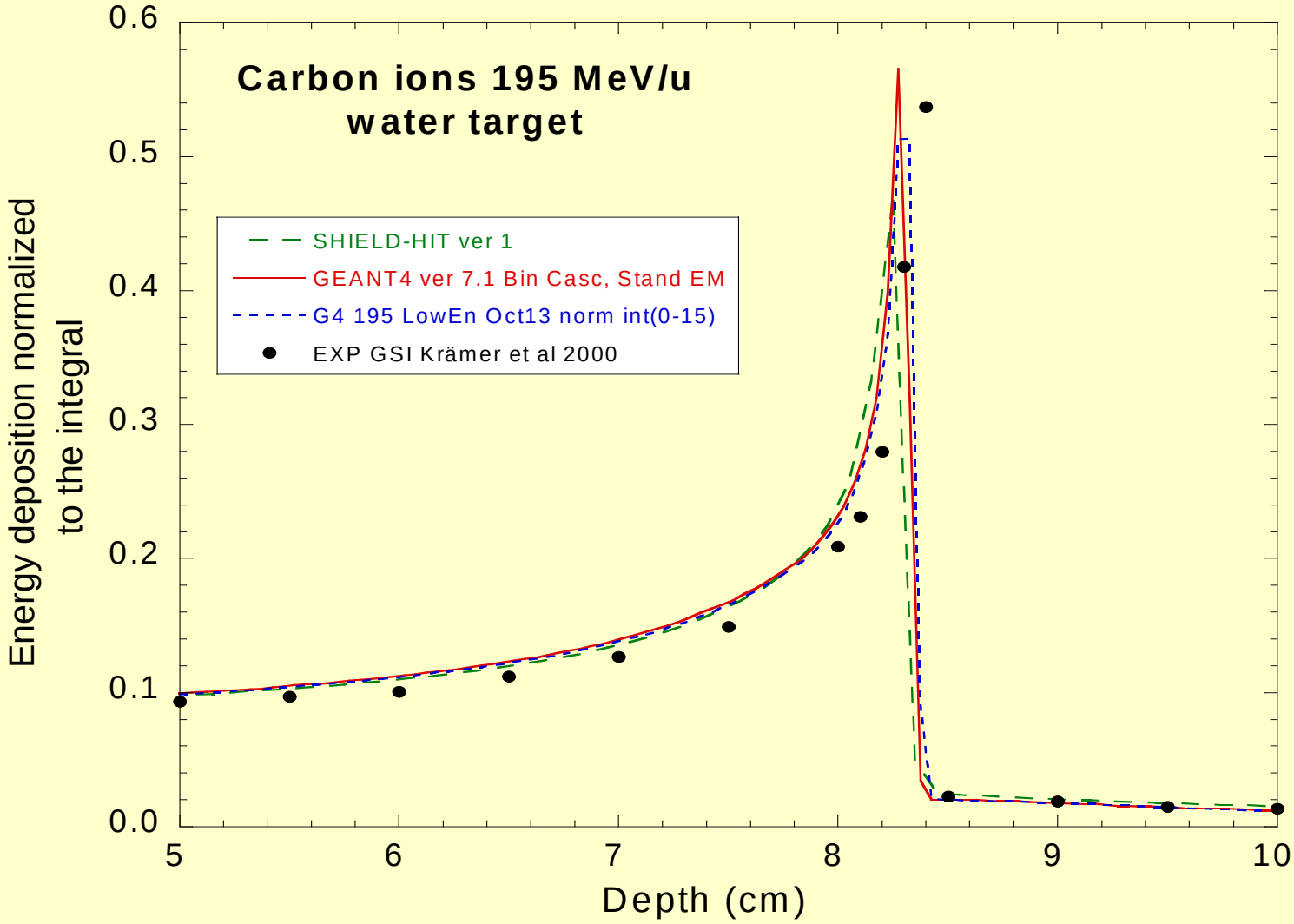

12C 300 MeV/u
Carbon ions water target
G4 C300 Au05 en dep MeV/cm
Exp dE/dx (MeV/u)
dE/dz /(MeV/cm)
Depth /cm
0
100
200
300
400
500
600
700
800
10
12
14
16
18
20

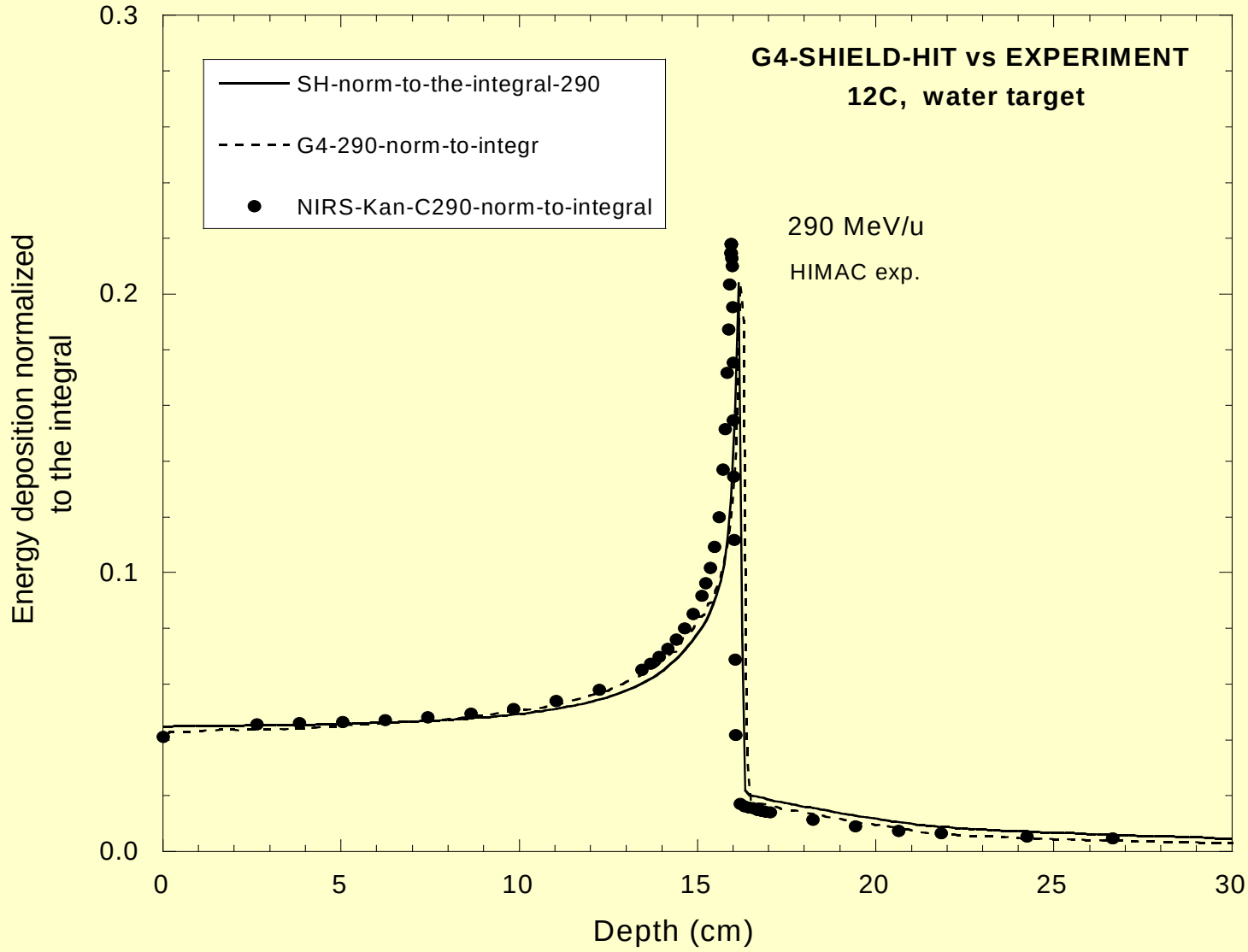

12C 400 MeV/u
Carbon ions water target
G4 C400 Oct10-05 En dep MeV/u
Exp dE/dx (MeV/u)
dE/dz /(MeV/cm)
Depth /cm
0
100
200
300
400
500
0
5
10
15
20
25
30
35
40

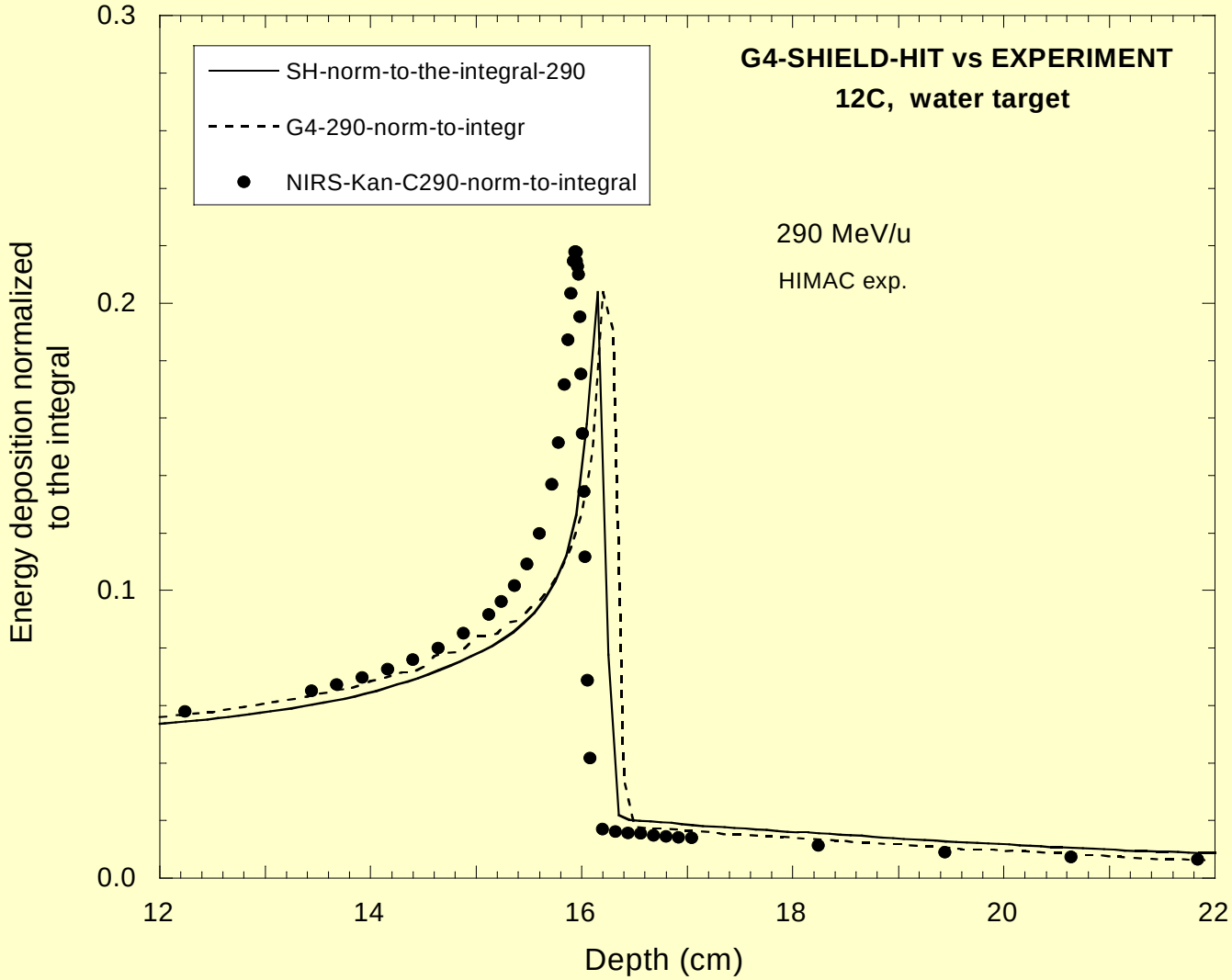

12C 400 MeV/u
Carbon ions water target
G4 C400 Oct10-05 En dep MeV/u
Exp dE/dx (MeV/u)
Exp GSI
G4
dE/dz /(MeV/cm)
Depth /cm
0
100
200
300
400
500
20
22
24
26
28
30

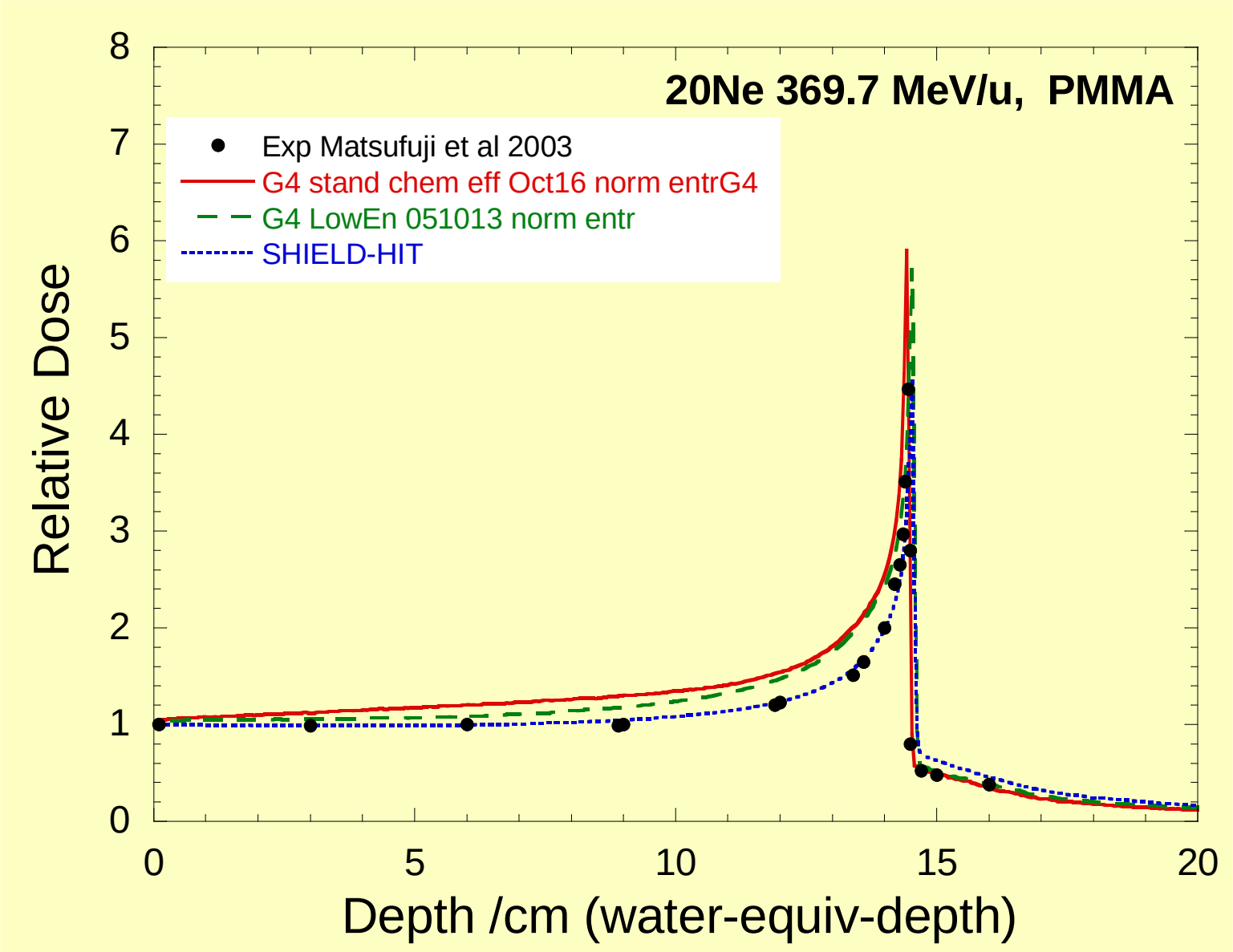

12C 400 MeV/u
Carbon ions water target
Experiment norm to integr(0-30)
G4 C400 Au05 norm int
G4 LowEn Oct13 norm interg (0-30)
En Dep norm intergr
0,15
0,1
0,05
0
20
22
24
26
28
30
32
Depth /cm

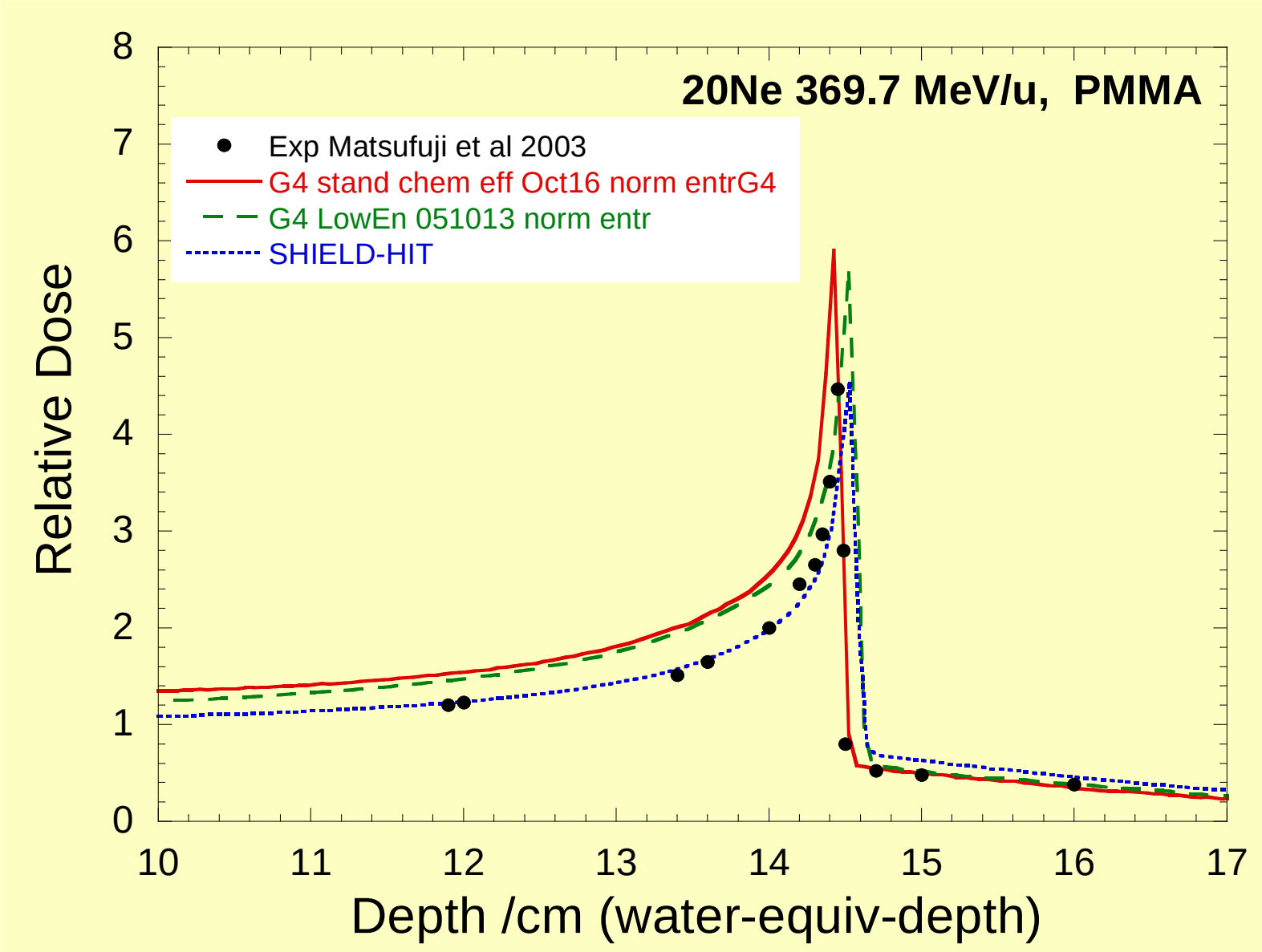

Carbon ions 195 MeV/u
water target
SHIELD-HIT ver 1
GEANT4 ver 7.1 Bin Casc, Stand EM
G4 195 LowEn Oct13 norm int(0-15)
EXP GSI Krämer et al 2000
Energy deposition normalized to the integral
Depth (cm)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15


Carbon ions 195 MeV/u
water target
SHIELD-HIT ver 1
GEANT4 ver 7.1 Bin Casc, Stand EM
G4 195 LowEn Oct13 norm int(0-15)
EXP GSI Krämer et al 2000
Energy deposition normalized to the integral
Depth (cm)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
5
6
7
8
9
10


G4-SHIELD-HIT vs EXPERIMENT
12C, water target
SH-norm-to-the-integral-290
G4-290-norm-to-integr
NIRS-Kan-C290-norm-to-integral
290 MeV/u
HIMAC exp.
Energy deposition normalized to the integral
Depth (cm)
0.0
0.1
0.2
0.3
0
5
10
15
20
25
30


SH-norm-to-the-integral-290
G4-290-norm-to-integr
NIRS-Kan-C290-norm-to-integral
G4-SHIELD-HIT vs EXPERIMENT
12C, water target
290 MeV/u
HIMAC exp.
Energy deposition normalized to the integral
Depth (cm)
0.0
0.1
0.2
0.3
12
14
16
18
20
22


20Ne 369.7 MeV/u, PMMA
Exp Matsufuji et al 2003
G4 stand chem eff Oct16 norm entrG4
G4 LowEn 051013 norm entr
SHIELD-HIT
Relative Dose
Depth /cm (water-equiv-depth)
0
1
2
3
4
5
6
7
8
0
5
10
15
20


20Ne 369.7 MeV/u, PMMA
Exp Matsufuji et al 2003
G4 stand chem eff Oct16 norm entrG4
G4 LowEn 051013 norm entr
SHIELD-HIT
Relative Dose
Depth /cm (water-equiv-depth)
0
1
2
3
4
5
6
7
8
10
11
12
13
14
15
16
17

Conclusions

- Problems with accurate comparison with experiments:
  - beam energy in front of the phantom, beam energy spread
  - use in MC calculations of the recommended stopping power data ICRU49 (p,α), ICRU73 (heavier ions)
- Position of the Bragg peak obtained by different MC codes within ± 2 mm
- Geant4 results agree reasonably well with the experimental data regarding position/height of the Bragg peak
- Contribution to the energy deposition from the fragmentation processes is quite good for ions up to ^{12}C and energies up to 200 MeV/u,

  Geant4 reproduces well the Bragg peak curve in this energy region
- For higher ion energies above about 200 MeV/u verification of the nuclear inelastic interactions required
- Validation of the partial cross-sections for production of secondary particles necessary

Acknowledgements

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