Update on the G4-Med project and on the Geant4 Advanced Examples for medical applications

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Update on the G4-Med project, a Geant4 benchmarking system for bio-medical physics applications

Susanna Guatelli, University of Wollongong, Australia
on behalf of the Geant4 Medical Simulation Benchmarking Group

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Geant4 Medical Simulation Benchmarking Group

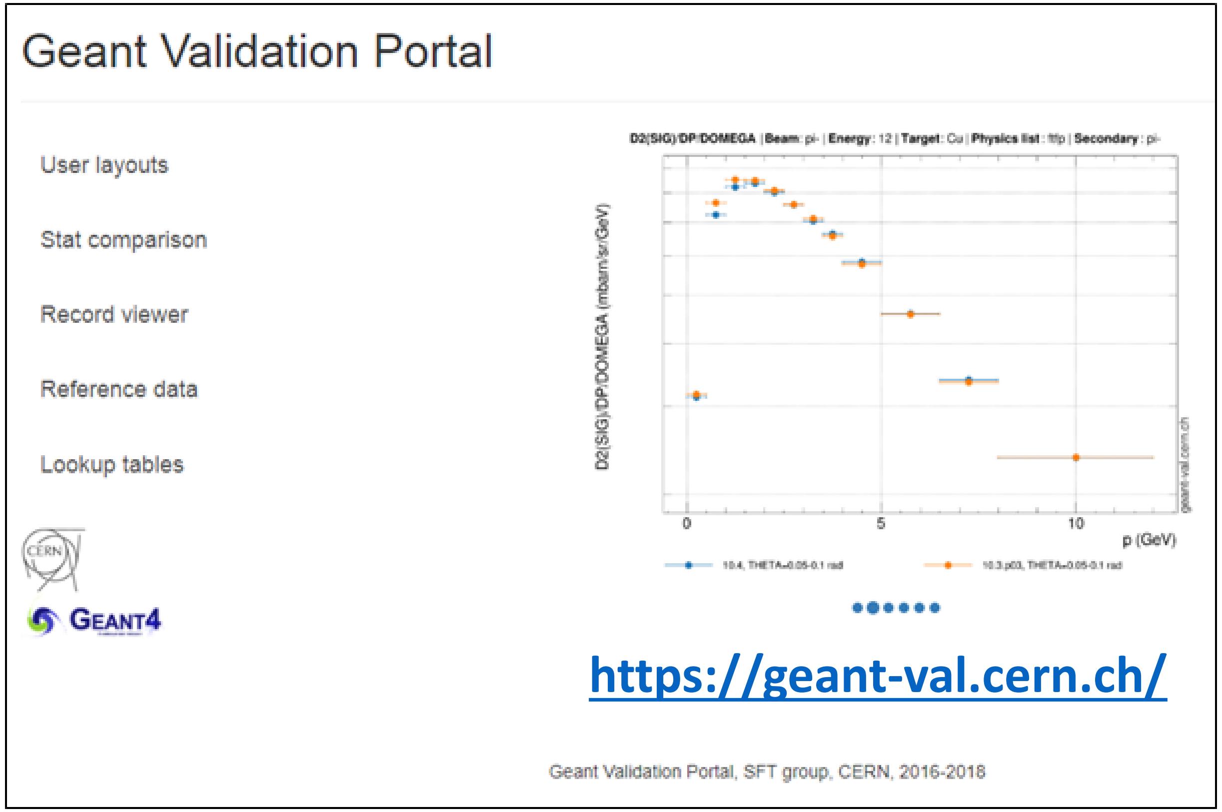
https://twiki.cern.ch/twiki/bin/view/Geant4/G4MSBG

- Created in 2014.
- **Current Coordination Team:**
  - **Coordinator: Susanna Guatelli (Univ. Wollongong, Australia)**
  - **Deputy-coordinator: Pedro Arce (CIEMAT, Spain)**
- 45 researchers; 30 institutions from 12 different countries

Motivation & Goals

- **G4-Med project:**
  - 19 tests to benchmark Geant4 pre-built physics lists for medical physics applications
    - Against reference data and experimental measurements
  - Executed at CERN in regression testing
- **Goals:**
  - Provide physics list recommendations
  - Monitor physics capability of Geant4
- **Webpage:** https://twiki.cern.ch/twiki/bin/view/Geant4/G4MSBG

Regression tests on the CERN computing infrastructure



https://geant-val.cern.ch/

Tested Geant4 Physics Constructors and Lists

Electromagnetic Physics Constructors

- **G4EmStandardPhysics** (a.k.a. “option0”)
  - Usually used as reference by Geant4 physics developers for high-energy physics.
- **G4EmStandardPhysics_option3** (“**EMY**” suffix in physics list naming convention)
  - Based of G4EmStandardPhysics with more accurate settings to model dE/dx, nuclear stopping & fluorescence.
- **G4EmStandardPhysics_option4** (“**EMZ**” suffix)
  - <u>Deemed to be the most accurate combination</u> of Geant4 models, regardless of CPU efficiency.
- **G4EmLivermorePhysics** (“**LIV**” suffix)
  - Includes data-driven low-energy models for e^- ionization and γ based on the Livermore evaluated data libraries.
- **G4EmPenelopePhysics** (“**PEN**” suffix)
  - Includes low-energy models for e^-, e^+ & γ re-engineered from PENELOPE code

Tested Geant4 Physics Constructors and Lists

Hadronic Physics Constructors

For proton therapy

- **QGSP_BIC_HP**
  - **G4EmStandardPhysics_option4** is used by default since Geant4-10.5.
- **QGSP_BIC_EMY** is same as previous, but…
  - **No HP libraries** for neutrons.
  - G4EmStandardPhysics_**option3** is used.
- **QGSP_BERT_HP** differs from QGSP_BIC_HP in:
  - EM interactions are modeled with "**option0**".
  - For incident **p** & **n**, Bertini model (own Precompound+Evaporation) is used for hadronic inelastic scattering.

For carbon ion therapy:

- **G4IonBinaryCascade -** *LightIonBinaryCascade* model.
- **G4IonQMDPhysics -** Quantum Molecular Dynamics (QMD) model.
- **G4IonINCLXXPhysics -** Liège Intranuclear-Cascade model (INCL).

Tests included in G4-Med

https://twiki.cern.ch/twiki/bin/view/Geant4/G4MSBG

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TWiki > Geant4 Web > G4MSBG (2019-04-23, LucianoPandola)

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Welcome to the Twiki web page of the G4MSBG initiative: G4-Med

Purpose

The aim of the Geant4 Medical Physics Benchmarking Group (G4MSBG) is to develop a fully automatised Geant4 benchmarking and regression testing system for medical physics applications, called G4-Med. A set of Geant4 Physics Constructors and Lists of interest for medical physics applications are tested. The tests are integrated in the geant-val test system to be executed for benchmarking and regression testing. The test are executed using the CERN computing infrastructure.

List of current tests

Currently the G4-Med system includes 18 tests.

Test	geant-val layout	Authors
Photon attenuation coefficients	PhotonAttenuation	S. Guatelli, L. Pandola
Electron stopping powers	ElectronDEDX	V. Ivanchenko
Low energy electron backscattering	ElectronBackScat	P. Dondero, A. Mantero,V. Ivanchenko, M. Novak
Electron scattering from foils at 13-20 MeV kinetic energies	ElecForwScat	B. Faddegon, J. Ramos-Méndez
Bremsstrahlung yield	Bremsstrahlung	B. Faddegon,J. Ramos-Méndez
Fano cavity	Fano cavity	P. Arce , M. Maire, M. Novak
Electron Dose Point Kernel	LowEElecDPK	S. Incerti, M.-C. Bordage, I. Kyriakou, Y. Perrot
Microdosimetry	Microyz	S. Incerti, I. Kyriakou
Brachytherapy - dose rate	Brachy-ir	S. Guatelli, D. Cutajar
Dosimetry - clinical 5-6 MeV electron beam	To be added	L. Desorgher
Dosimetry for mammography	Mammo	C. Fedon, I. Sechopoulos
Hadronic nucleus-nucleus inelastic cross section	NucNucInelXS	D. Sakata, S. Guatelli, E. Simpson
Bragg curves in water for 67.5 MeV protons	LowEProtonBraggPeak	B. Faddegon, J. Ramos-Méndez
Absolute neutron yield for protons	ProtonC12NeutronYield	B. Faddegon, J. Ramos-Méndez
Production cross sections of different fragments	C12FragCC	C. Omachi, T. Toshito, T. Sasaki
62 MeV /n C-12 fragmentation on Carbon target	LowEC12Frag	C. Mancini-Terracciano
400 MeV/n C-12 fragmentation	C12Frag	D. Bolst, S. Guatelli, F. Romano
Estimation of proton radiobiological damage	LowEProtonRBE	G. Petringa, GAP Cirrone L. Pandola, G. Cuttone
Light ion (proton, 3He, carbon) range and depth dose curves in water	LightIonBraggPeak	M. Cortes-Giraldo, A. Perales, J. M. Quesada Molina

Publication: Med Phys, 48(1):19-56, 2021. [doi: 10.1002/mp.14226]

- Geant4 10.5:
  - Overall, *G4EmStandardPhysics_option4* (**_EMZ**) is recommended for accurate simulations.
  - **QGSP_BIC_HP** (_EMZ) physics list provides a good overall description.

Outline

- Improvements in Geant4 11.0 for medical physics
- Results of the regression testing of the G4-Med tests with Geant4 11 release
- New tests
- Conclusions and outlook

Of interest for Geant4, GAMOS, GATE and TOPAS users

Geant4 11.0: major release

- Please, read the **Geant4 Release Notes** with all the changes, including
  - **Multi-threading** at the level of the **event**
  - **More efficient** management of the physics processes (updated ***`G4PhysicsVector`***)
  - Gamma linear polarization may be enabled on top of EM gamma physics in all the EM physics constructors (important for synchrotron radiation)
    - Enable via user interface **`G4EmParameters::SetEnablePolarisation(G4bool val)`**
    - Example of use in **`G4LowEPPhysics`** to describe low energy (E < 10 MeV) polarised X-/gamma ray transport in Geant4 (J. M. C. Brown and M. R. Dimmock, NIM B, 502, 2021, 176-182)
  - Quantum entanglement in positron annihilation may be also enabled
    - **`G4EmParameters:: SetQuantumEntanglement(G4bool v)`**
    - UI command: “/process/ em /QuantumEntanglement true”
    - E.g. in PET applications

Improvements in the physics of Geant4
for biomedical applications

- **Geant4 EM physics component**
  - General clean-up
  - Implementation of EPICS2017 for photon processes
    - Possible to use it in the Livermore low-energy EM constructor (via UI commands)
    - Evaluated and included into **G4EMLOW8.0**
    - Li Z. , Michelet C., et al. Phys. Med. 95 (2022) 94 -115
    - Documentation: http://geant4.in2p3.fr/styled -4/styled -8/
  - Implementation of a new data library modelling atomic de-excitation and PIXE ("ANSTO" data lib)
    - X-RAY fluorescence transition probabilities calculated within the Hartree-Fock (HF) approach
    - Bakr S et al (2021) NIM B 507: 11 – 1915, Bakr S et al (2018), NIM B 436: 285–291
  - New ion ionisation model **`G4LinhardSorensenIonModel`**
    - ICRU73 and ICRU90 data for energy < 2 MeV/amu, Linhard-Sorensen model above
  - Geant4-DNA physics models extend to gold (nanoparticle radio-enhancement in radiotherapy)
  - Added new IRT-syn model to model free radical diffusion with Geant4-DNA
- **Hadronic physics component**
  - General clean-up
  - Gamma Nuclear cross section: New IAEA 2019 data library, verified against EXFOR and PDG data

Results of the regression testing of the G4—Med tests

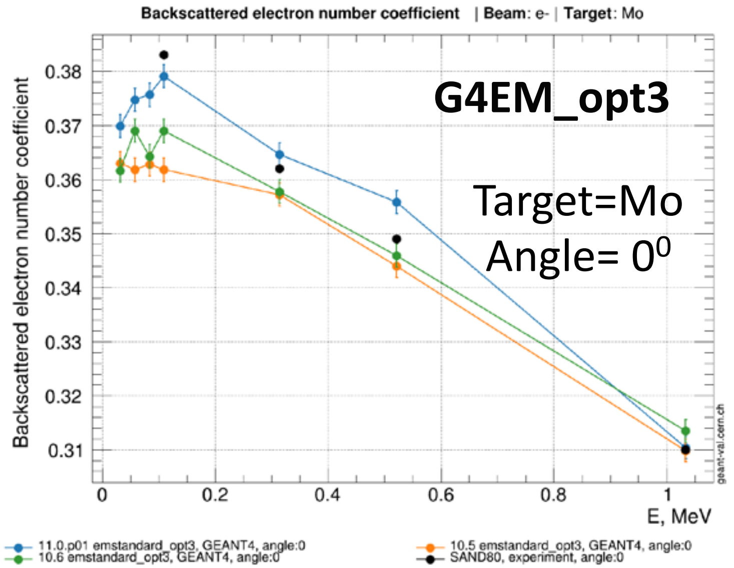
Geant4 10.5, 10.6 and Geant4 11.p01

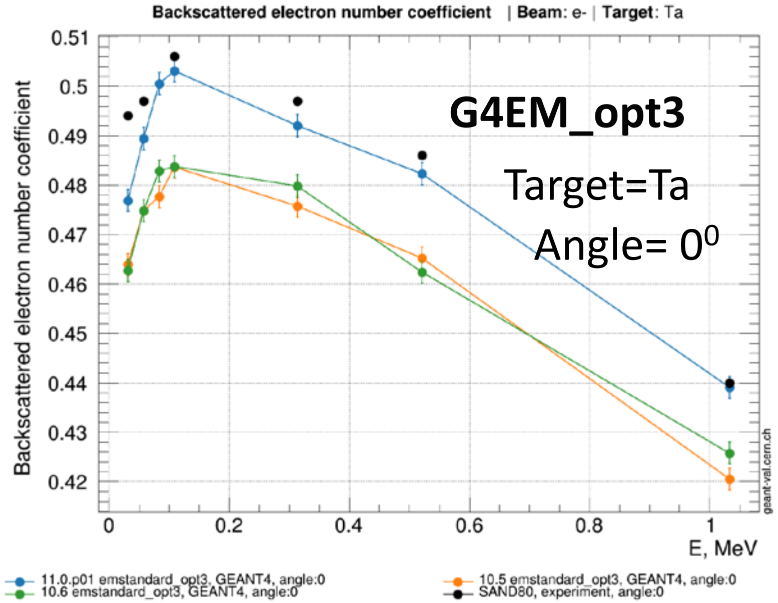
Comments on significant changes only

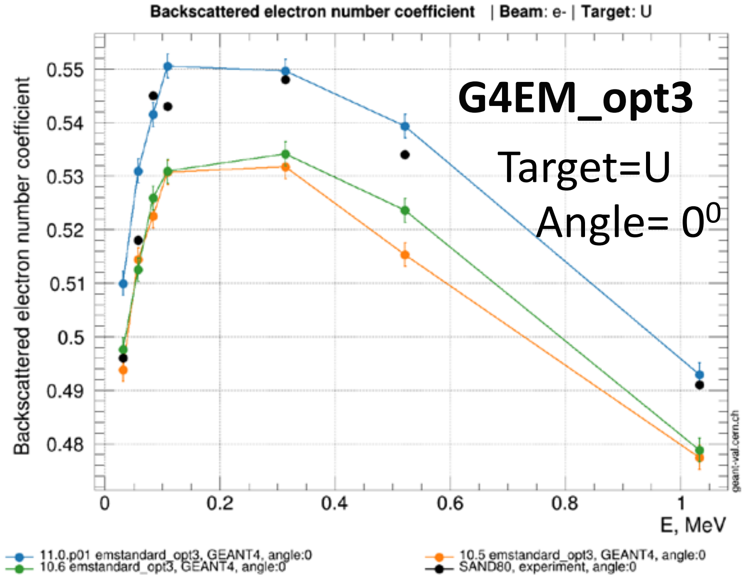
Electron backscattering tests (1)

(Authors: P. Dondero & A. Mantero, SHWARD)

10.5, **10.6**, **11.0 p01**



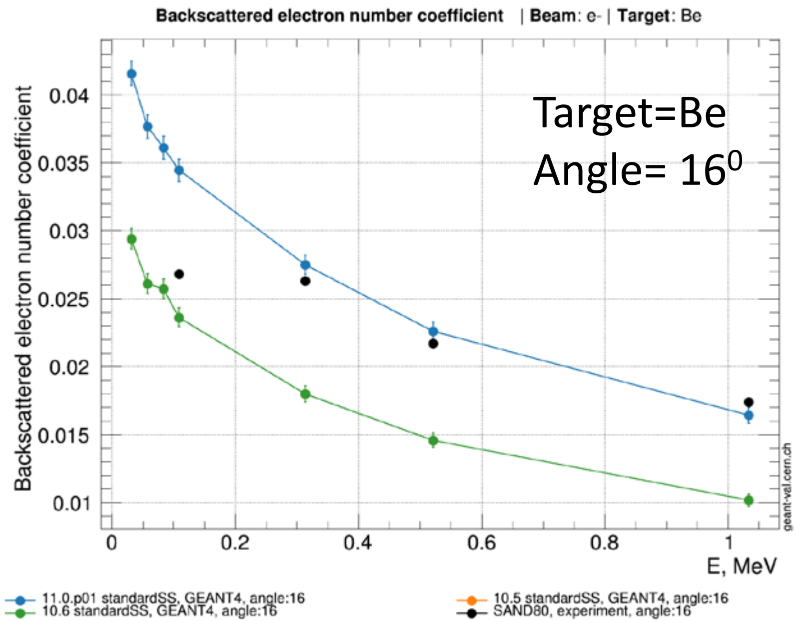


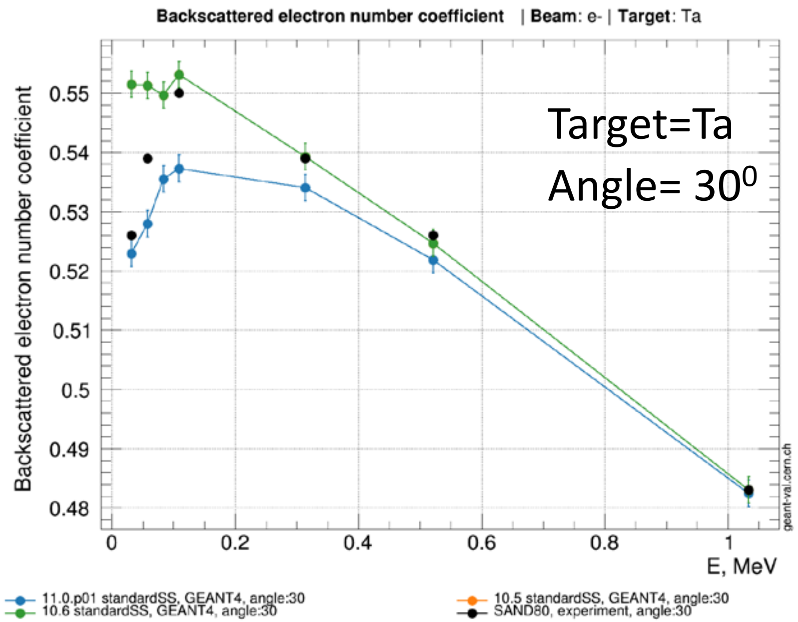


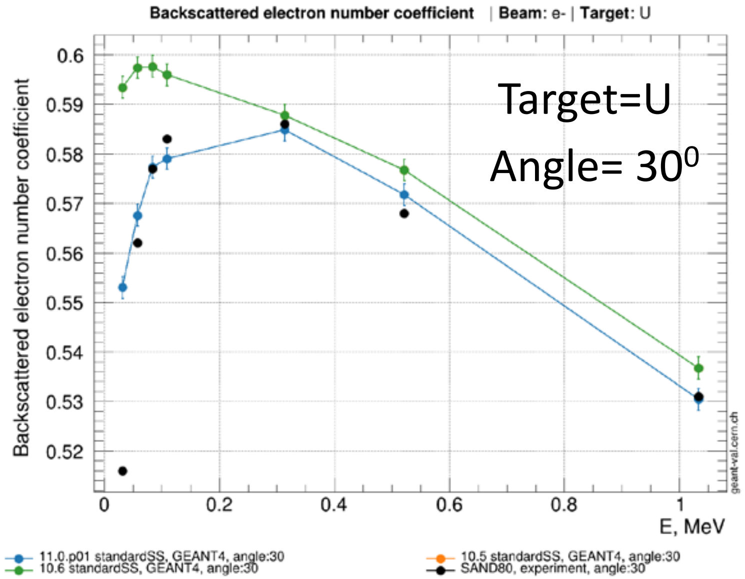
- Better agreement in terms of backscattering coefficient for high Z, for G4EmStandard_option3
  - Probably due to optimisation of the msc parameters
    - RangeFactor=0.03 (from 0.04)
    - Use of 'SafetyPlus' step limitation instead of 'DistanceToBoundary'
- No change for G4EmStandard_option4, G4EmStandard_GS

Electron backscattering tests (2)

G4EmStandardPhysics_SS







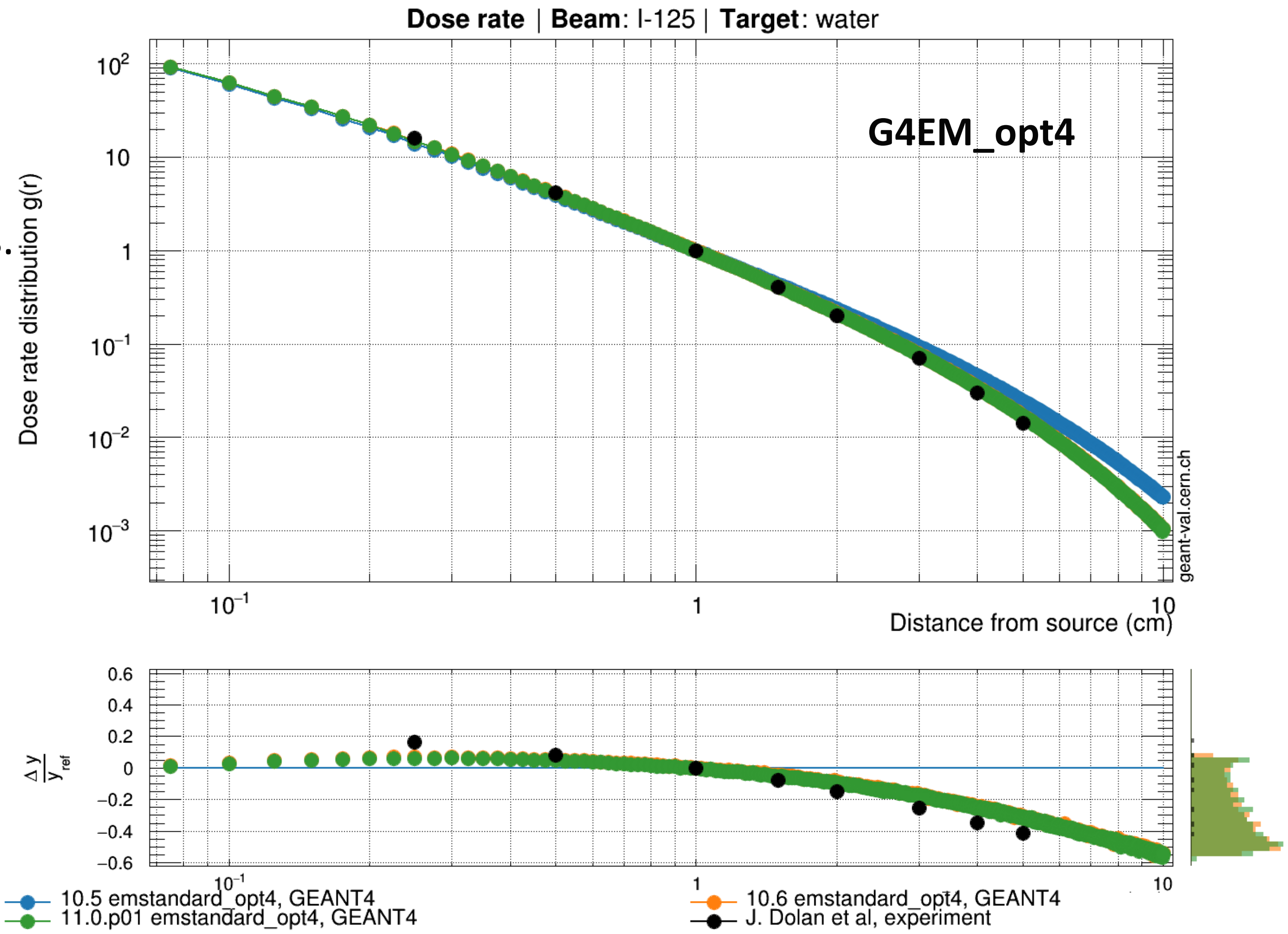
10.6, **11.0 p01**

There is a general improvement in the Single Scattering model

Brachytherapy test

10.5, 10.6, 11.0 p01

- I-125 brachytherapy source
- Exp measurements: Dolan J et al, Med. Phys. 33:12, 2006
- Since Geant4 10.6 better agreement with reference data at large distances for I-125.
- In G4Penelope, G4Livermore, G4EMOpt3, G4EmOpt4
- Probably due to multiple scattering
- Same results between 10.6 and 11.00.p01

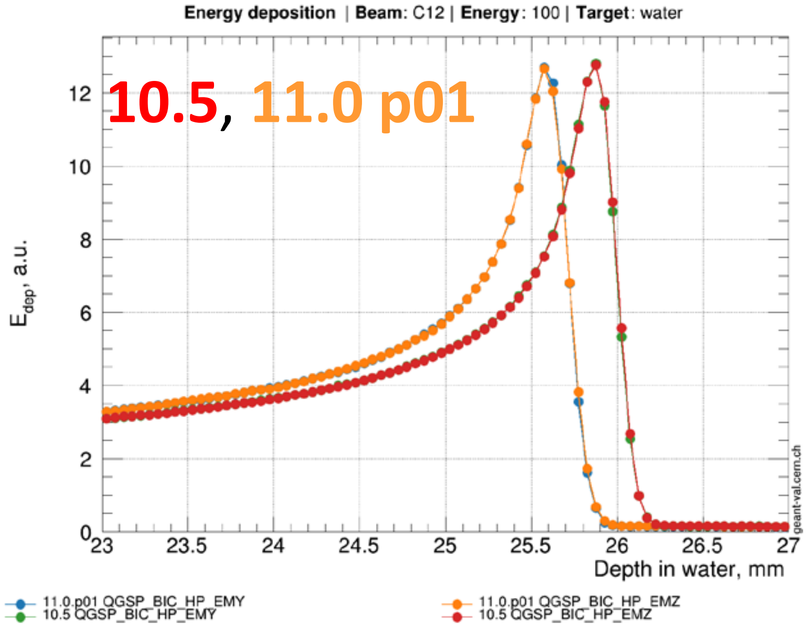


By D. Cutajar, S. Guatelli, A. Le, A. Rosenfeld (University of Wollongong)

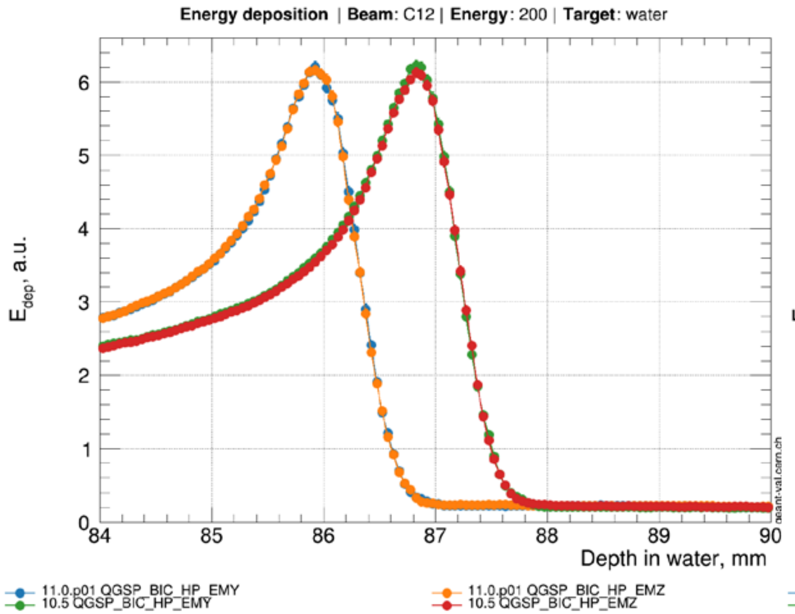
Proton and carbon ion beam ranges in water

Authors: M. Cortes Giraldo and J. M. Quesada Molina, Sevilla University

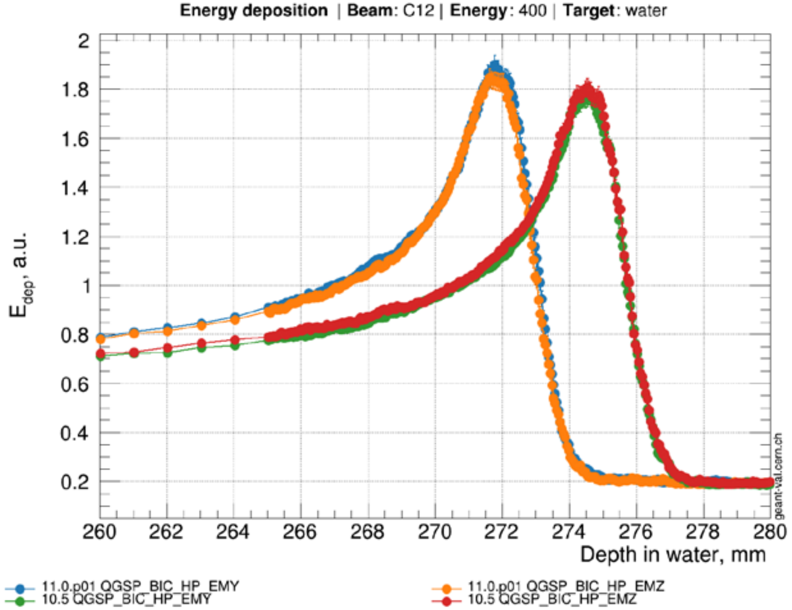
100 MeV/amu ^{12}C



200 MeV/amu ^{12}C



400 MeV/amu ^{12}C



- Same results for incident protons and alpha particles
- Significant differences for carbon ions deriving from the new ion ionisation model G4LinhardSorensenIonModel with ICRU73 and ICRU90 data for energy < 2 MeV/amu, Linhard-Sorensen model above.
- Now this has been solved in the Geant4 11.1 beta release (checked in 11.0ref08 as well).

Heavy Ion Therapy test

Introduced more recently in geant-val

A. Chacon (ANSTO), S. Guatelli (UOW), M. Safavi-Naeini (ANSTO) et al.

Test for in-vivo PET in Heavy Ion Therapy

- ^{12}C ion beams produce secondary positron-emitting fragments. The resulting positrons annihilate in the target.
- The spatio-temporal distribution of annihilations can be imaged using a PET scanner.
- The **yields of the positron-emitting nuclei** ^{11}C, ^{10}C and ^{15}O obtained from Geant4 are compared to the experimental data obtained at the HIMAC heavy-ion treatment facility at QST in Chiba, Japan.
- **Phantom materials:** PMMA, gelatin and polyethylene
- **Incident beams:** 150-350 MeV/amu ^{12}C and 148/290 MeV/amu ^{16}O.

Yield and distribution of positron-emitting fragments in heavy ion beam therapy

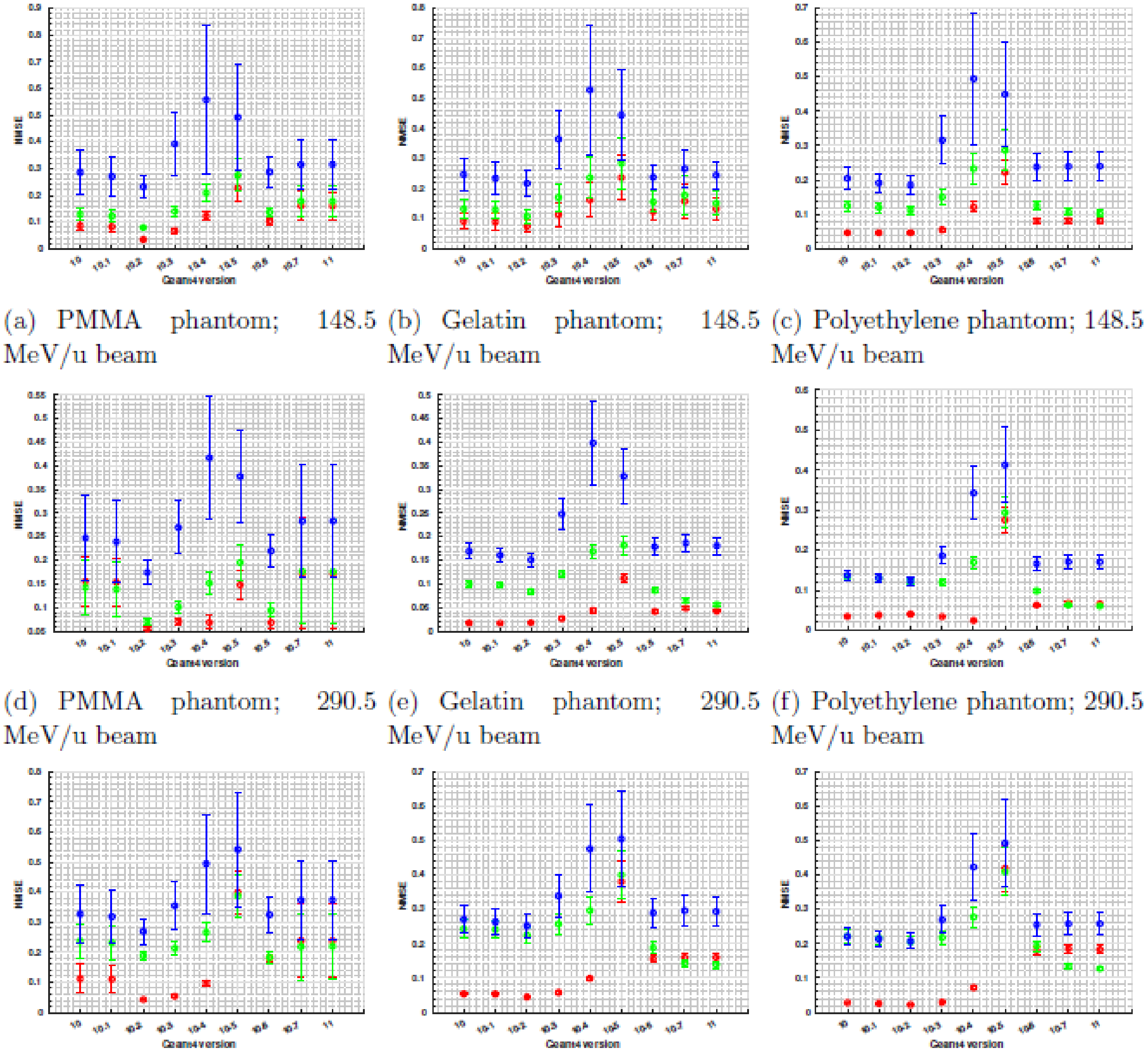
Table 1: Beam parameters for each ion species and energy. All beams had an energy spread of 0.2 % of the nominal energy; 95% confidence intervals are listed for beam flux.

Ion	Energy (MeV/u)	σ_x (mm)	σ_y (mm)	Beam flux (pps)
^{12}C	148.5	2.77	2.67	$1.8\times10^9 \pm 3.8\times10^7$
^{12}C	290.5	3.08	4.70	$1.8\times10^9 \pm 6.4\times10^7$
^{12}C	350	2.50	2.98	$1.8\times10^9 \pm 4.6\times10^7$
^{16}O	148	2.79	2.89	$1.1\times10^9 \pm 2.8\times10^7$
^{16}O	290	2.60	4.90	$1.1\times10^9 \pm 7.0\times10^7$

normalised mean square error (NMSE)

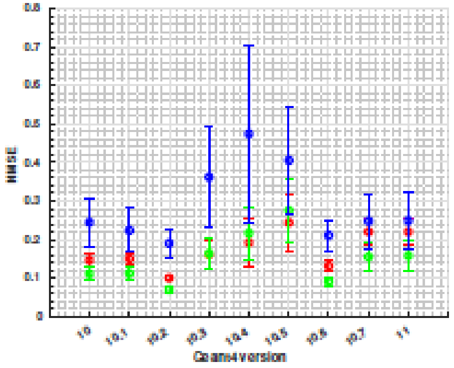
$$NMSE = \frac{\sum_{i=1}^{N_{reg}} |S_i - E_i|^2}{\sum_{i=1}^{N_{reg}} |E_i|^2}$$

BIC,
QMD
INCL

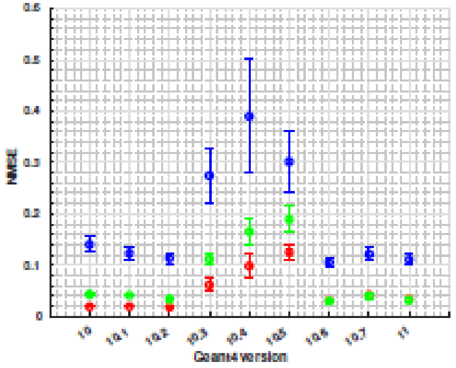


(a) PMMA phantom; 148.5 MeV/u beam
(b) Gelatin phantom; 148.5 MeV/u beam
(c) Polyethylene phantom; 148.5 MeV/u beam
(d) PMMA phantom; 290.5 MeV/u beam
(e) Gelatin phantom; 290.5 MeV/u beam
(f) Polyethylene phantom; 290.5 MeV/u beam
(g) PMMA phantom; 350 MeV/u beam
(h) Gelatin phantom; 350 MeV/u beam
(i) Polyethylene phantom; 350 MeV/u beam

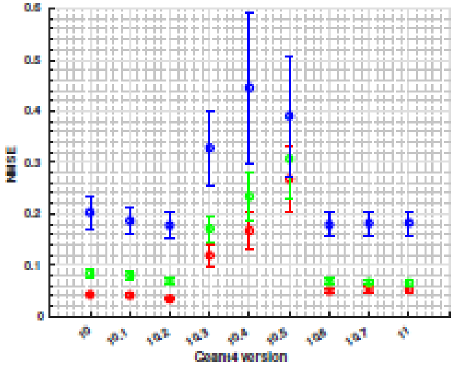
Figure 5: The NMSE in the build-up and Bragg peak region using carbon beams for *all positron emitting fragments.*



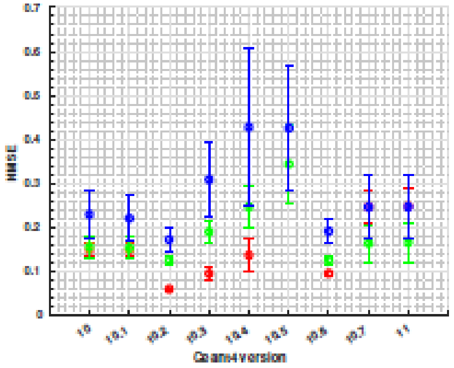
(a) PMMA phantom; 148 MeV/u beam



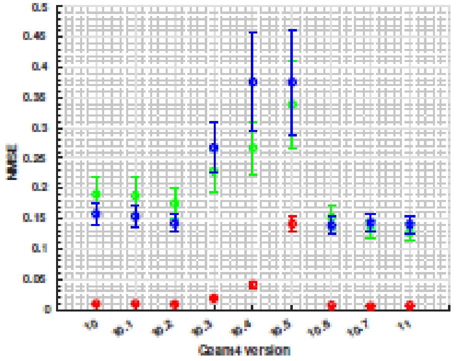
(b) Gelatin phantom; 148 MeV/u beam



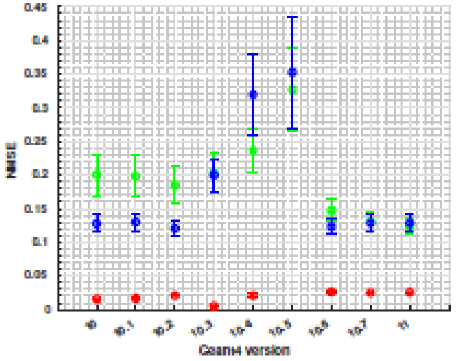
(c) Polyethylene phantom; 148 MeV/u beam



(d) PMMA phantom; 290 MeV/u beam



(e) Gelatin phantom; 290 MeV/u beam



(f) Polyethylene phantom; 290 MeV/u beam

Figure 7: The NMSE in the build up and Bragg peak region using oxygen beams for *all positron emitting fragments.*

Remarks:

- The best model is BIC with Geant4 10.2
- 10.3-10.5 were generally the worst preforming across the test scenarios and these versions should be avoided if possible
- Note: For incident protons use QGSP_BIC_AllHP as it showed better agreement with experimental measurements (see talk by J. Quesada-Molina)

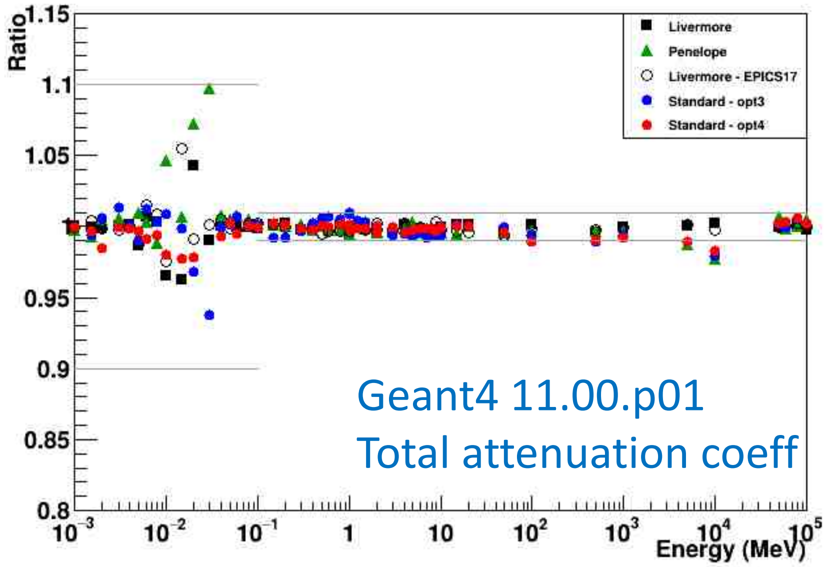
New tests

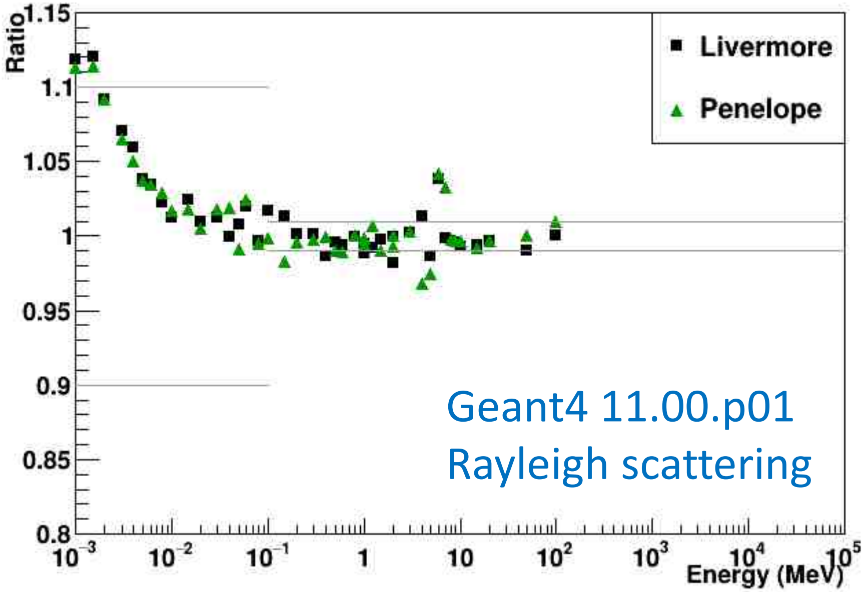
to be included in the G4-Med testing suite

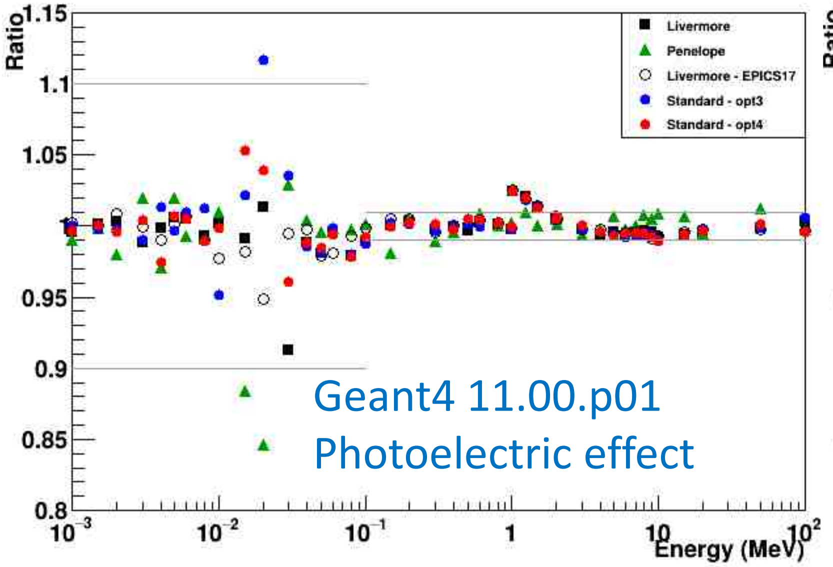
Photon attenuation coefficients tests

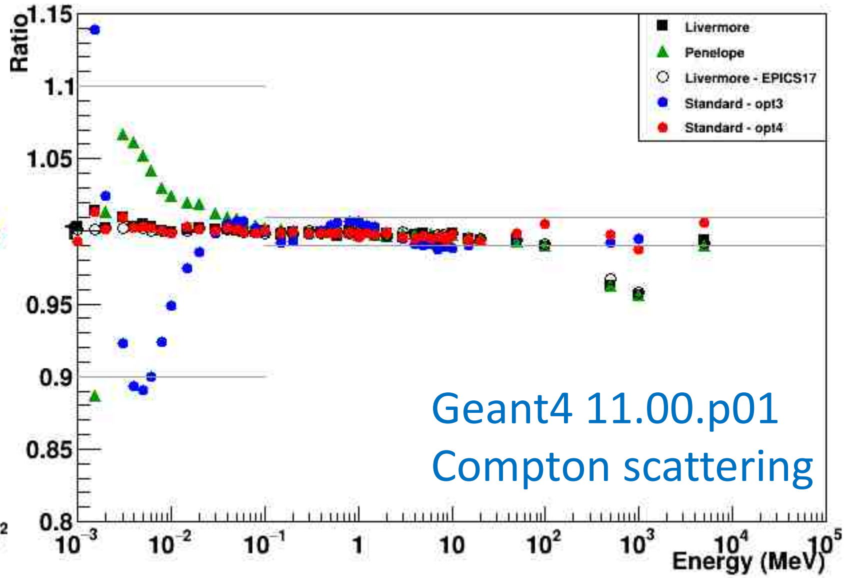
By S. Guatelli (UOW), Z. Li, C. Michelet and S. Incerti (LP2i)

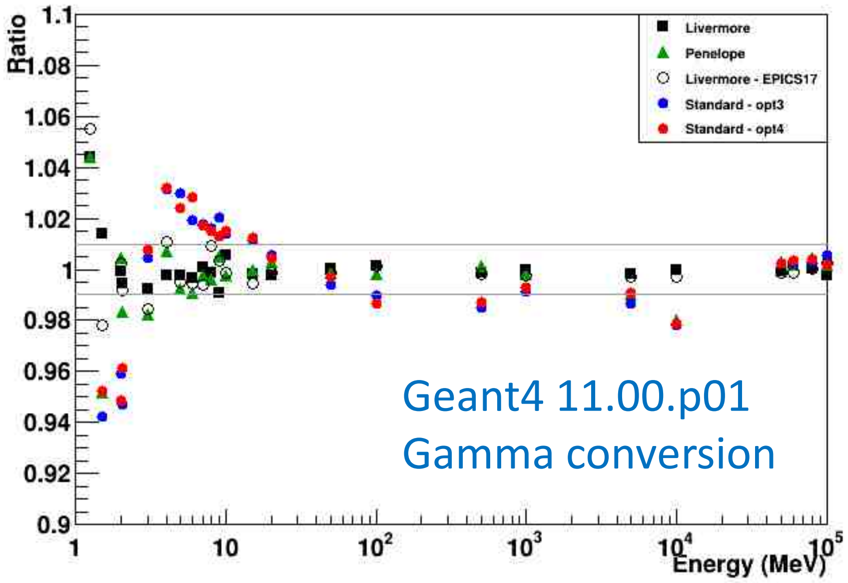
- Reference: NIST XCOM
- New: Add EPICS17
- The results of the photon attenuation tests in water do not change when comparing 10.5, 10.6 and 11.0 cand01, 11.00.p01









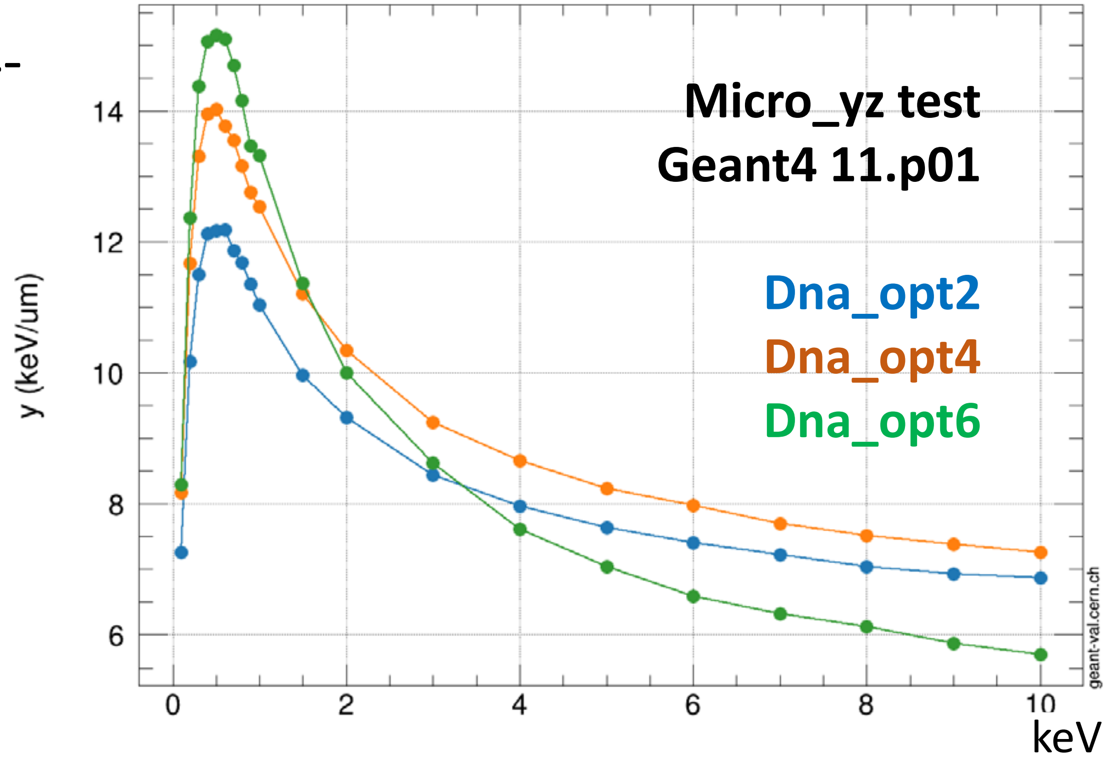


Add tests on Geant4-DNA Physics Lists

- Regression testing to control how the Geant4-DNA physics lists change
  - Microdosimetry test
  - Dose Point Kernels
  - Range test

By I. Kyriakou (Ioannina University) and S. Incerti, LP2i

Microdosimetry test, 10 nm diameter water SV



Frequency–mean lineal energy as a function of the incident electron energy

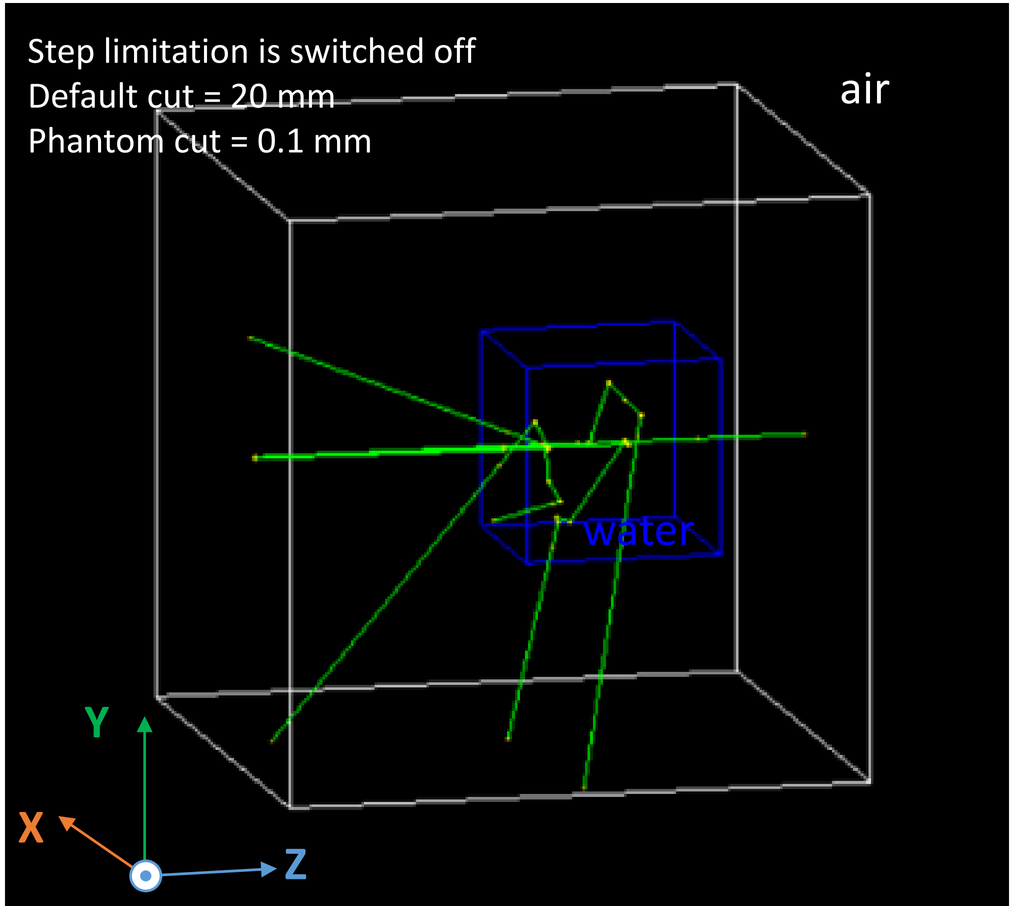
Test for small field dosimetry

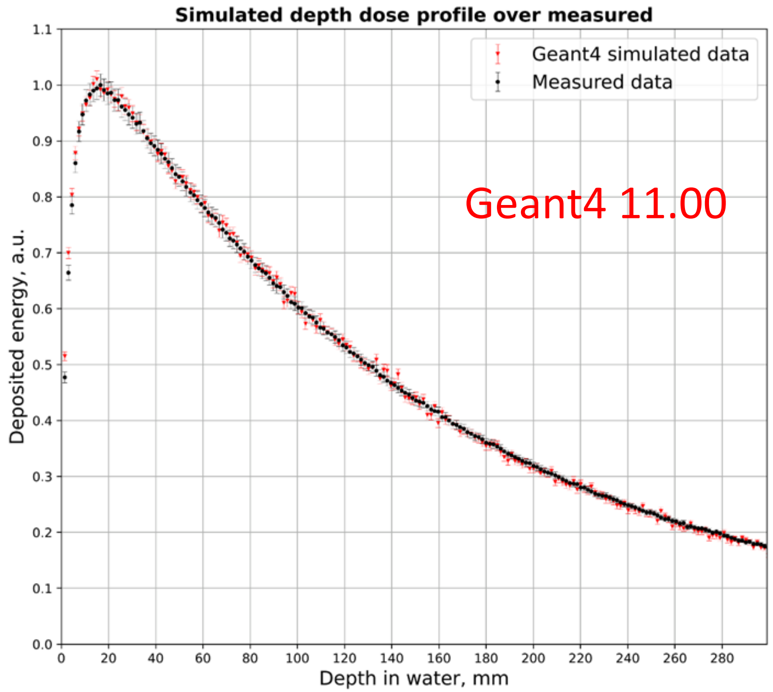
I. Filipev, G. Biasi, S. Guatelli, A. Rosenfeld,
University of Wollongong

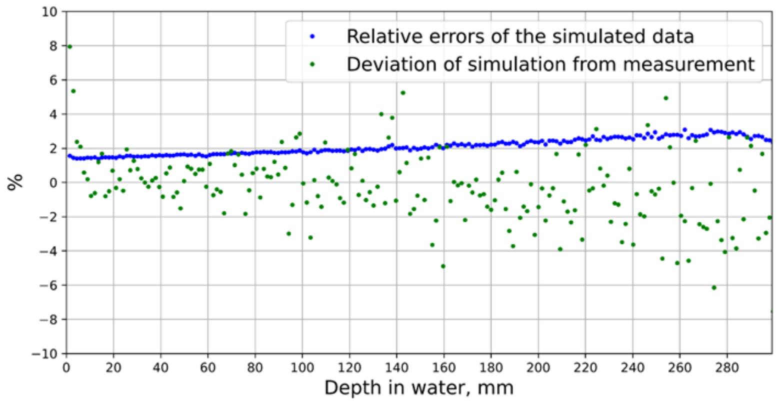
Biasi G, et al. (2018) CyberKnife® fixed cone and Iris™ defined small radiation fields: Assessment with a high-resolution solid-state detector array. *Journal of applied clinical medical physics*,19:547-57.

Source:
CyberKnife with IRIS collimator
Field size: 60 mm
PHSP plane is at 40 cm from isocentre along Z axis

Phase-space files source:
https://www-nds.iaea.org/phsp/photon/Cyberknife_IRIS/







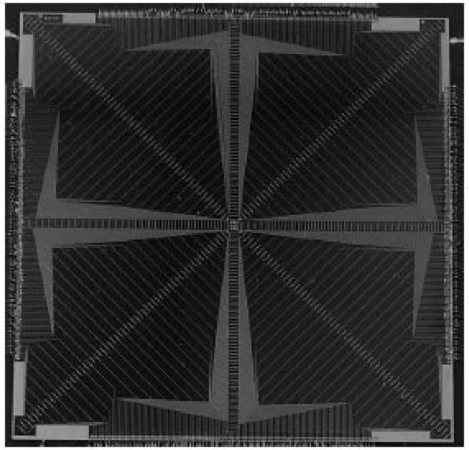


FIG. 2. The Octa is a 2D monolithic silicon array detector consisting of 512 diodes operated in passive mode and arranged in four intersecting orthogonal linear arrays. Each diode has a sensitive area of 0.032 mm^2 with pitch of 0.3 mm along the vertical and horizontal arrays and of 0.43 mm along the two diagonal arrays.

Hadrotherapy: LET validation with ion beams

G. Petringa and P. Cirrone, LNS, INFN, Italy

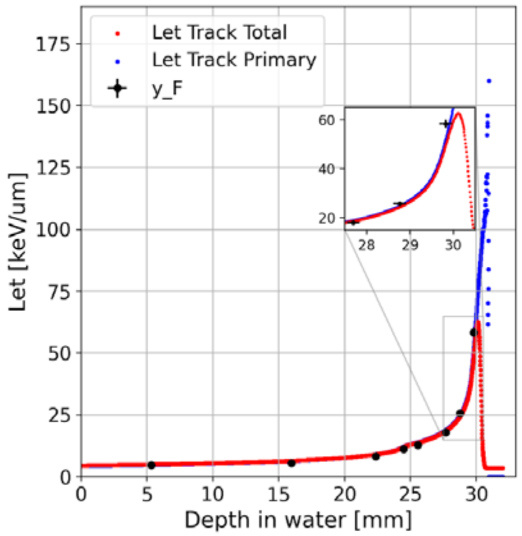
Hadrontherapy Algorithms

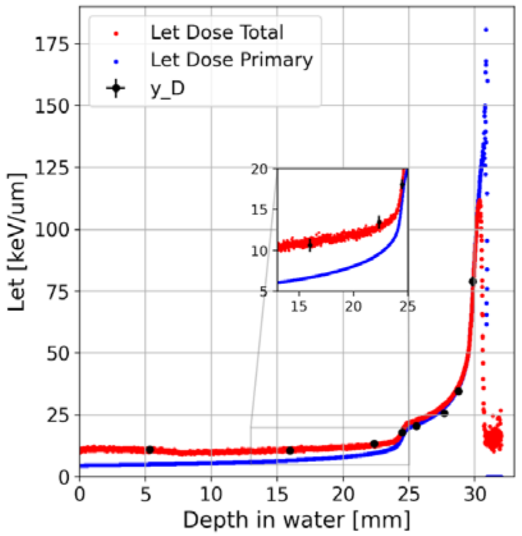
$$\bar{L}_d = \frac{\sum_{i=1}^{N} L_i \varepsilon_i}{\sum_{i=1}^{N} \varepsilon_i}$$

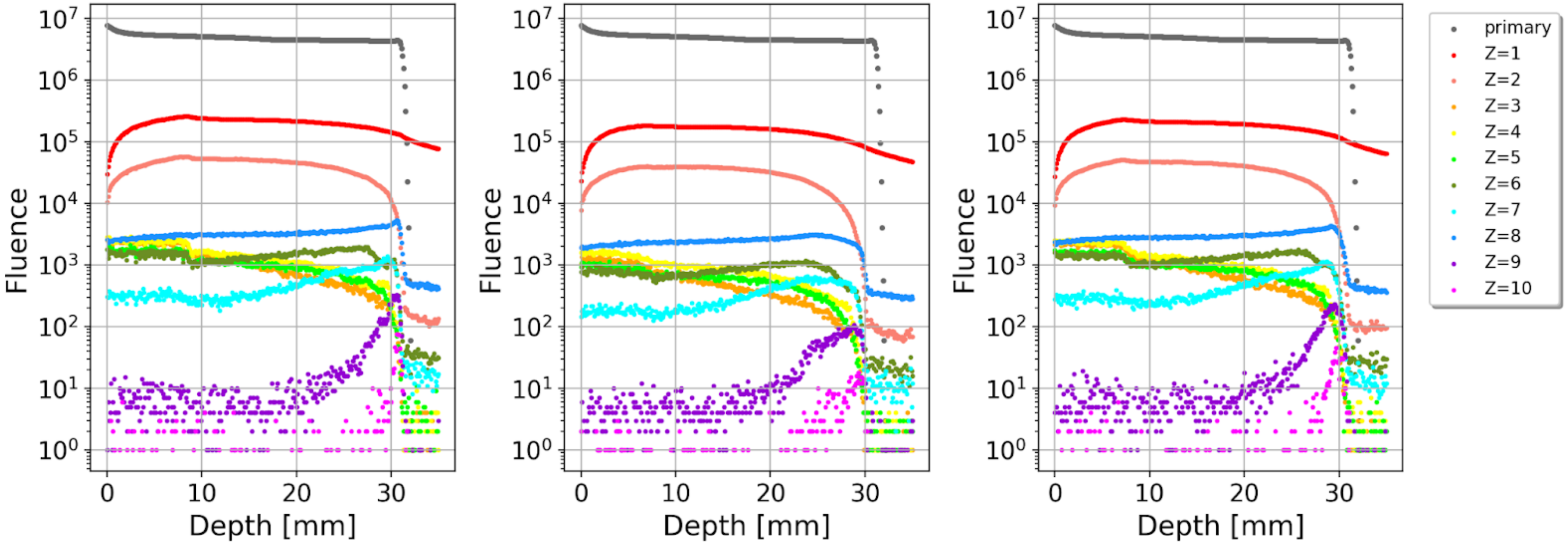
$$\bar{L}_T = \frac{\sum_{i=1}^{N} L_i l_i}{\sum_{i=1}^{N} l_i}$$

$$\bar{L}_d^{Total} = \frac{\sum_{j=1}^{n} [\sum_{i=1}^{N} L_i \varepsilon_i]_j}{\sum_{j=1}^{n} [\sum_{i=1}^{N} \varepsilon_i]_j}$$

$$\bar{L}_T^{Total} = \frac{\sum_{j=1}^{n} [\sum_{i=1}^{N} L_i l_i]_j}{\sum_{j=1}^{n} [\sum_{i=1}^{N} l_i]_j}.$$







- 62 MeV/n ^{4}He beam (FE and modulated)
- Laboratori Nazionali del Sud (INFN, I)
- Experimental data acquired with two microdosimetric detectors: Si-microplus probe and nano-TEPC
- Collaboration between LNL-INFN, LNS-INFN, Poli-MI and UOW

Summary and Conclusions

- The Geant4 physics continues to evolve
  - We suggest to use recent patches 10.7.4 and 11.0.3
- The G4-Med tests have proved
  - To **monitor** how changes in the Geant4 physics component translate in physical quantities of interest
  - to **support** significantly the development of the Geant4 physics component
- The next steps are to
  - Add test on **radioactive decay** (important for nuclear medicine)
  - Modelling of **ionization chambers**
  - Add more tests on **hadronic physics** (e.g. total inelastic cross section tests of production of C-10 and C-11 important for carbon ion in-vivo PET and Prompt Gamma imaging)
  - Add tests in applications scenarios not currently covered, e.g.
    - Calculation of **S-values**, for internal dosimetry
- Acknowledgement: the Geant4 Medical Simulation Benchmarking Group

Geant4 Advanced examples
…. For medical physics

Geant4 Working Group
Coordinator: S. Guatelli
Deputy-Coordinator: F. Romano

14 examples (out of 29) are dedicated to medical physics applications

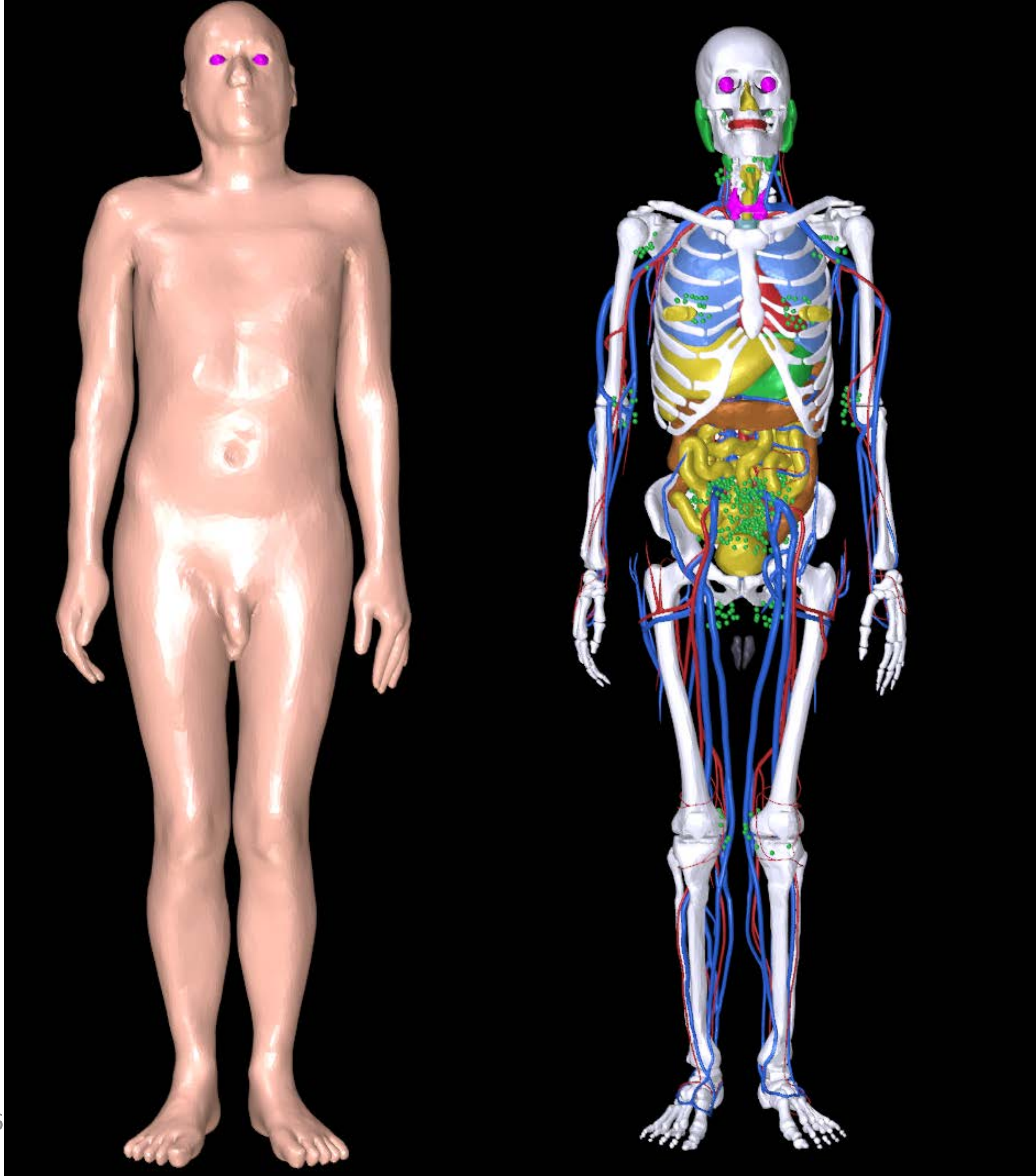
doiPET	**A. Ahmed , S. Guatelli , M. Safavi**	Simulation of a detector system for PET
gammaknife	**F. Romano**	A device for Stereotactic Radiosurgery with Co60 sources for treatment of cerebral diseases
gorad	**M. Asai**	Model of a NASA space mission
hadrontherapy	**G.A.P.Cirrone**	Simulation of a transport beam line for proton and ion therapy
human_phantom	**S. Guatelli**	Dosimetry in analytical anthropomorphic phantoms
ICRP110_HumanPhantoms	**S. Guatelli, M. Large, A. Malaroda, J. Allison**	Dosimetry in ICRP110 Phantoms
ICRP145HumanPhantom	**H. Han, J. Allison, S. Guatelli**	Dosimetry in ICRP145 Phantoms
Iort_therapy	**G. Miluzzo, J. Pensavalle , F. Romano**	Simulation of a IORT device
medical_linac	**B. Caccia, S. Pozzi, C. Mancini, G.A.P. Cirrone**	A typical LINAC accelerator for IMRT,
microbeam	**S. Incerti**	Simulation of a cellular irradiation microbeam line using a high resolution cellular phantom
nanobeam	**S. Incerti**	Simulation of a nanobeam line facility
purging_magnet	**J. Apostolakis**	Electrons travelling through the magnetic field of a purging magnet in a radiotherapy treatment head
radioprotection	**D. Bolst, S. Guatelli, J. Magini, G. Miluzzo, F. Romano**	Microdosimetry with diamonds and silicum detectors for radioprotection in space missions
STCyclotron	**F. Poignant, S. Guatelli**	Modelling the production of radio-isotopes

- Upgrade and maintenance of existing examples
- Release of new examples of interest for the community

See talk by F. Romano: Recent developments of Geant4 Advanced Examples for medical applications, Monday 24th October

New Advanced example: ICRP145Phantom

- ICRP Publication 145 on Adult Mesh-type Reference Computational Phantoms
  - Ann ICRP . 2020 Oct;49(3):13-201. doi: 10.1177/0146645319893605.
- Use of the General Particle Source
- Calculation of the **dose in the organs of the phantoms**
- To be released in Geant4 v.11.01, with the permission of the ICRP, in agreement with the original developers of the models/Geant4 simulation (available on the web):
  - **Principal developer**: Haeginh Han / Hanyang University, Republic of Korea
  - Min Cheol Han / Yonsei University Health System, Republic of Korea
  - Banho Shin / Hanyang University, Republic of Korea
  - Chansoo Choi / University of Florida, USA
  - Yeon Soo Yeom / Yonsei University, Republic of Korea
  - Jonghwi Jeong / National Cancer Center, Republic of Korea
  - Chan Hyeong Kim / Hanyang University, Republic of Korea
- To be released in Geant4 11.1



Conclusions

- The Geant4 Advanced Examples offer a wide set of Geant4 applications for medical physics
  - In the past couple of years we implemented ICRP phantoms to perform dosimetric calculations (ICRP110, ICRP145)
  - See talk by F. Romano: Recent developments of Geant4 Advanced Examples for medical applications, Monday 24th October
  - Acknowledgement: The Geant4 Advanced Examples Working Group