G4_Med, a Geant4 benchmarking tool for medical physics applications


¹CIEMAT, Spain, ²CMRP, University of Wollongong, Australia, ³CRCT (INSERM and Paul Sabatier University), France, ⁴INFN LNS Catania, Italy, ⁵Universidad de Sevilla, Spain, ⁶Radiophysics Institute, Switzerland, ⁷SWHARD srl, Italy, ⁸Former SLAC, USA, ⁹University of California San Francisco, USA, ¹⁰Radboud University Medical Center, The Netherlands, ¹¹CENBG, France, ¹²Tomsk State University, Russian Federation, ¹³IHEP, Protvino, Russian Federation, ¹⁴Ioannina University, Greece, ¹⁵Roma 1, INFN, Italy, ¹⁶LAPP, IN2P3, France, ¹⁷CERN, Switzerland, ¹⁸Nagoya Proton Therapy Center, Japan, ¹⁹INFN Gran Sasso, Italy, ²⁰Clínica Universidad de Navarra, Spain, ²¹IRSN, France, ²²NPL, UK, ²³Lund University, Sweden, ²⁴KEK, Japan, ²⁵ANU, Australia, ²⁶SLAC, USA
Geant4

• Monte Carlo code modelling particle transport and interactions in matter
  • Maintained by a large international Collaboration (> 100 members)
  • www.geant4.org

Geant4 Collaboration Meeting, October 2017, Wollongong, Australia
Applications

- Verification of radiotherapy Treatment Planning Systems
- Improvement/optimisation of QA instrumentation
- Dosimetry and production of radiopharmaceuticals
- Imaging (e.g. PET, SPECT, CT)
- Detector design
- Radiation protection in Earth Labs, aviation and space
  - Design shielding solutions

![Graph showing number of publications per year in PubMed](image)
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)

• 37 researchers; 25 institutions from 12 different countries
Motivation & Goals

- Geant4 offers many **pre-built physics lists**. Which one is more adequate for a specific medical physics application scenario?

- **G4-Med project:**
  - 18 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

---

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

---

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

**Purpose**

The aim of the Geant4 Medical Physics Benchmarking Group (G4MSBG) is to develop a fully automated 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 `g4-test-utility` system to be executed for benchmarking and regression testing. The tests are executed using the CERN computing infrastructure.

**List of current tests**

Currently the G4-Med system includes 18 tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>g4-test layout</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon attenuation coefficients</td>
<td>PhotonAttenuation</td>
<td>S. Guatelli, L. Pandola</td>
</tr>
<tr>
<td>Electron stopping powers</td>
<td>ElectronStop</td>
<td>V. Ivanchenko</td>
</tr>
<tr>
<td>Low energy electron backscattering</td>
<td>ElectronBackScat</td>
<td>P. Dondi, A. Mantero, V. Ivanchenko, M. Novak</td>
</tr>
<tr>
<td>Electron scattering from tiles at 15-20 MeV kinetic energies</td>
<td>ElectraScat</td>
<td>B. Faddegon, J. Ramos-Mendez</td>
</tr>
<tr>
<td>Bremsstrahlung yield</td>
<td>Bremsstrahlung</td>
<td>B. Faddegon, J. Ramos-Mendez</td>
</tr>
<tr>
<td>Fano cavity</td>
<td>Fano cavity</td>
<td>P. Arce, M. Maire, M. Novak</td>
</tr>
<tr>
<td>Electron Dose Prompt Kernel</td>
<td>LowElecOKP</td>
<td>S. Incerti, M.-C. Bordo, I. Kyrkou, Y. Perrot</td>
</tr>
<tr>
<td>Microdosimetry</td>
<td>MicrIRy</td>
<td>S. Incerti, I. Kyrkou</td>
</tr>
<tr>
<td>Brachytherapy - dose rate</td>
<td>Brachy-ir</td>
<td>S. Guatelli, D. Cutajar</td>
</tr>
<tr>
<td>Dosimetry - clinical 5-6 MeV electron beam</td>
<td>Dosimetry</td>
<td>L. Desorgher</td>
</tr>
<tr>
<td>Dosimetry for mammography</td>
<td>Mammo</td>
<td>C. Fedon, I. Scopacoulo</td>
</tr>
<tr>
<td>Hadron nuclear-track etched dosimetry</td>
<td>NuTrackX</td>
<td>D. Sakato, S. Guatelli, E. Simpson</td>
</tr>
<tr>
<td>Bragg curves in water for 67.5 MeV protons</td>
<td>LowEProtonBraggPeak</td>
<td>B. Faddegon, J. Ramos-Mendez</td>
</tr>
<tr>
<td>Absolute neutron yield for protons</td>
<td>ProtonC12NeutronMed</td>
<td>B. Faddegon, J. Ramos-Mendez</td>
</tr>
<tr>
<td>Production cross sections of different fragments</td>
<td>C12FragCC</td>
<td>C. Omiachi, T. Teshio, T. Tsuuki</td>
</tr>
<tr>
<td>52 MeV/n C-12 fragmentation on Carbon target</td>
<td>LowEC12Rag</td>
<td>C. Mancini-Terracciano</td>
</tr>
<tr>
<td>400 MeV/n C-12 fragmentation</td>
<td>C12Frag</td>
<td>D. Bold, S. Guatelli, F. Romano</td>
</tr>
<tr>
<td>Light ion (proton, O, C, carbon) range and depth dose curves in water</td>
<td>LightIonBraggPeak</td>
<td>M. Cortes-Giraldo, A. Perales, J. M. Quevedo-Molina</td>
</tr>
</tbody>
</table>
Integration in *geant-val* for Automatized Regression Tests

**Publication:** Luc Freyermuth, Dmitri Konstantinov, Grigorii Latyshev, Ivan Razumov, Witold Pokorski, Alberto Ribon
EPJ Web Conf. 214 05002 (2019)
DOI: 10.1051/epjconf/201921405002

---

**G4_Med** is integrated in *geant-val* to execute regularly automatized regression tests on the CERN computing infrastructure

https://geant-val.cern.ch/
Welcome to the Twiki web page of the G4MSBG initiative: G4-Med

Purpose

The aim of the Geant4 Medical Physics Benchmark Group (G4MSBG) is to develop a fully automated 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 tool 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.

<table>
<thead>
<tr>
<th>Test</th>
<th>geant-val layout</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon attenuation coefficients</td>
<td>PhotonAttenuation</td>
<td>S. Guatelli, L. Pandola</td>
</tr>
<tr>
<td>Electron stopping powers</td>
<td>ElectronDEOX</td>
<td>V. Ivanchenko</td>
</tr>
<tr>
<td>Low energy electron backscattering</td>
<td>ElectronBackScat</td>
<td>P. Dondero, A. Mantero, V. Ivanchenko, M. Novak</td>
</tr>
<tr>
<td>Electron scattering from falls at 13-20 MeV kinetic energies</td>
<td>ElecForwScat</td>
<td>B. Faddegon, J. Ramos-Mendez</td>
</tr>
<tr>
<td>Bremsstrahlung yield</td>
<td>Bremsstrahlung</td>
<td>B. Faddegon, J. Ramos-Mendez</td>
</tr>
<tr>
<td>Fano cavity</td>
<td>Fano cavity</td>
<td>P. Arlo, M. Maisly, M. Novak</td>
</tr>
<tr>
<td>Electron Dose Point Kernel</td>
<td>LowEElectDPK</td>
<td>S. Incerti, M. C. Bondage, I. Kyntakou, Y. Perrot</td>
</tr>
<tr>
<td>Microdosimetry</td>
<td>Microz</td>
<td>S. Incerti, I. Kyntakou</td>
</tr>
<tr>
<td>Brachytherapy - dose rate</td>
<td>Brachy-r</td>
<td>S. Guatelli, D. Cutajar</td>
</tr>
<tr>
<td>Dosimetry - clinical 5-6 MeV electron beam</td>
<td>To be added</td>
<td>L. Descovich</td>
</tr>
<tr>
<td>Dosimetry for mammography</td>
<td>Nanno</td>
<td>C. Petion, I. Techopoulos</td>
</tr>
<tr>
<td>Hadronic nucleus-nucleus inelastic cross section</td>
<td>NuclNucinelXS</td>
<td>D. Sakata, S. Guatelli, E. Simpson</td>
</tr>
<tr>
<td>Bragg curves in water for 5 Ar 5 MeV protons</td>
<td>LowEBraggPeak</td>
<td>B. Faddegon, J. Ramos-Mendez</td>
</tr>
<tr>
<td>Absolute neutron yield for protons</td>
<td>ProtonC12Neutron</td>
<td>B. Faddegon, J. Ramos-Mendez</td>
</tr>
<tr>
<td>Production cross sections of different fragments</td>
<td>C12FragCC</td>
<td>C. Omachi, T. Teshita, T. Sasaki</td>
</tr>
<tr>
<td>62 MeV/n C-12 fragmentation on Carbon target</td>
<td>LowEC12Frag</td>
<td>C. Marconi-Terracciano</td>
</tr>
<tr>
<td>400 MeV/n C-12 fragmentation</td>
<td>C12Frag</td>
<td>D. Boldt, S. Guatelli, F. Romano</td>
</tr>
<tr>
<td>Estimation of proton radiobiological damage</td>
<td>LowEProtonRDE</td>
<td>G. Pettigrew, GAP Cinorio, L. Pandola, G. Cuttone</td>
</tr>
<tr>
<td>Light ion (proton, 3He, carbon) range and depth dose curves in water</td>
<td>LightionBraggPeak</td>
<td>M. Cortes-Giraldo, A. Penales, J. M. Quercada Molina</td>
</tr>
</tbody>
</table>
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)  
- Deemed to be the most accurate combination of Geant4 models, regardless of CPU efficiency.

G4EmLivermorePhysics (“LIV” suffix)  
- Includes data-driven low-energy models for $e^-$ ionization and $\gamma$ based on the Livermore evaluated data libraries.

G4EmPenelopePhysics (“PEN” suffix)  
- Includes low-energy models for $e^-$, $e^+$ & $\gamma$ re-engineered from PENELOPE code
<table>
<thead>
<tr>
<th>Geant4</th>
<th>Opti0</th>
<th>Opti3</th>
<th>Opti4</th>
<th>Livermore</th>
<th>Penelope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh scattering and photoelectric effect</td>
<td>Standard</td>
<td>G4KleinNishinaModel</td>
<td>( G_4 \text{LowE}^P \text{ComptonModel} \ [18] ) for ( E &lt; 20 \text{MeV} ) *</td>
<td>Livermore</td>
<td>Penelope</td>
</tr>
<tr>
<td>Compton scattering</td>
<td>Standard</td>
<td>Standard</td>
<td>Penelope for ( E &lt; 20 \text{MeV} ) \ (Standard for ( E &gt; 20 \text{MeV} )</td>
<td>Livermore</td>
<td>Penelope</td>
</tr>
<tr>
<td>Gamma conversion</td>
<td>Standard</td>
<td>Standard</td>
<td>Penelope for ( E &lt; 1 \text{GeV} ), Standard for ( E &gt; 20 \text{MeV} ) \ (Standard for ( E &gt; 1 \text{GeV} )</td>
<td>Penelope</td>
<td></td>
</tr>
<tr>
<td>( e^- ) and ( e^+ ) ionisation</td>
<td>Standard</td>
<td>Standard</td>
<td>Livermore for ( e^- ) for ( E &lt; 100 \text{keV} ), Penelope for ( e^+ ) for ( E &lt; 100 \text{keV} ), Standard for ( E &gt; 100 \text{keV} )</td>
<td>Livermore</td>
<td>Penelope</td>
</tr>
<tr>
<td>( e^- ) and ( e^+ ) bremsstrahlung</td>
<td>Standard</td>
<td>( G_4 \text{SelzlerBergerModel} ) for ( E &lt; 1 \text{GeV} ), ( G_4 \text{eBremsstrahlungRelModel} ) for ( E &gt; 1 \text{GeV} )</td>
<td>Penelope</td>
<td>Penelope</td>
<td></td>
</tr>
<tr>
<td>( e^+ ) annihilation</td>
<td>Standard</td>
<td></td>
<td></td>
<td></td>
<td>Penelope</td>
</tr>
<tr>
<td>( e^- ) and ( e^+ ) multiple scattering</td>
<td>Urban model [20] for ( E &lt; 100 \text{MeV} ), Wentzel for ( E &gt; 100 \text{MeV} )</td>
<td>Default model</td>
<td>Goudsmit-Saunderson model [21], [22] for ( E &lt; 100 \text{MeV} )</td>
<td>Penelope</td>
<td></td>
</tr>
<tr>
<td>Coulomb Scattering</td>
<td>on</td>
<td>off</td>
<td>on</td>
<td></td>
<td>Penelope</td>
</tr>
<tr>
<td>MseStepLimiting Type</td>
<td>jUseSafety</td>
<td>jUseDistanceToBoundary</td>
<td>jUseSafetyPlus</td>
<td>jUseSafetyPlus</td>
<td>jUseSafetyPlus</td>
</tr>
<tr>
<td>Bremsstrahlung angular distribution</td>
<td>ModifiedTsai</td>
<td>2BS</td>
<td></td>
<td></td>
<td>Penelope</td>
</tr>
</tbody>
</table>
Brachytherapy test

- Based on the Advanced Example *brachytherapy*
- $^{192}$Ir Flexisource (HDR brachytherapy)


Agreement within $2\sigma$ with reference data for all EM constructors
Internal breast dosimetry

• Typical breast phantom (50% glandular 50% adipose)
• Dose scored in 30 positions at 4 different depths
• Comparison with experimental measurements (TLDs) at 20 keV

- Agreement within $1\sigma$ with the experimental measurements
- Best performance (on average) with “Opt4”
- Performance of “Opt 0” worsens with increasing depth

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:

- **G4IonQMDPhysics** - Quantum Molecular Dynamics (QMD) model.
Partial Hadronic Model Inventory –

important for particle therapy

At rest absorption, $\mu$, $\pi$, $K$, anti-$p$

Radioactive decay

High Precision

Evaporation

Fermi breakup

Multifragment

Photon Evap

Pre-compound

Binary cascade

Bertini-style cascade

1 MeV  10 MeV  100 MeV  1 GeV  10 GeV  100 GeV  1 TeV

Photo-nuclear, electro-nuclear

Electro-nuclear dissociation

QMD (ion-ion)

Binary Ion Cascade

INCL

Quark Gluon string

Fritiof string
300 MeV/n $^{12}$C ion charge-changing cross section

Authors: C. Omachi (Nagoya Proton Therapy Center, Nagoya, Japan), T. Sasaki (KEK, Japan), T. Toshito (Nagoya Proton Therapy Center, Nagoya, Japan)

Bragg Curves in Water for Proton & C-12 Beams at Therapy Energies

- Initial energy spread adjusted from experimental Bragg curves.
- Simplified geometry model for simulation
  - Depths of 82% distal level are compared.
- “option0” not accurate enough for $^{12}$C, other EM constructors agree within 2-3 sigma.
- For proton beams, all physics constructors agree within experimental uncertainties.

Ref. Data: D. Schardt et al., GSI Report 2008-1
Fragment Yields for $^{12}$C @ 400 MeV/u on Water Target

INCL++ reproduced better angular distribution, but QMD & BIC provided better energy distributions.

D. Bolst et al., NIM A 869 (2017)
Test on cell survival curve modelling for proton therapy

Authors: G.A. P. Cirrone, G. Cuttone and G. Petringa, INFN LNS, Catania, Italy

- Reproduce in-vitro cell survival curves against experimental measurements, performed at the CATANA facility
  - at 20 mm depth in water, corresponding to the mid of a clinical 62 MeV modulated clinical proton beam
  - prostate DU145 cells and breast cancer cell line MDA-MB-231
  - Using Geant4 and LEM III

Conclusions & Outlook

• Currently, 18 tests have been included in G4_Med to benchmark EM and Hadronic physics capabilities of Geant4 for medical physics applications.
  • Some test physical quantities, others include more realistic scenarios.

• G4_Med is integrated in geant-val for regular executions on the CERN computing infrastructure.

• Overall, G4EmStandardPhysics_option4 (_EMZ) is recommended for accurate simulations.

• QGSP_BIC_HP (_EMZ) physics list provides a good overall description.

• Future work will focus in two main aspects:
  • Inclusion of new tests and refinement of existing ones.
  • Assessment of the different physics list choices in terms of accuracy and CPU performance across future releases of the Geant4 toolkit.

• More information at our TWiki page:  https://twiki.cern.ch/twiki/bin/view/Geant4/G4MSBG

• Paper accepted as a Special Issue of Medical Physics,

Thank you