Geant4 for medical physics: recent developments

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Key points of Geant4 for Medical Physics

RADIATION FIELD MODELING
GEOMETRY
PHYSICS AND ITS VALIDATION BY INDEPENDENT TEAMS
USER-FRIENDLY SCORING
ANALYSIS TOOLS
BIASING
GUI AND VISUALISATION
MEDICAL PHYSICS EXAMPLES
GATE, TOPAS, GAMOS

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

Outline

- Recent developments of Geant4 for medical physics
  - Physics component and its validation
  - Geant4 examples

- Note
  - No reference to developments of Geant4-DNA (see talk of Sebastien Incerti)
  - TOPAS (talk by Joseph Perl)
  - GATE (talk by Alex Malaroda)

Physics

PHYSICS PROCESSES AND MODELS
PHYSICS LISTS

Physics processes provided by Geant4: an overview

- **EM physics**
  - “standard” processes valid from 1 keV to 100 TeV
  - “low energy” from technical limit of O(10 eV) to 100 TeV (however this can be changed via UI Commands, eg 1 GeV)
  - Down to eV for Geant4-DNA in liquid water
  - optical photons
- **Weak interaction physics**
  - decay of subatomic particles
  - radioactive decay of nuclei
- **Hadronic physics**
  - pure strong interaction physics valid from 0 to 100 TeV
  - electro- and gamma-nuclear
- **Parameterized or “fast simulation” physics**

Electromagnetic Processes

- **Standard Package - Condensed history approach (Berger 1963)**
  - Complete set of processes covering charged particles and photons.
  - Energy range 1 keV – 100 TeV
- **Low Energy Package:**
  - **More suitable for medical physics applications**
  - More precise description at low energy for e^+, e^-, γ
    - More atomic shell structure detail
  - Two alternative approaches - Condensed history approach (Berger 1963)
    - Penelope, version 2008, physics models (limit: ~100 eV)
    - Approached based on the Livermore Data Libraries (technical limit: O(10 eV))
  - Geant4-DNA. Talk by S. Incerti, Recent developments of the Geant4-DNA extension of the Geant4 Monte Carlo simulation toolkit"

EM Physics Lists

Documented in:
http://geant4.cern.ch/collaboration/working_groups/electromagnetic/physlist10.3.shtml

Emstandard_option3

- G4UrbanMscModel for multiple scattering of all charged particles;
- G4KleinNishinaModel is used for the Compton scattering
- G4IonParametrisedLossModel is used for ion ionisation, this model is based on ICRU73 ion stopping data;
- G4RayleighScattering process is used with the default Livermore Rayleigh scattering model;
- Fluorescence is enabled by default.
- G4NuclearStopping process is used for alpha, He3, ions.

Emlivermore

- EmStandard_option 4, with approach based on Livermore data libraries approach for photons and electrons
- There is also emlivermore_polarised physics list

Emstandard_option4

- Use the most accurate standard and low-energy models.
- The corresponding physics constructor includes following modifications with the G4EmStandardPhysics_option3.cc:
  - G4KleinNishinaModel is used above 20 MeV, G4LowEPComptonModel is used below
  - G4PenelopeGammaConversion model is used for gamma conversion below 1 GeV;
- For e+ and e- in G4UrbanMscModel an accurate algorithm of sampling of lateral displacement is enabled;

Empenelope

- EmStandard_option 4, with approach based on Penelope MC for photons, electrons, positrons

G4-DNA Physics Lists
Refer to Talk by Sebastien Incerti

New PIXE cross sections

- Authors: S. Bakr[a], D. D. Cohen[b], R. Siegele[b], S. Incerti[c,d], V. Ivanchenko[e,f], A. Mantero[g], A. Rozenfeld[a], S. Guatelli[a]

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[c] CNRS/IN2P3, Centre d'Etudes Nucléaires de Bordeaux-Gradignan,
[d] Université de Bordeaux, Centre d'Etudes Nucléaires de Bordeaux-Gradignan,
[e]Geant4 Associates International Ltd,
[f]Tomsk State University,
[g] SWHARD s.r.l

- Based on recommended cross sections developed by D. Cohen at ANSTO
  - Systematically validated against experimental measurements
  - Cross sections for protons and alpha particles
  - To be released as soon as possible

- See the Talk by Samer Bakr

Attenuation coefficient tests

- K. Amako et al, IEEE TNS, 52(4), 910-918, 2005.
  - Comparison of
    - Attenuation coefficients
    - Stopping Power and Range of e^-, p and α

  With respect to NIST

- The project is to have systematic regression tests on gamma ray cross sections
  - The test are extended to a larger set of materials

Comparison of Geant4 Electromagnetic Physics Models Against the NIST Reference Data

Katsuya Amako, Susanna Guatelli, Vladimir N. Ivanchenko, Michel Maire, Barbara Mascialino, Koichi Murakami, Petteri Nieminen, Luciano Pandola, Sandra Parlati, Maria Grazia Pia, Michela Piergentili, Takashi Sasaki, and Laszlo Urban

***Abstract*—The Geant4 Simulation Toolkit provides an ample set of physics models describing electromagnetic interactions of particles with matter. This paper presents the results of a series of comparisons for the evaluation of Geant4 electromagnetic processes with respect to United States National Institute of Standards and Technologies (NIST) reference data. A statistical analysis was performed to estimate quantitatively the compatibility of Geant4 electromagnetic models with NIST data; the statistical analysis also highlighted the respective strengths of the different Geant4 models.**

***Index Terms*—Geant4, Monte Carlo, NIST, validation.**

I. Introduction

GEANT4 is an object oriented toolkit [1] for the simulation of the passage of particles through matter. It offers an ample set of complementary and alternative physics models for electromagnetic and hadronic interactions, based on theory, experimental data or parameterizations.

The validation of Geant4 physics models with respect to authoritative reference data is a critical issue, fundamental to establish the reliability of Geant4-based simulations. This paper is focused on the validation of Geant4 electromagnetic models, with the purpose to evaluate their accuracy and to document their respective strengths. It presents the results of comparisons of Geant4 electromagnetic processes of photons, electrons, protons and α particles with respect to reference data of the United States National Institute of Standards and Technologies (NIST) [2], [3] and of the International Commission on Radiation Units and Measurements (ICRU) [4], [5].

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Digital Object Identifier 10.1109/TNS.2005.852691

TABLE I
GEANT4 ELECTROMAGNETIC MODELS IN THIS COMPARISON STUDY

Particle	Geant4 Models in Electromagnetic Packages
Photon	Geant4 Low Energy - EPDL Geant4 Low Energy - Penelope Geant4 Standard
Electron	Geant4 Low Energy - EEDL Geant4 Low Energy - Penelope Geant4 Standard
Proton	Geant4 Low Energy - ICRU 49 Geant4 Low Energy - Ziegler 1985 Geant4 Low Energy - Ziegler 2000 Geant4 Standard
α	Geant4 Low Energy - ICRU 49 Geant4 Low Energy - Ziegler 1977 Geant4 Standard

The simulation results were produced with Geant4 version 6.2. The Geant4 test process verifies that the accuracy of the physics models will not deteriorate in future versions of the toolkit with respect to the results presented in this paper.

II. Overview of Geant4 Electromagnetic Physics Packages

The Geant4 Simulation Toolkit includes a number of packages to handle the electromagnetic interactions of electrons, muons, positrons, photons, hadrons and ions. Geant4 electromagnetic packages are specialised according to the particle type they manage, or the energy range of the processes they cover.

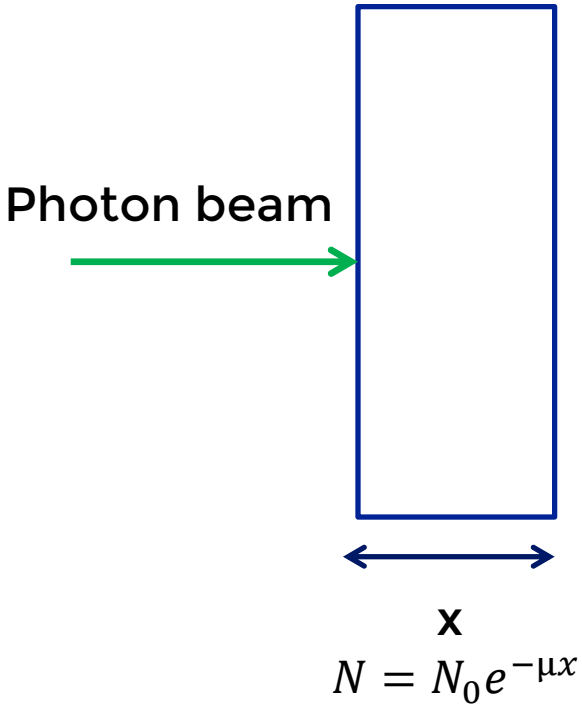
The physics processes modeled in Geant4 electromagnetic packages include: multiple scattering, ionization, Bremsstrahlung, positron annihilation, photoelectric effect, Compton and Rayleigh scattering, pair production, synchrotron and transition radiation, Cherenkov effect, refraction, reflection, absorption, scintillation, fluorescence, and Auger electrons emission [1].

Alternative and complementary models are provided in the various packages for the same process. The Geant4 electromagnetic models studied in this paper are listed in Table I.

A. Standard Electromagnetic Package

The Geant4 Standard electromagnetic package [8] provides a variety of models based on an analytical approach, to describe the interactions of electrons, positrons, photons, charged hadrons and ions in the energy range 1 keV–10 PeV.

Test: Simulation set-up



Authors: S. Guatelli, S. Incerti, V. Ivantchenko, L. Pandola

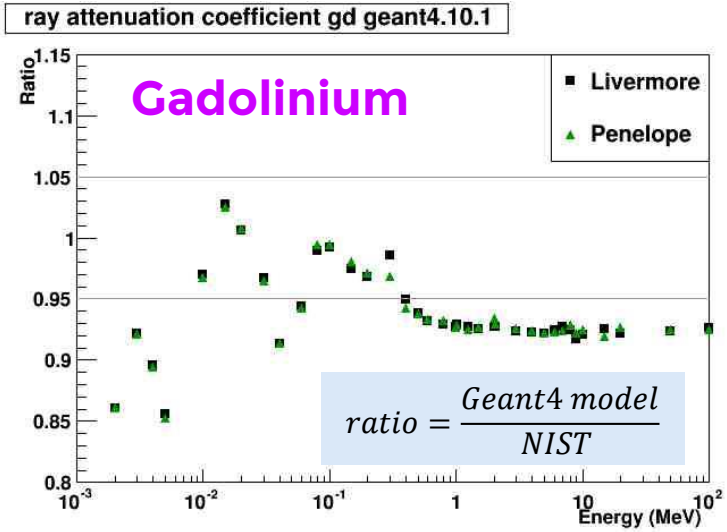
- **Physics lists:**
  - EMStandard_opt0
  - EMStandard_opt3
  - EMStandard_opt4
  - Livermore
  - Penelope

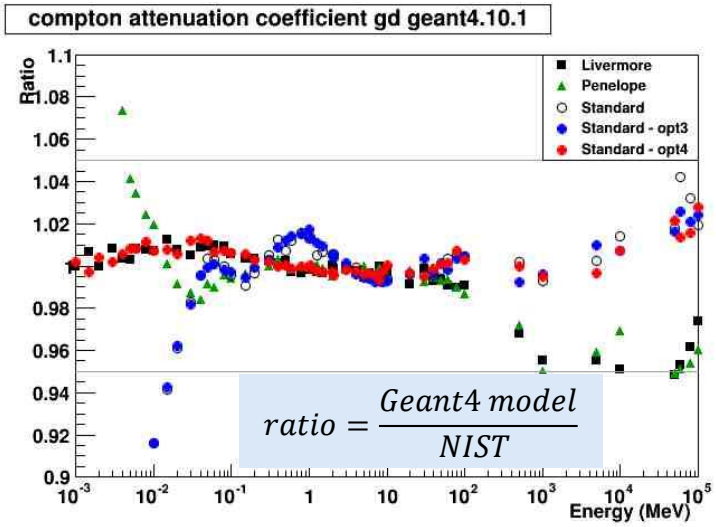
- Calculate the attenuation coefficients:
  - Total
  - Rayleigh scattering
  - Photoelectric effect
  - Compton scattering
  - Gamma conversion

- Regression testing: G4 10.0, 10.1, 10.2.p02

Summary of the results

- Regression tests: Geant4 10.0, 10.1 and 10.2.p02
- Overall good agreement (<5%)
- Rayleigh cross sections are different from NIST
- Compton Scattering
  - Penelope, Standard opt0 and 3 have differences below few keV
- Regression test: no differences

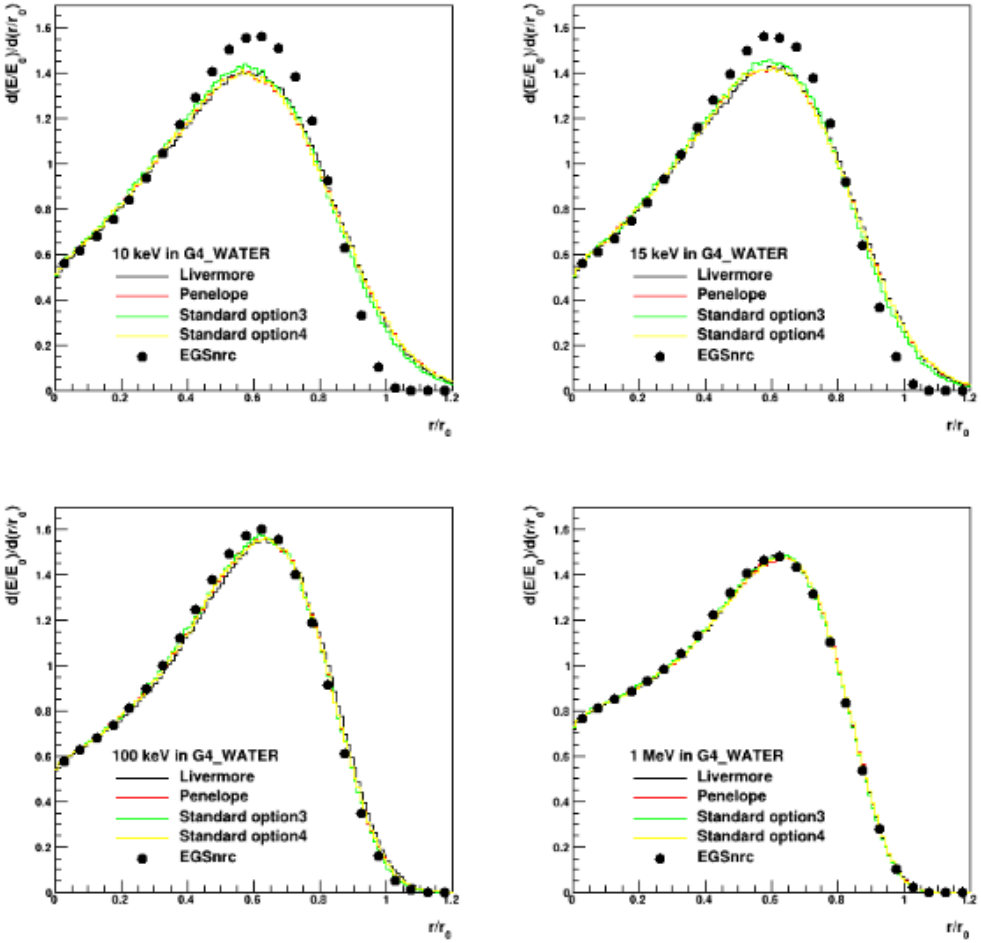




Dose point kernel test

Geant4 10.3-ref04

- **Author: S. Incerti**
- Dose distribution around a point source of electrons
- Good agreement between Geant4 and EGSnrc (golden standard), especially at higher energy
- Similar performance of the G4 physics lists
- Note: this is not comparison to experimental measurements



Electron backscattering I

Geant4 10.4-beta

Authors: A. Mantero and P. Dondero

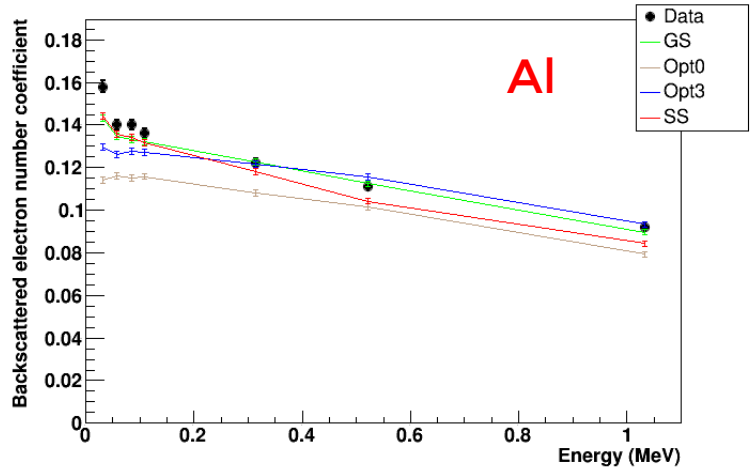
Monoenergetic electrons are incident normally on the target

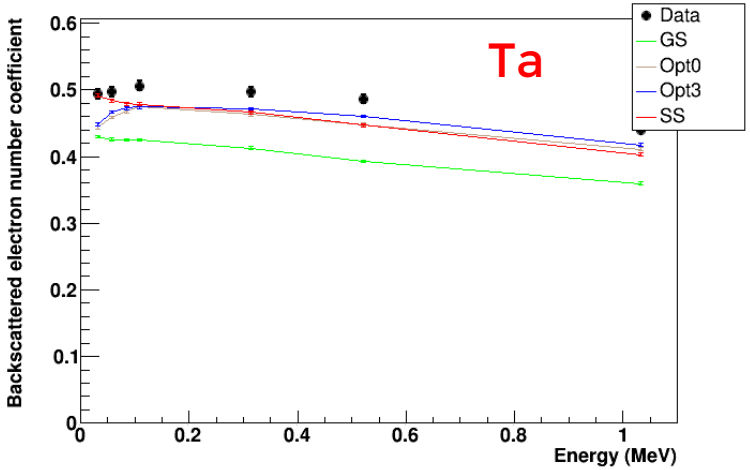
- **Opt 0**: G4UrbanMscModel for multiple scattering of e+ and e- below 100 MeV
- **Opt3** : Urban multiple scattering model
- **GS**: Goudsmit-Saunderson (GS) multiple scattering
- **SS**: Single Coulomb scattering with Mott corrections

Reference data: Sandia reference data

Results:

- Single Coulomb scattering (SS) is the best below 0.1 MeV
- Opt3 and GS are generally better than Opt0. They are much faster than SS.
- To use the Single Coulomb Scattering, refer to the emstandardSS physics list

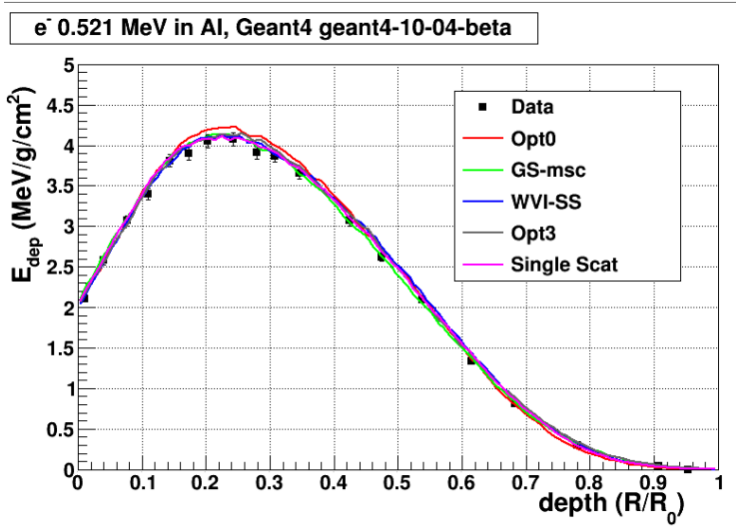


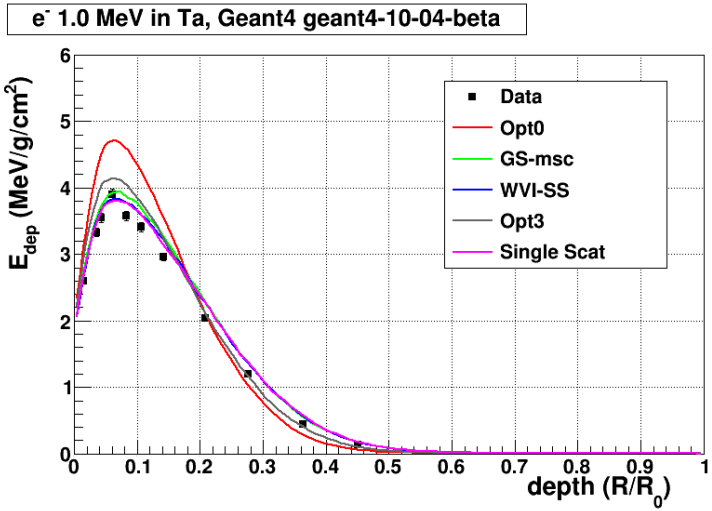


Energy deposition of e-

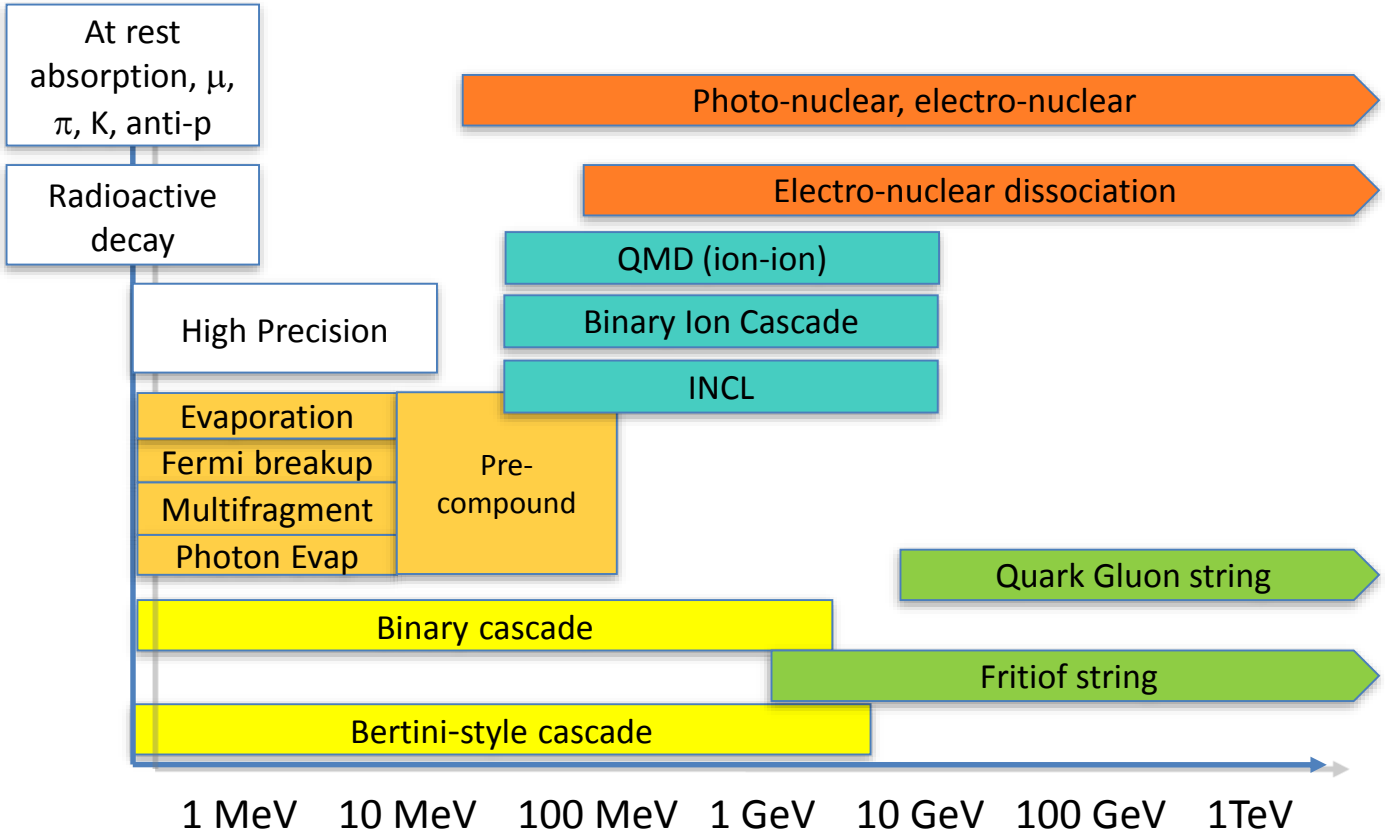
Author: V. Ivantchenko

- Comparison against the Sandia reference data
- The agreement with the reference data is better with a strong step limitation (SS, GS, Opt3)
- GS and Opt3 with strong step limits are equivalent to SS





Partial Hadronic Model Inventory



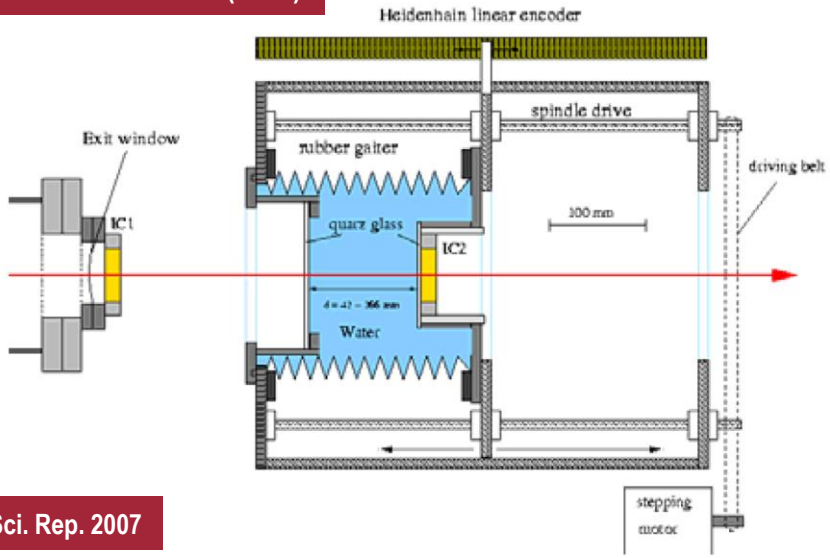
Geant4 for hadron Therapy

VALIDATION OF PHYSICS

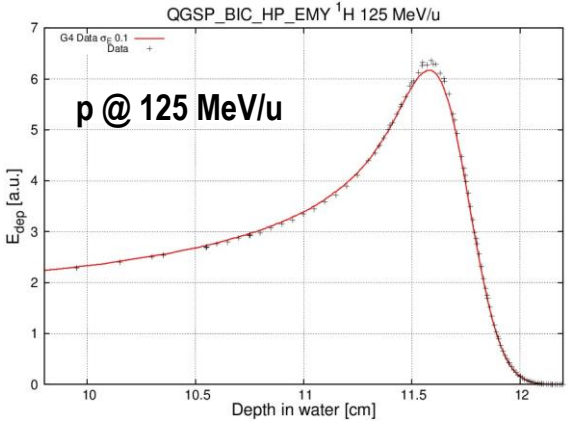
Validation of Light Ion Transportation in Water

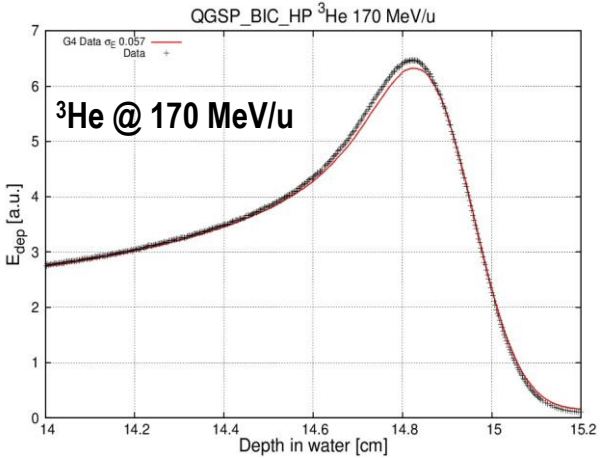
A. Perales, M.A. Cortés-Giraldo, D. Schardt, J.A. Pavón, M.I. Gallardo & J.M. Quesada

Perales *et al.*, contribution to ESTRO 36 (2017)



Schardt *et al.*, GSI Sci. Rep. 2007





- Experimental measurements of energy deposition vs depth in water @ GSI (Germany)
- Beam line elements → Simulated using water equivalent thickness.
- Various ion beams (Z <= 8).

C-12 Bragg Peak validation

Lechner A,Ivanchenko VN, Knobloch J, “Validation of recent Geant4 physics models for application in carbon ion therapy”, NIM B 268 (2010), 2343-2354

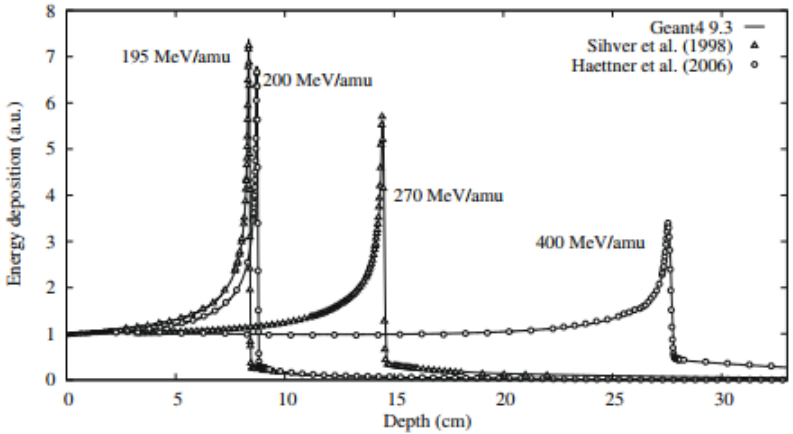
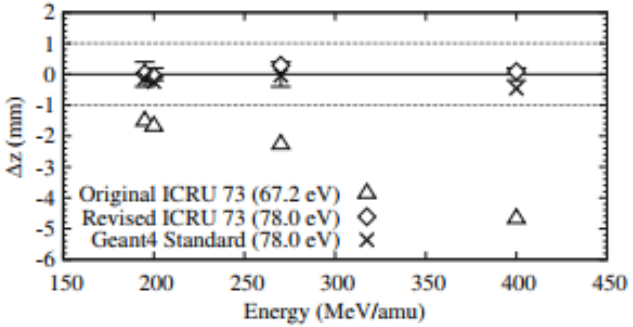


Fig. 2. Comparison of simulated and measured ^{12}C depth-dose profiles in water (0.997 g/cm^3). Simulations were performed with Geant4 9.3, using revised ICRU 73 stopping power tables [22] and the QMD nuclear reaction model [33]. Experimental data derive from Sihver et al. [31] (triangles) and Haettner et al. [32] (circles), where profiles of Haettner et al. [32] were shifted to match more precise measurements of the peak position by D. Schardt et al. [61]. All experimental data by courtesy of D. Schardt.



The revised ICRU 73 tables for water adopt a mean excitation energy of 78 eV, compared to 67.2 eV in the original ICRU 73 tables (see P. Sigmund, A. Schinner and H. Paul, "Errata and Addenda for ICRU Report 73", 2009).

Validation of fragmentation

- The accuracy of different fragmentation models in Geant4 were benchmarked for a 400MeV/u ^{12}C beam
  - BIC, QMD, INCL

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

E Haettner, H Iwase[1], M Krämer, G Kraft and D Schardt

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Fragmentation yields, angular and energy distribution of fragments

Validation with statistical analysis

Regression testing

See talk by D. Bolst: validation of Geant4 Fragmentation for Heavy Ion Therapy

Med Phys Benchmarking I

Automatised regression testing for medical physics: work in progress

Bruce Faddegon[1], Pedro Arce[2], David Bolst[3], Dean Cutajar[3], Giacomo Cuttone[4], Paolo Dondero[5], Andrea Dotti[6], Susanna Guatelli[3], Miguel Ant. Cortés Giraldo[7], Sebastien Incerti[8], Vladimir Ivanchenko[9,10], Mathieu Karamitros[8], Alfonso Mantero[5], José Manuel Quesada Molina[7], Luciano Pandola[4], Álvaro Perales[7], Jan Perrot[8], José Ramos-Méndez[1], Francesco Romano[11], Ioannis Sechopoulos[12]

[1]University of California San Francisco, US [2]Ciemat, Spain,[3]CMRP, University of Wollongong, [4]INFN, [5]swhard srl, Italy, [6]SLAC, US, [7] Universidad de Sevilla, Spain, [8]CENBG, France, [9]Geant4 Associates International Ltd, [10]Tomsk State University, Russia, [11]NPL, UK, [12]Radboud University Nijmegen Medical Centre, The Netherlands

Med Phys Benchmarking II

Geant 4 + docker + Microsoft Azure

Integrated environment for building, assembling, and run distributed applications

Cloud computing service created by Microsoft

Automatised tests

- ELECTRON DOSE KERNELS
- GAMMA ATTENUATION COEFFICIENTS
- PROTON AND LIGHT IONS BRAGG CURVES
- ION FRAGMENTATIONS
- FANO CAVITY
- ELECTRON STOPPING POWERS
- ELECTRON BACKSCATTERING
- DOSE RATE DISTRIBUTION FOR BRACHYTHERAPY

Other tests to automatise

- BREMSSTRAHLUNG
- NEUTRON YIELD FROM PROTON IRRADIATION
- X-RAY IMAGING

Activities partially supported by Microsoft Corporation via a Azure4Research grant (Life Science track). PI: A. Dotti (SLAC)

Last developments in the Geant4 examples for medical physics

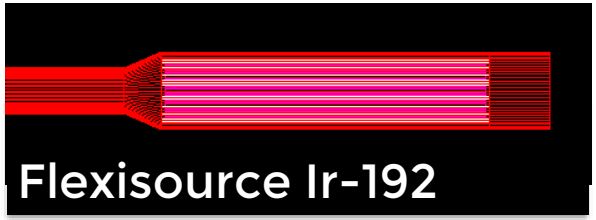
BRACHYTHERAPY
HADRONTHERAPY
DICOM INTERFACE
FUTURE EXAMPLES

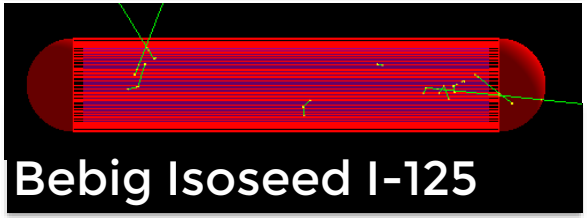
Advanced Example: Brachytherapy

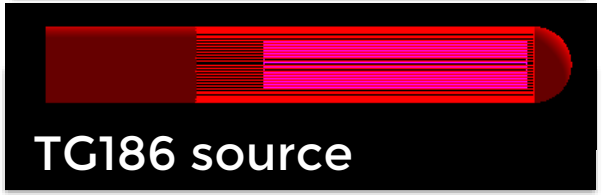
- **Current authors: S. Guatelli and D. Cutajar (CMRP, UOW)**

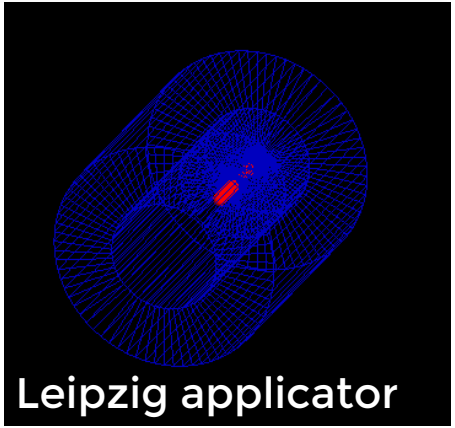
- Calculation of the energy deposition in a water phantom of:
  - Bebig Isoseed I-125
  - Flexisource Ir-192 (Med. Phys 33(12), 2006, 4578-4582)
  - Ir-192 TG186 reference source (Med. Phys. 42 (2015), 3048-3062.
  - Leipzig applicator

- It shows how to define a radioactive source
  - With the definition of the emitted particles from the radionuclide
  - Or with the Radioactive Decay module







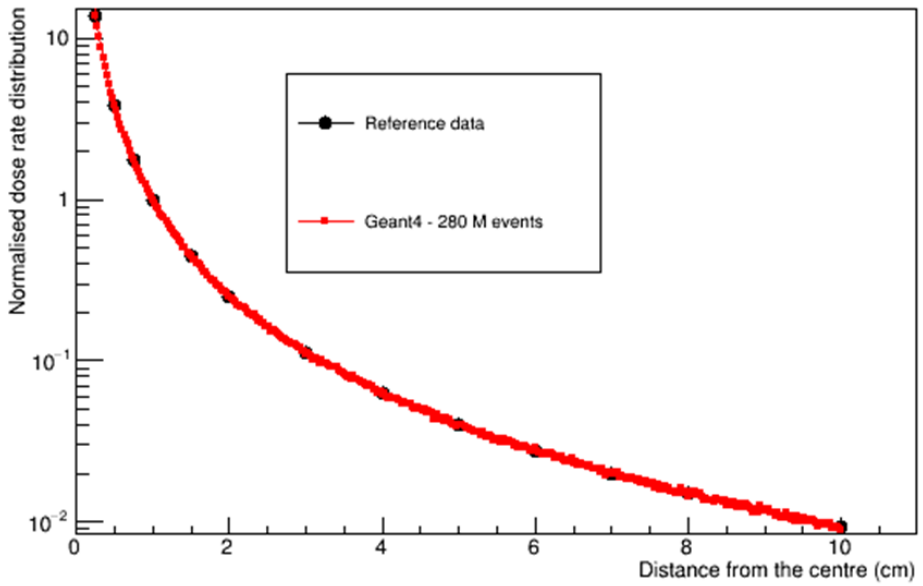


"comparison" directory

- Since Geant4 10.3, it is possible to calculate the dose rate distribution in a water phantom and compare directly to reference data

$$g(r) = \frac{\dot{D}(r,\theta_0)G(r_0,\theta_0)}{\dot{D}(r_0,\theta_0)G(r,\theta_0)}$$

Example: `root comparison.C`



Reference data:

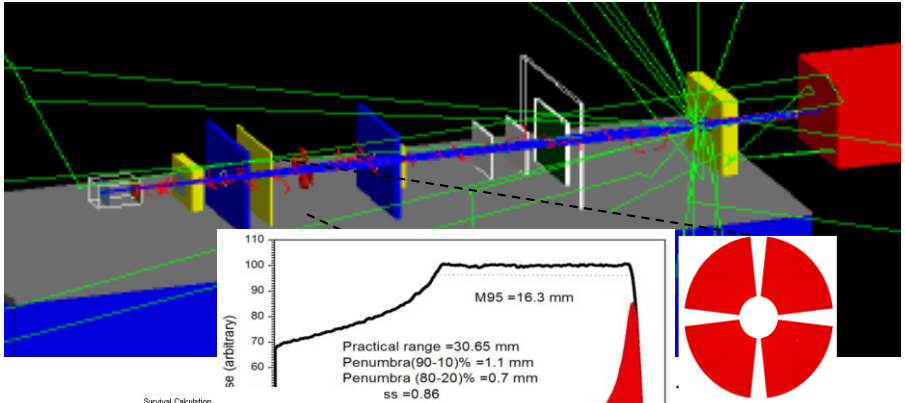
- Granero et al, Med. Phys 33(12), 2006, 4578-4582
- Flexisource
- used for source consensus data for TG43 based dose planning systems (ESTRO.org)

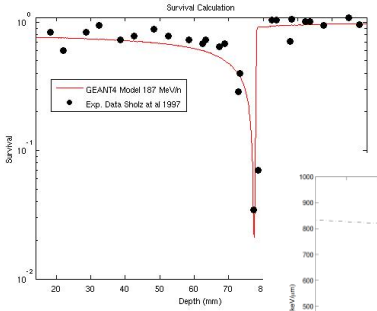
The advanced hadrontherapy example

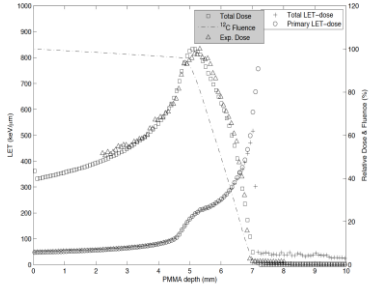
- **Current authors**: GAP Cirrone, G. Cuttone, G. Milluzzo, L. Pandola, J. Pipek, P. Pisciotta, G. Petringa, F. Romano

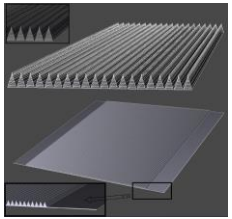
- Paper with recent developments published: *Front. Oncol., in-press, 2017 doi: 10.3389*

- Two beamlines simulated
  - **Proton therapy** facility for eye melanoma treatment
    - Completely **revised modulator class**, with possibility to easily modify the flatness region (*NIM A, Vol. 806, 101-108, 2016*)
  - **Ion transport beam** line for multidisciplinary example.
    - Geometry revised **and new elements** included
- **Dose average LET** computations currently based on *PMB 59 (12):2863-2882 (2014).*
  - Recent improvements on track/dose LET computations, studying dependences on simulation parameters
- **Bragg peak validation** for low energy protons (up to 60 MeV) and ions (up to 80 MeV/n)
- **RBE calculations** with LEM
  - Comparisons with proton data in progress
- **In-vivo** simulation studies using the DICOM interface (*NIM A, Vol. 846, 2017*)







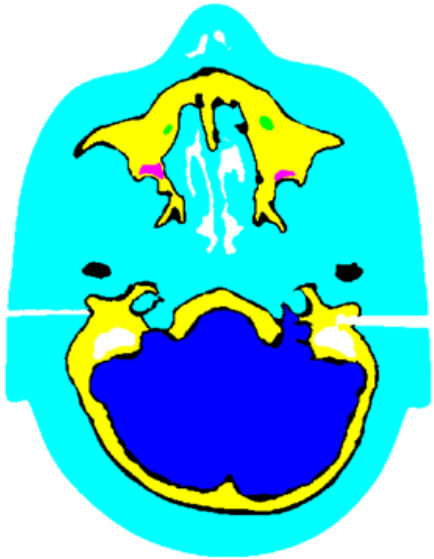


New development in the DICOM Interface

- The DICOM interface is an extended example of Geant4
- 128 slices and matrix size of 1024×1024 pixels
- Unique for its anatomical details and high spatial resolution (0.18 x 0.18 mm^2 pixel size).
  - Slice thickness: 1.25 mm
  - Homogeneous brain, Spinal disks, ear canals, sinus cavities, deciduous and descending teeth with enamel and dentin.
- To be released in Geant4 10.4 within the DICOM interface
- Flag **DICOM_HEAD =1**

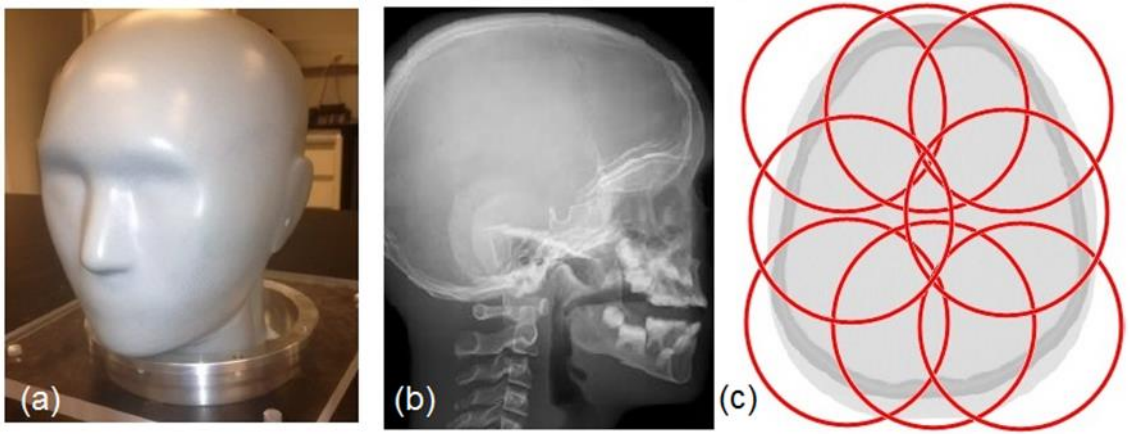
Giacometti, V., Guatelli, S., Bazalova-Carter, M., Rosenfeld, A.B., Schulte, R.W. (2017) Physica Medica, 33, pp. 182-188

HN715,CIRS



Geant4 model

The DICOM_HEAD

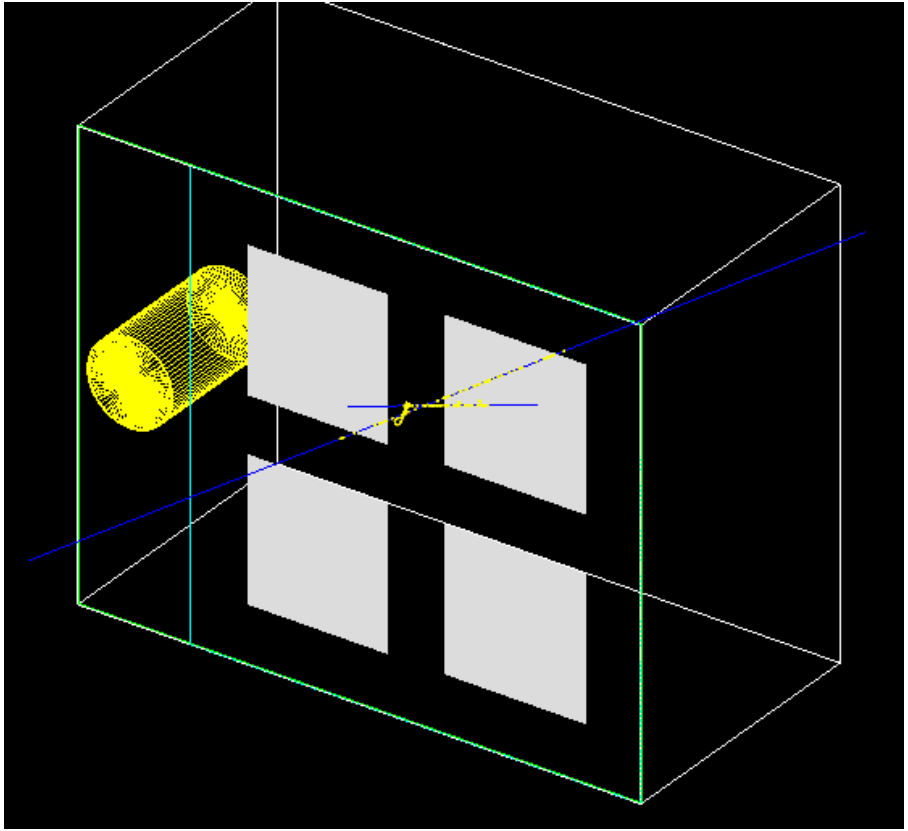


Eight helical CT scans of the head phantom acquired with a 64-detector-row CT scanner (Lightspeed, GE Healthcare, Waukesha, WI)

Segmentation: clean from noise and identify uniquely materials, especially at boundaries

The advanced radioprotection example

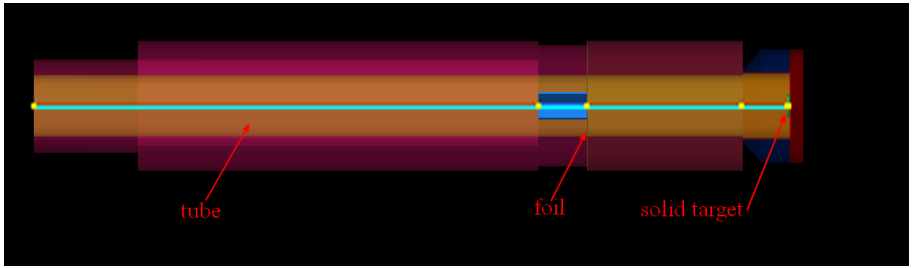
- **Current authors: S. Guatelli and J. Davis**
- Calculate the energy deposition spectra in a diamond microdosimeter, deriving from Galactic Cosmic Rays (protons and alpha particles)
  - Spectra from CREME96
- Microdosimeter designed by A. Rozenfeld and Collaborators
  - documented in J. Davis, et al., IEEE Trans. Nucl. Sci., Vol. 59, pp. 3110-3116, 2012.



(Future) Advanced Example: STCyclotron

- Goal: Predict the production of **medical radio-isotopes** and undesired by-products yields

- Main features :
  - Modelling of a solid target system based on the GE PETtrace cyclotron from the South Australian Health and Research Institute
  - Physics list QGSP_BIC_AllHP uses the ParticleHP model for charged particles (p, d, t, ^{3}He, alpha) below 200 MeV (TENDL data libraries)
  - User-friendly GUI available
  - Full radio-isotope analysis
    - Benchmarked with ^{64}Ni(p,n)^{64}Cu



F. Poignant, S. Penfold, J. Asp, P. Takhar, P. Jackson, GEANT4 simulation of cyclotron radioisotope production in a solid target, Phys.Med. **32** (2016), 728

- Code made available by the authors
  - Working with G4 9.6.
  - Work in progress for migration to

  G4 10.0, g4anaylsis and MT
  - Aiming to release it in 10.4
  - Integration by L. Pandola and e F. Poignant

Conclusions

- There is a constant effort to improve Geant4 for medical physics applications
  - Not only in physics, but in all the components (geometry, scoring, UI, visualisation, etc)
  - There are many Geant4 examples for medical physics (Brachy, hadrontherapy, human_phantom, medical linac, DICOM, G4-DNA examples, iort_therapy, etc)
  - Development of tools such as GATE, TOPAS and GAMOS to facilitate the use of Geant4 for medical physics
- **User Forum**: http://hypernews.slac.stanford.edu/HyperNews/geant4/get/medical_app
- **Many Geant4 Schools** around the world
  - 5th International Geant4 School, Catania (Italy), 23-27 October 2017.
  - Geant4 Tutorial 2017 at the Massachusetts Institute of Technology, Boston (USA), 6-9 November 2017.

Next Geant4 School at CMRP

- At CRMP, 2011, 2013 and 2016
  - 3 days schools for medical physics
  - with “Beginners” and “More experienced” sessions
  - Lectures + Hands-on sessions

- **Next school: April 2019**
  - 5 days school
  - Supported by
    - the School of Physics and CMRP, UOW
    - Australian Research Council (Guatelli, Emfietzoglou, Kyriakou, Incerti, McMahon, ARC DP 170100967)
  - School similar to 2016 with on top 2 days dedicated to radiobiology/nanomedicine applications of Geant4

Geant4 school, 2016, CMRP