IV Geant4 International User Conference at the physics-medicine-biology frontier

Recent developments of Geant4 Advanced Examples for medical applications

Francesco Romano[1] and Susanna Guatelli[2]

on behalf of the Geant4 Advanced Example Working Group

[1] Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Italy
[2] Centre For Medical and Radiation Physics, University of Wollongong, NSW, Australia

INFN CATANIA
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

Naples, 24-26 October 2022

CENTRE FOR MEDICAL RADIATION PHYSICS

Geant4 Advanced examples

Illustrate realistic applications of Geant4 in typical experimental environments

25 members, 29 examples

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

…for medical physics

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 (→ eFLASH_therapy)	**J. Pensavalle , G. Miluzzo, F. Romano**	Simulation of a IORT device (→ simulation of electron FLASH LINAC)
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 (→ exp_microdosimetry)	**D. Bolst, S. Guatelli, J. Magini, G. Parisi, G. Milluzzo, F. Romano**	Microdosimetry with solid state detectors for radioprotection in space missions and hadron therapy
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

Advanced example:

ICRP110Phantom

Developers: M. Large, S. Guatelli, A. Malaroda (Wollongong University) and J. Allison (G4AI)

Implementation in Geant4 of ICRP110 phantoms with the kind permission of the International Commission on Radiological Protection.

Reference publication: Zankl M 2010 Adult male and female refence computational phantoms: ICRP Publication 110 Ann. ICRP vol 39 (Oxford: Elsevier) pp 1-165.

Dosimetry in voxelised geometry and entire organs

See talk N. 26 of Jason Paino

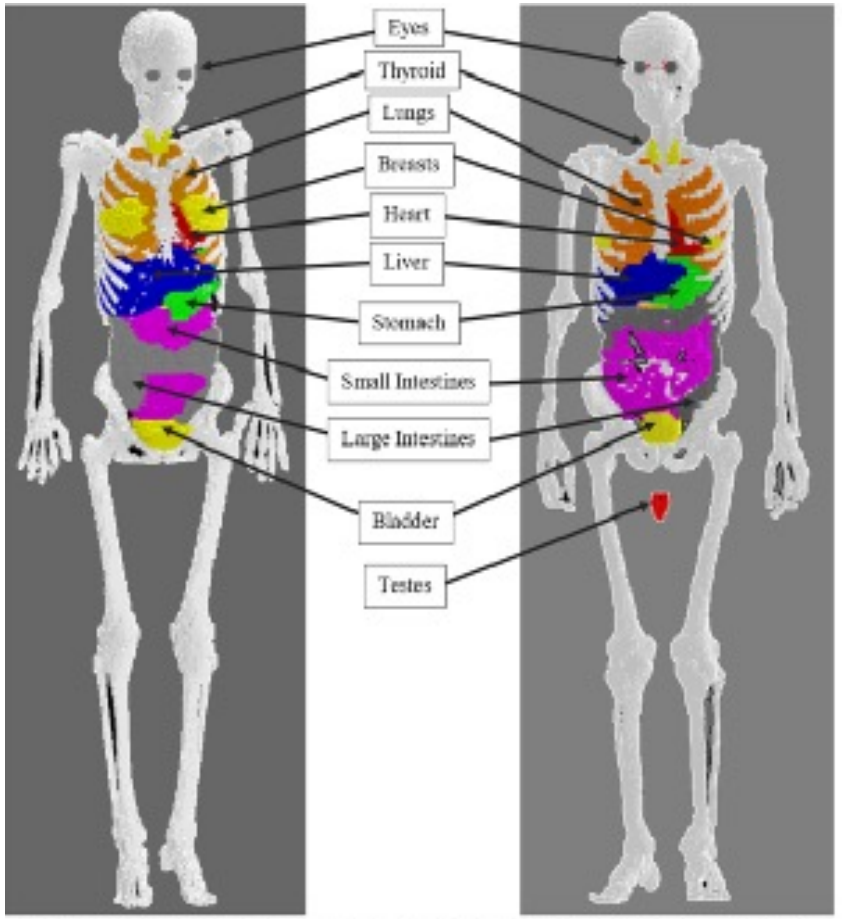


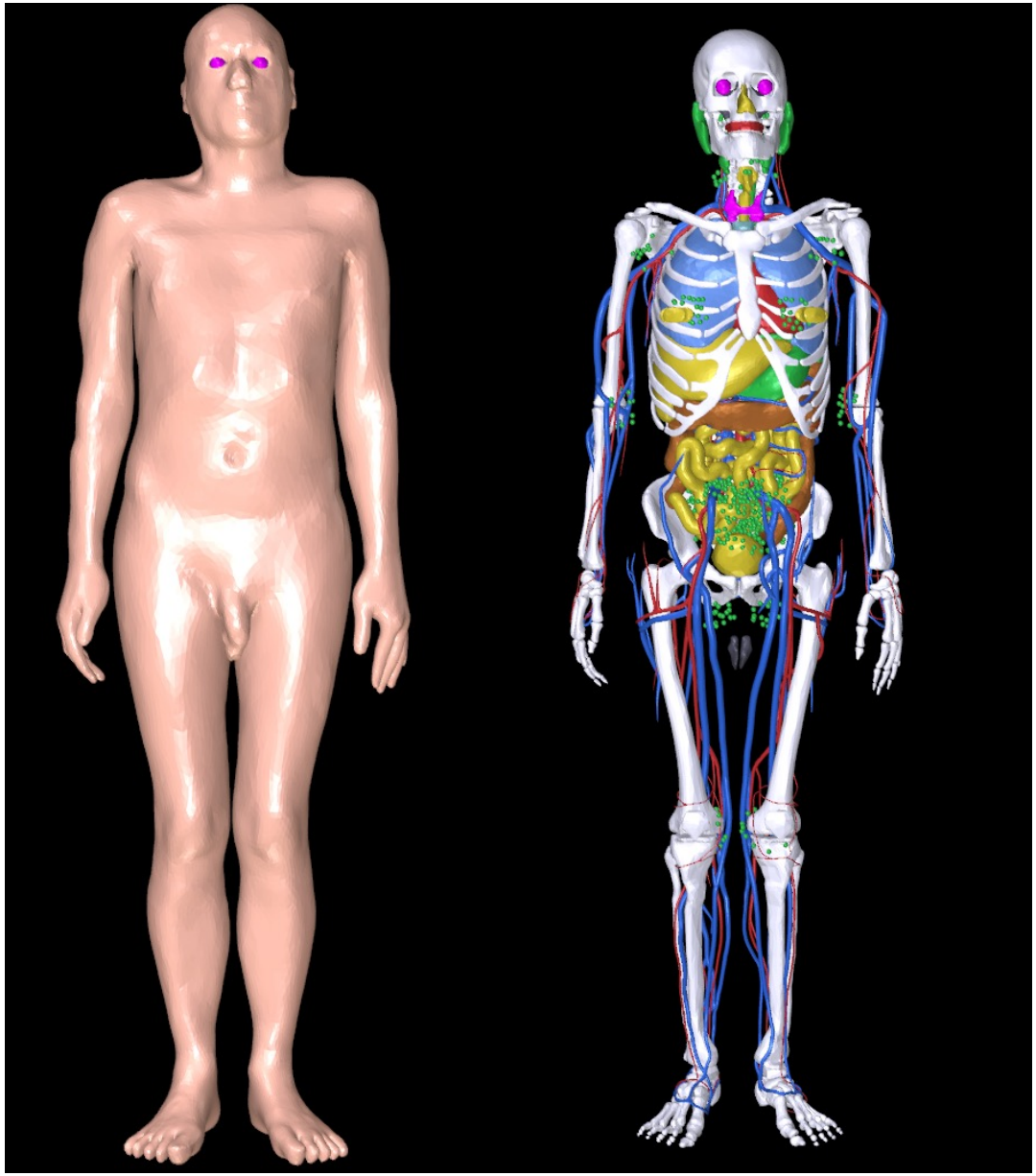
Figure 1. 3D rendering of whole body ICRP110 Reference Female (left) and Reference Male (right) voxel phantoms as modelled in the Geant4 application *ICRP110Phantoms*, in which skin, muscle, cartilage and adipose tissue are not visualised.

M J Large et al 2020 J. Phys.: Conf. Ser. 1662 012021

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
  - J. Allison / G4AI
- Code review done

See talks N. 44 and 32 of Jay Archer and Matthew Large



Advanced Example: Brachytherapy

Current authors: S. Guatelli, D. Cutajar, A. Le (CMRP, UOW)

Calculation of the energy deposition in a water phantom of:

Bebig Isoseed I-125, Oncura 6711

Flexisource Ir-192 (Med. Phys 33(12), 2006, 4578-4582)

Ir-192 TG186 reference source (Med. Phys. 42 (2015), 3048-3062.

Leipzig applicator

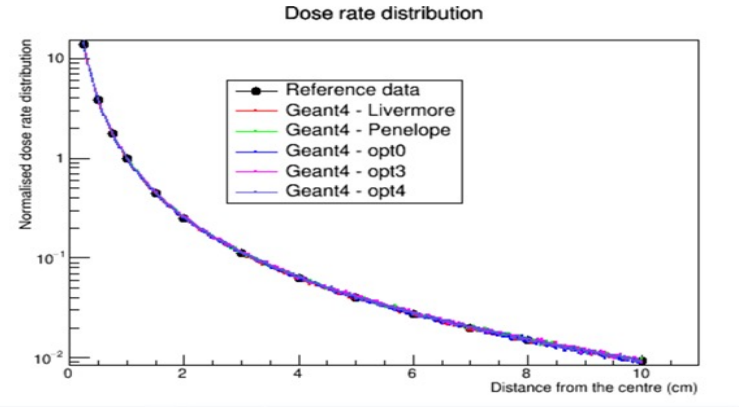
It shows how to define a radioactive source

With the definition of the emitted particles from the radionuclide

Or with the Radioactive Decay module

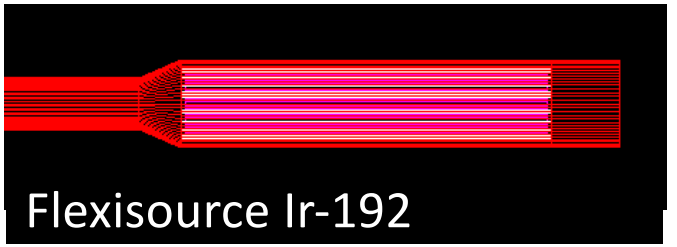
Calculate the energy deposition/dose in a water phantom (scoring mesh)

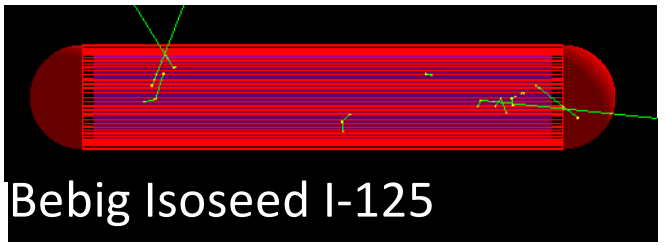
Comparison against reference data

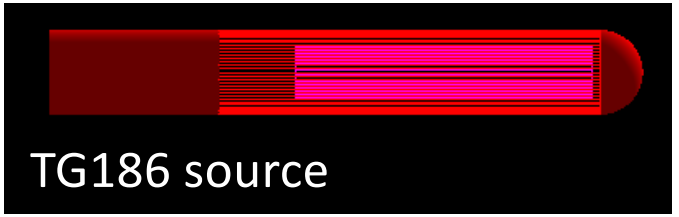


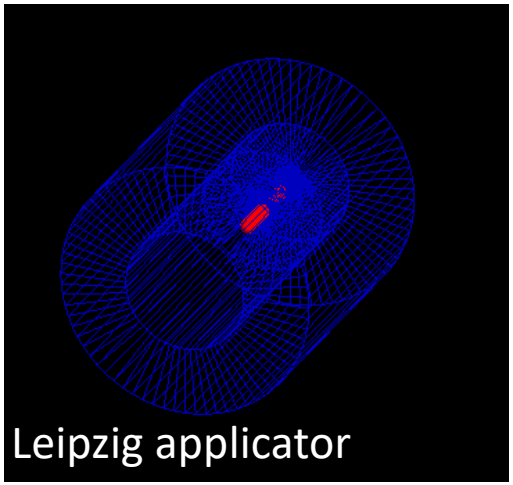
Flexi source (HDR)

Comparison to reference data:
Granero et al, Med. Phys 33(12), 2006, 4578-4582









CENTRE FOR MEDICAL RADIATION PHYSICS

UNIVERSITY OF WOLLONGONG AUSTRALIA

Advanced examples: Microbeam & nanobeam

Current authors:
S. Incerti (CENBG, France) & I. Kyriakou (Ioannina University, Greece)

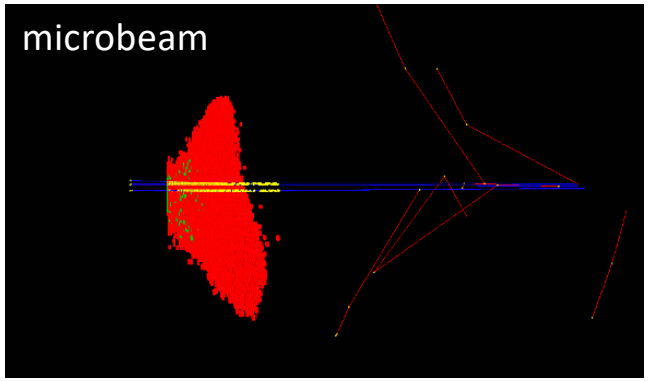
Based on real irradiation setups available at CENBG

Microbeam

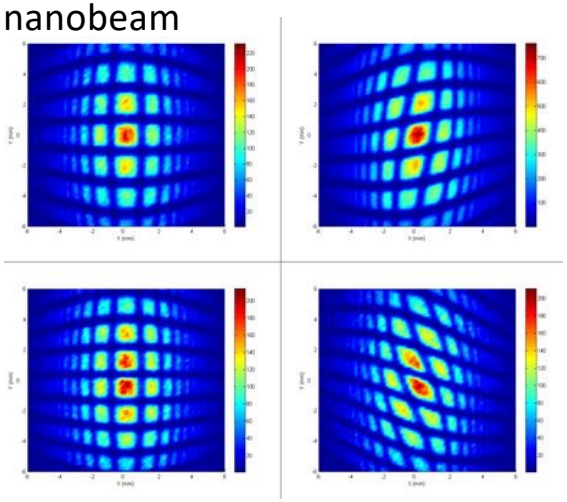
- Simulation of **3 MeV singe alpha particle** irradiation of a **biological cell** (keratinocyte HaCat)
- The cell is implemented as a **3D voxellized phantom**, including realistic chemical composition
- All beam line elements are implemented (quadrupoles, ion gas counter, irradiation chamber…)
- Allows extraction of absorbed dose at voxel scale, dE/dx…

Nanobeam

- Simulation of a **highly-focusing beam line** (sub-micron targeting accuracy)
- Two stage demagnification: doublet / triplet of quadrupoles
- Implements **several quadrupole fields models**
  - Square, analytical, interpolated from OPERA 3D map
- Allows extraction of beam profiles & images, aberration coefficients…



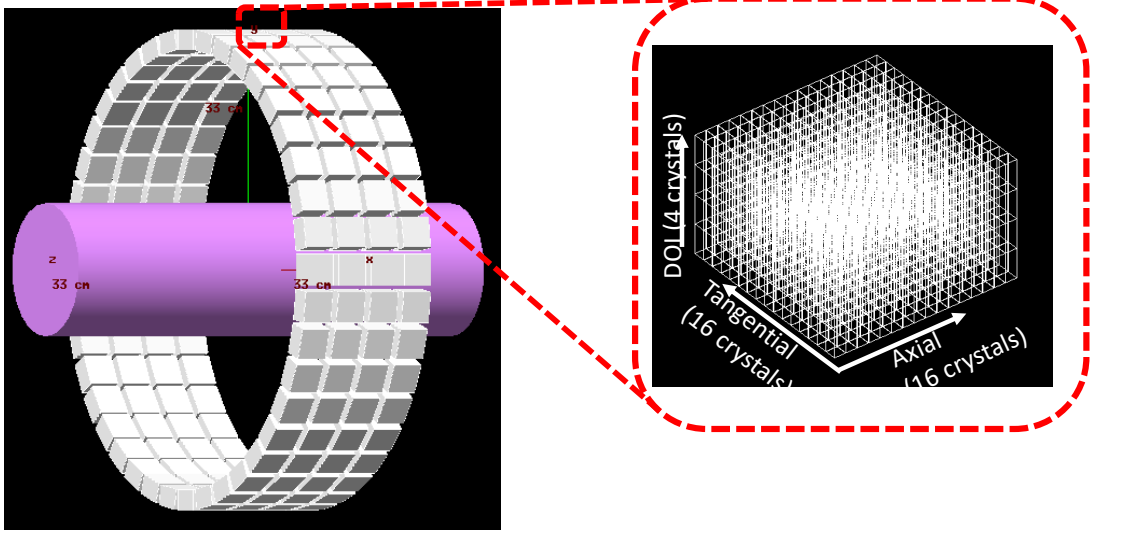
nanobeam



Advanced example: doiPET

Current authors:
A. Ahmed, A. Chacon, (Australian Nuclear Science Technology and Organisation)
S. Guatelli, . A. Chacon, University of Wollongong

- Nuclear medicine/PET
- Currently under integration in Geant4



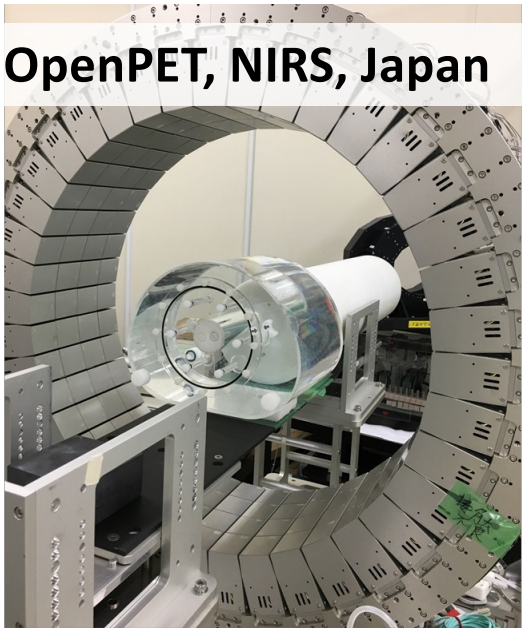
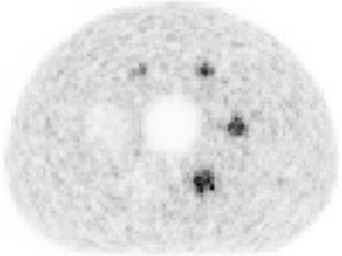
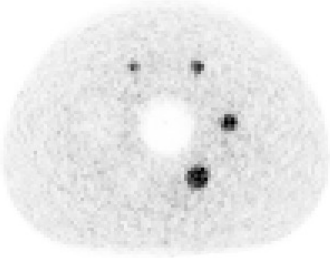


Fig. DOI-enabled whole-body PET scanner (image from Taiga-lab, NIRS, Japan)

(a) Experimental



(b) Simulation



Medical Linac

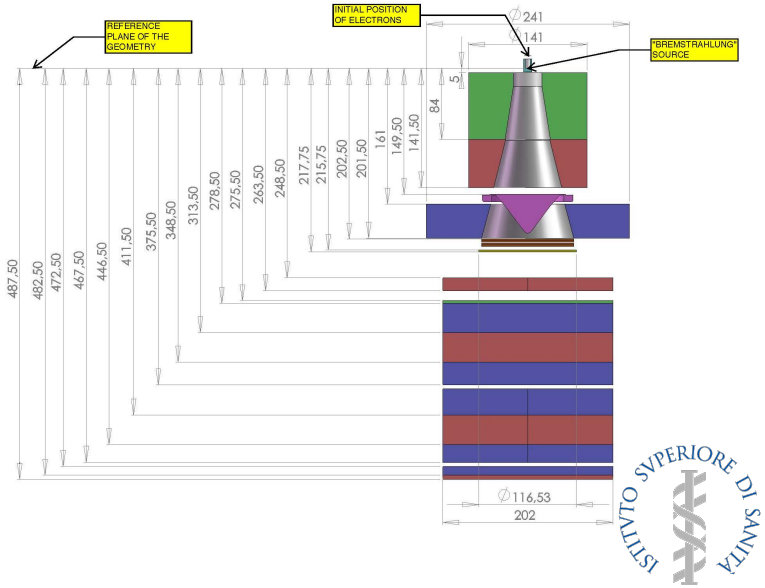
MedLinac advanced example: an update redesign with reliable and available dosimetry data

B.Caccia[1], C. Mancini Terracciano[2], S. Pozzi[1]

[1]ISS (Italian National Institute of Health) and INFN, Rome Italy– [2]Physics Dep., Sapienza Univ. of Rome and INFN, Italy

Medical Linac advanced example will be updated and modified on the base of data made available by the Eurados Linac Action intercomparison. This standard model can be used to help users develop the skills needed to build and calibrate a Geant4 simulation of a medical accelerator and perform a dosimetric analysis.

Saturne 43 LNHB linac



EURADOS Report 2020-05: B. Caccia, V. Blideanu, M. Le Roy, H. Rabus, R. Tanner: "A model validation scheme for Monte Carlo simulations of a medical linear accelerator: geometrical description and dosimetric data used in the "Linac Action"", Neuherberg, October 2020. Full Report downloadable from the EURADOS website.
DOI: 10.12768/9rvp-fq82

EURADOS European Radiation Dosimetry Group

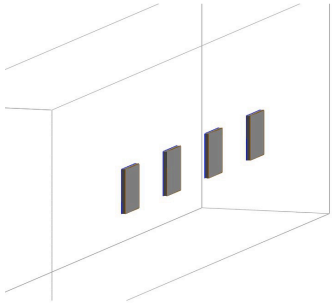
ISTITUTO SUPERIORE DI SANITÀ

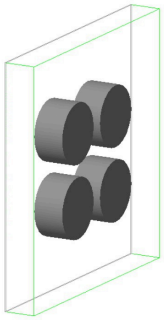
Advanced example: Radioprotection
→ experimental_microdosimetry
(simulation of detectors for microdosimetry)

Current authors: D. Bolst and S. Guatelli (UOW, Australia), J. Magini and G. Parisi (Surrey University, UK), G. Milluzzo and F. Romano (INFN Catania, Italy)

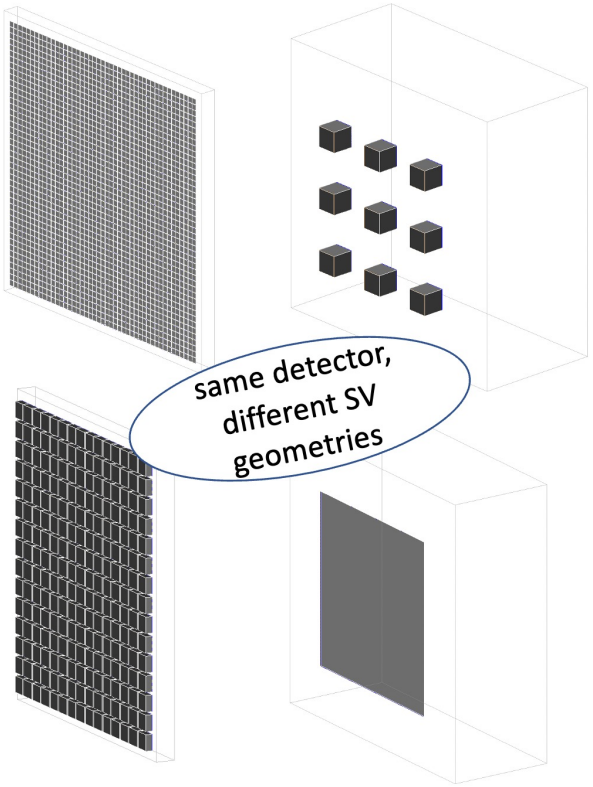
- Originally developed for radioprotection studies in space missions (here is the name….)
- In the last years extended to clinical microdosimetric applications (proton and ion therapy)
- Now a **general-purpose versatile example** for the simulation of several microdododosimeters:
  - Silicon microdosimeters
  - diamond microdosimeters
  - TEPC (in progress)
- Several functionalities available also for a novice User
  - Implementation of simple macro commands for easily changing the different geometrical configurations and parameters
  - Python scripts for microdosimetric spectra and data analysis (first version)
  - Simulation of double-stage gemotries for particle identification

Diamond microdosimeters



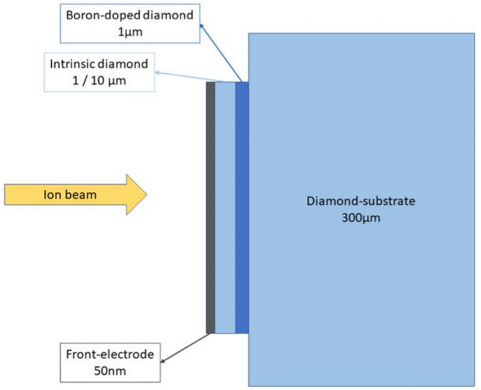


Silicon microdosimeters

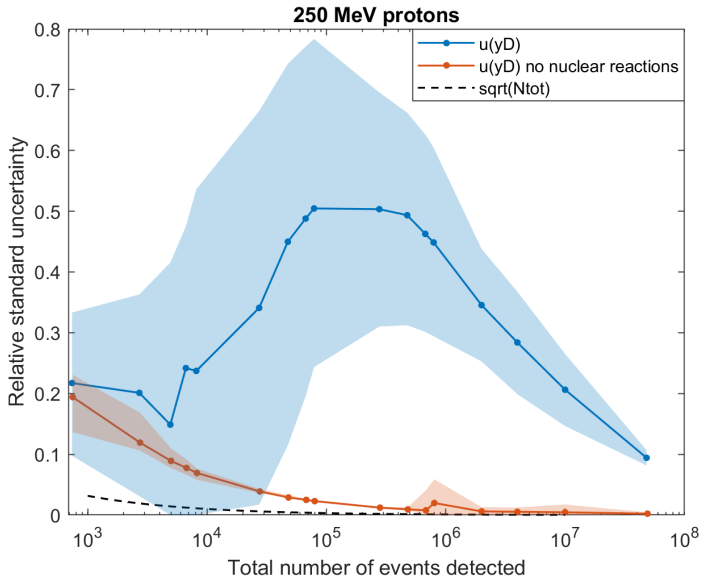


Advanced example: Radioprotection

Microdosimetric characterization of nuclear interaction events, and assessment of their effect on the dose-mean lineal energy uncertainty



Uncertainty analysis: counting statistics contribution



G. Parisi, G. Schettino and F. Romano, "*A systematic study of the contribution of counting statistics to the final lineal energy uncertainty in microdosimetry*", PMB 2022

Follow-up analysis: code upgrade

Each detected event

G4Step() -> GetTrack() -> GetCreatorProcess() -> GetProcessName();
IF generated by Nuclear Interaction

Nuclear interaction event

- Event ID (history #)
- Depostied energy
- Primary path length
- Particle Z

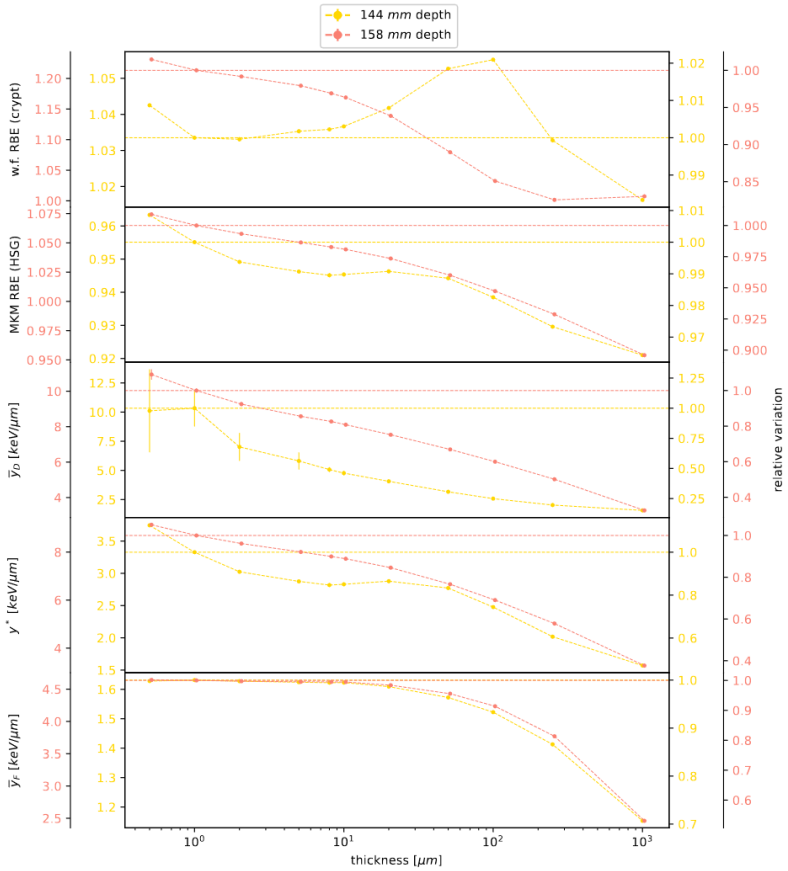
- Event ID
- Fragment Z
- Fragment A
- Deposited energy by the fragment
- Path length of the fragment
- Volume in which it was generated

➢ Contributions from each fragment:
- Microdosimetry spectrum
- Mean values

See talk N. 96 of Gabriele Parisi

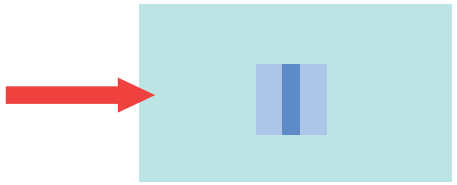
Advanced example: Radioprotection

Systematic uncertainty budget assessment

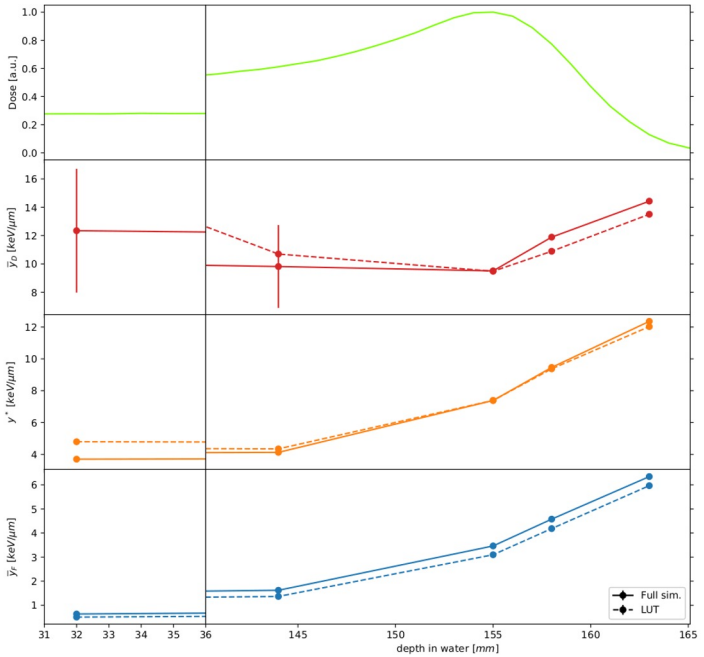


See talk N. 82 of Jacopo Magini

MKM linked to TPS through Geant4 LUT



Microdosimetric mean from LUT, obtained from a mono beam with energy E_i

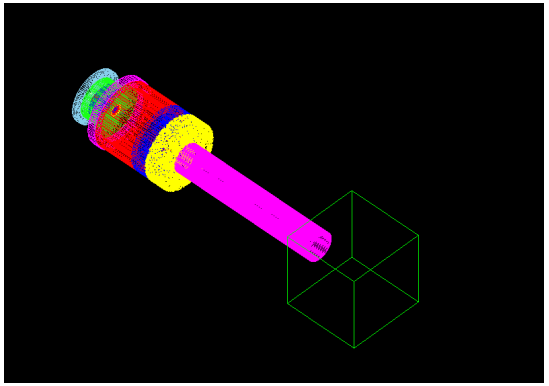


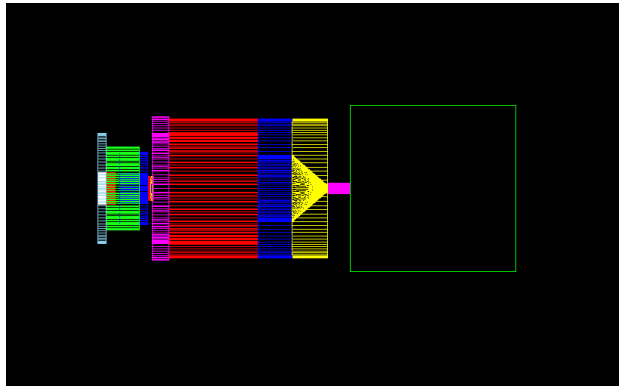
See talk N. 84 of Jacopo Magini

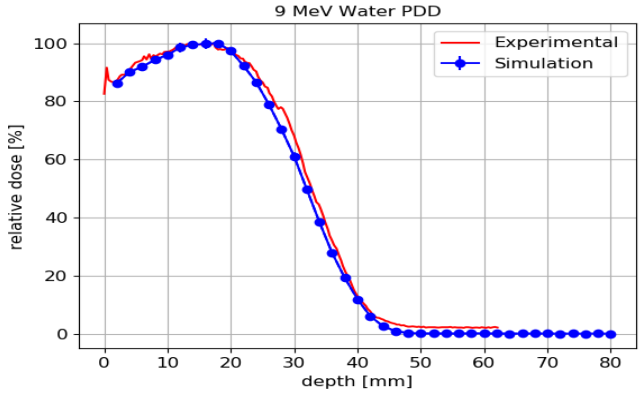
Advanced example: Iort_therapy → eFLASH_therapy

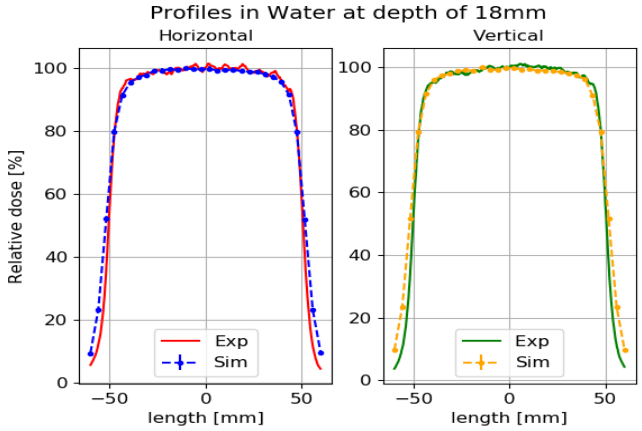
Current authors: J. Pensavalle (University of Pisa, Italy) G. Milluzzo (INFN Catania, Italy), F. Romano (INFN Catania, Italy)

- We accurately replicated the most relevant components of the ElectronFlash LINAC at CPRF by following the manufacturing specifications provided by Sordina Iort Technologies S.p.A.
- Variable applicator dimensions for different dose per pulse set-up (diameter 1cm to 10cm).
- From both the PDD and dose profiles, we can see a good agreement between simulation and validation.









See talk N. 93 of Jake Pensavalle

stim_pixe_tomography: an advanced example for 3D imaging of microscopic samples by proton tomography

Developed by Z. Li, C. Michelet and S. Incerti, at CENBG/LP2IB, France

Objectives

- Simulate STIM and PIXE tomography imaging processes
- Use simulated results as an input to generate tomographic images by reconstruction software packages
- Evaluate the accuracy of tomographic reconstruction methods designed for thick samples

STIM: Scanning Transmission Ion Microscopy

Measurement of the residual energy of the protons after passing through the sample

→ Visualization of the internal structure

Density Contrast Imaging ≈ Proton "Radiography"

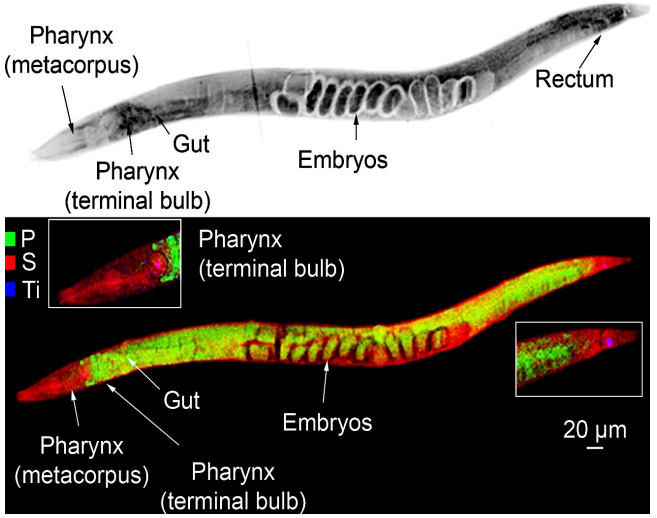
PIXE: Particle Induced X-ray Emission

Measurement of the energy of emitted X-rays

→ Location of chemical elements

→ Quantification

Minerals, trace metals, exogenous elements, *e.g.* here nanoparticles of TiO_2

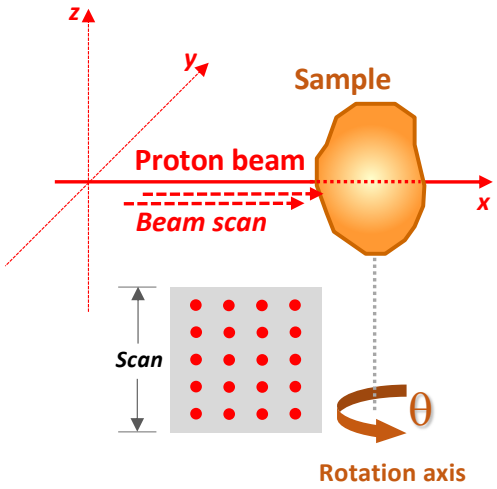


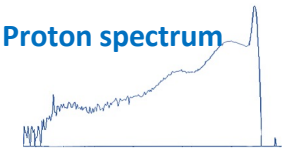
***Caenorhabditis elegans* (*C. elegans*), a small worm living in temperate soil environments**

Michelet C., Li Z. et al. *A Geant4 simulation of X-ray emission for three-dimensional proton imaging of microscopic samples*. Phys Med. 2022;94:85-93

stim_pixe_tomography: an advanced example for 3D imaging of microscopic samples by proton tomography

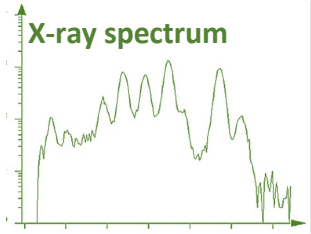
○ *Simulation process*





Energy of transmitted protons

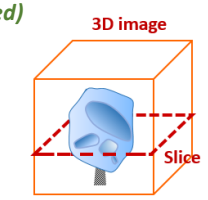
Energy of emitted X-rays

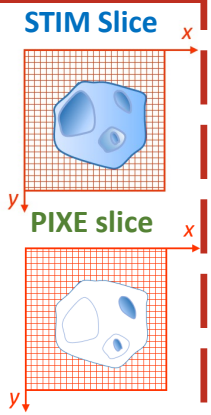


Tomographic images obtained by reconstruction software packages

Tomographic slice:
Mass density of material (g/cm³)

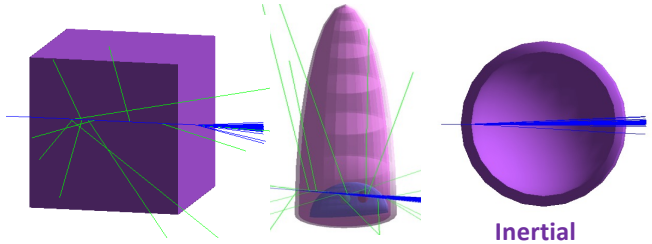
Tomographic slice:
Elemental composition (g/cm³ or g/g if normalized)





By comparing the quantitative reconstructed images with the reference values, which were set for constructing the phantom, we can evaluate or check the accuracy of reconstruction methods and the corrections implemented for X-ray attenuation.

○ *Models available in the example*



Simple cube

C. elegans

Inertial confinement fusion target

○ *Classical (2D) imaging*

The example was initially developed for applications in tomographic imaging. However, it is also suited for "classical" (2D) STIM and PIXE imaging.

○ *Using ion or Xray beam*

The type and energy of incident particles are defined in a .mac file used to run the code, they are very easy to modify. So any source can be used, e.g. ion or X-ray beam.

Summary and Conclusions

- Many advanced examples on medical physics: offer a wide set of Geant4 applications for medical physics
- Number increasing: newly proposed examples are being included
- Relevant number of young collaborators
- Big effort for benchmarking and experimental verifications
- Improvement of the web page: https://geant4.web.cern.ch/collaboration/working_groups/advanced_examples
- Migration to C++11/14/17
- Code review, update and maintenance







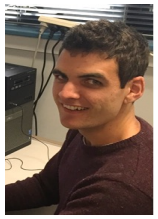


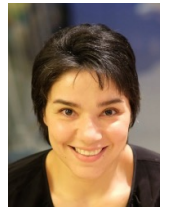
Thank you







Aknowledgements:

Many thanks to all the members of the Advanced Examples Working Group and also external collaborators for providing useful materials