Recent Geant4-DNA developments and perspectives

geant4-dna.org

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On behalf of the Geant4-DNA Collaboration

CNAO-IN2P3 collaboration meeting
Pavia, Italie
March 5, 2026

Geant4 version 11.4

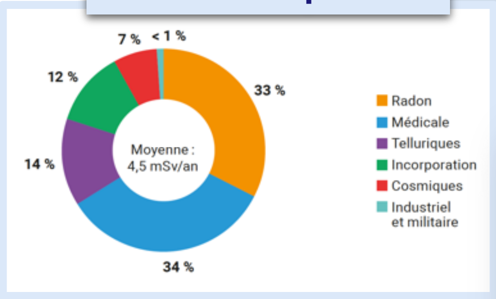
Context: exposure to ionizing radiation

1 mSv/an
Public

Increasing dose*

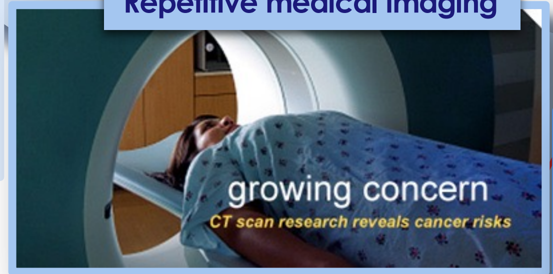
>100 mSv
Long-term effects

Chronic exposure



IRSN, France (2014-2019)

Repetitive medical imaging



UCSF & Harvard MS

~10 mSv / scanner abdomen

Space missions

ESA

Return trip
6 months: ~ 600 mSv

ESA

~2,6 times ISS

ESA

6 months = ~ 160 mSv

Radiotherapy

NCC

- **Major questions in radiation protection**
  - What are the **biological effects** of **low doses** of ionizing radiation?
  - What are the **risks** associated with **high doses**?

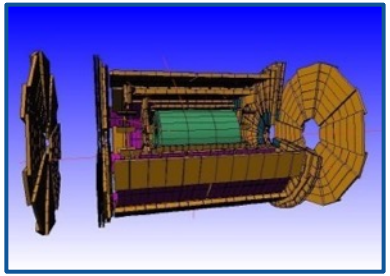
*« A major challenge lies in providing **a sound mechanistic understanding of low-dose radiation carcinogenesis** »*
L. Mullenders et al. (2009)

The Monte Carlo approach…

GEANT4-DNA

* Equivalent or effective

The « Geant4-DNA » project



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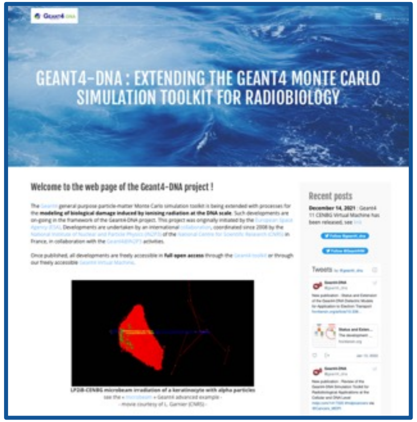


- **Initiated in 2001, based on an idea of the European Space Agency (P. Nieminen)**
  - To develop the **first open source platform** able to **simulate mechanistically the biological effects of ionizing radiation at cellular scale** during manned space missions
- **Set of C++ libraries able simulate the different stages of the effects of ionizing irradiation**
  - Open source, distributable (many OSs), user extensible (OO)
  - Radiation **physics** (particle-matter interactions), radiation **chemistry**, radiation **biology**…
- **Fully integrated in the « Geant4 » Monte Carlo simulation toolkit**
  - **Ge**ometry **an**d **t**racking – version **4**
    - Developed by an international collaboration, initially for the simulation of the large experiments of the LHC at CERN
- **First release of « Geant4-DNA » physics models in 2007**
  - Step-by-step simulation of particle transport down to very low energy (~10 eV) in the biological medium, under the coordination of **INFN Genova, Italy**
- **International collaboration funded in 2008**
  - Coordinated by IN2P3 / CNRS Nuclei & Particles (relected every 2 or 3 years)
  - At IN2P3, full activity of the **« Geant4 Master Project »**
  - 70 collaborators in Oct. 2025

The Geant4-DNA approach

MC Simulation Block

Physical stage
step-by-step modelling of physical interactions of incoming & secondary ionising radiation with biological medium (liquid water)

- Excited water molecules
- Ionised water molecules
- Solvated electrons

Physico-chemical/chemical stage

- Radical species production
- Diffusion
- Mutual chemical interactions

Geometrical models
DNA strands, chromatin fibres, chromosomes, whole cell nucleus, cells…
for the prediction of damage resulting from direct and indirect hits

DIRECT DNA damage

INDIRECT DNA damage

Prediction Block

Biological repair

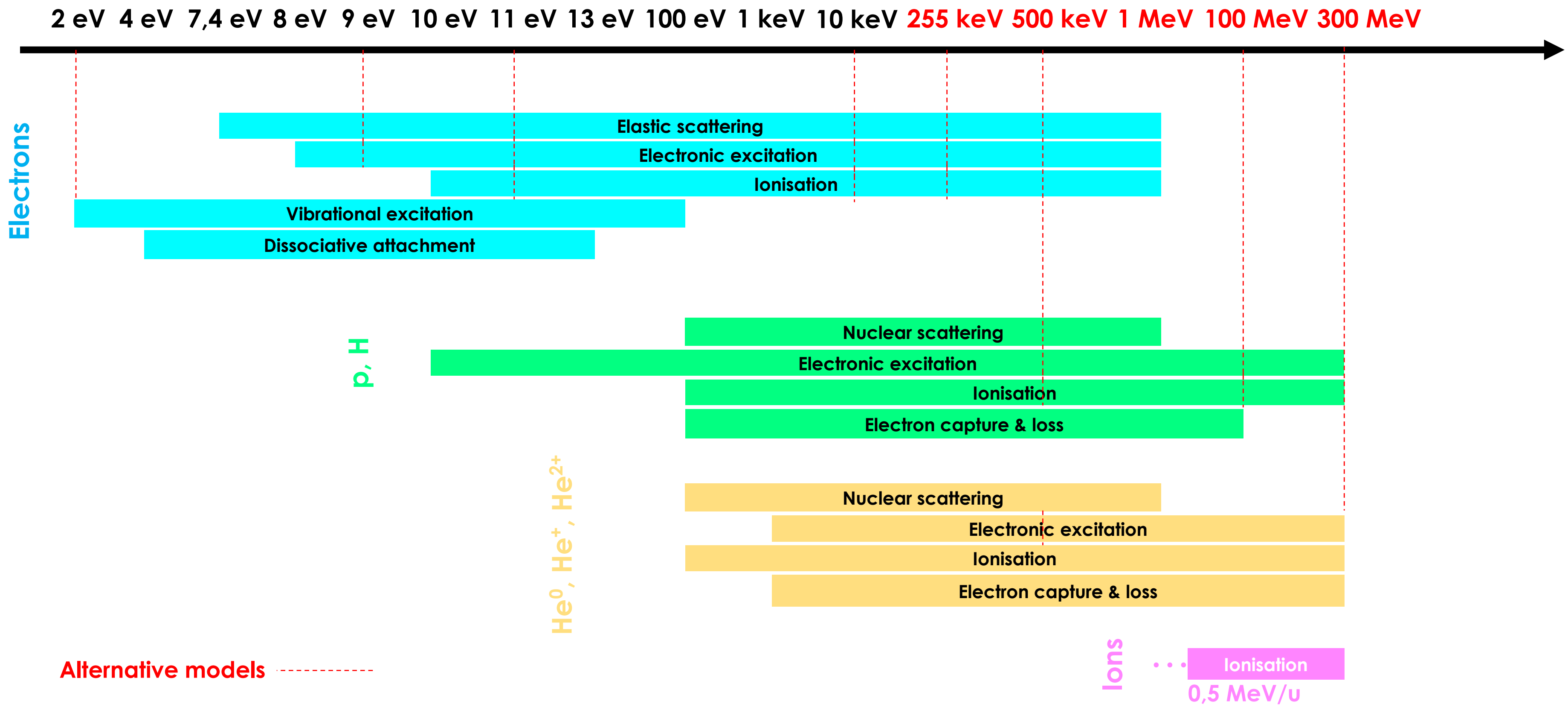
Prediction of biological end-effects using (semi-empirical) biological repair models

Input: early damage such as number of simple DSB and complex DSB

- Protein/enzyme kinetics
- Cell survival
- …

t=0 | $t=10^{-15}s$ | $t=10^{-9}\sim10^{-6}$ s

Physics / Energy coverage of physics processes in liquid water



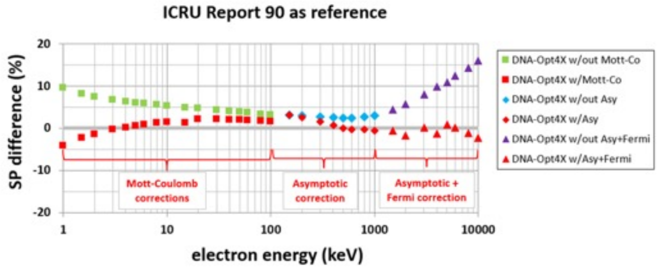
Coming soon!

[Appl. Sci. 15 (2025) 1183]

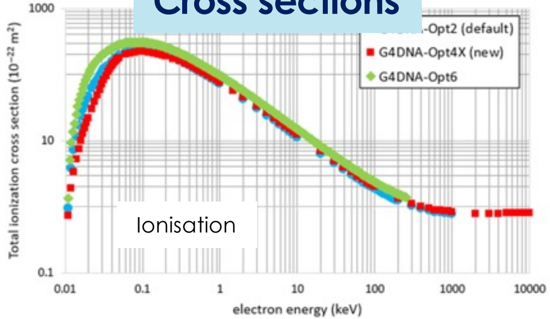
Ioannina U. et al.

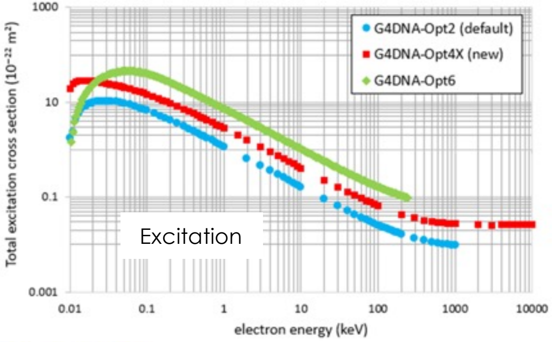
New liquid water model for electrons

- Will fully replace the option4 model, up to 10 MeV
  - Updated parameters of the Energy Loss Function
  - New theoretical corrections to the PWBA cross sections
    - most accurate theoretical approach among all constrcutors

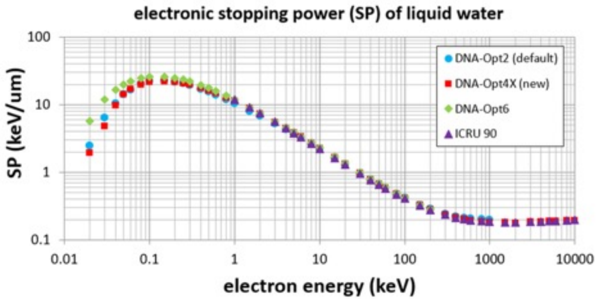


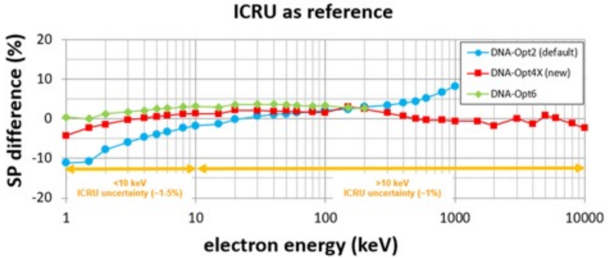
Cross sections



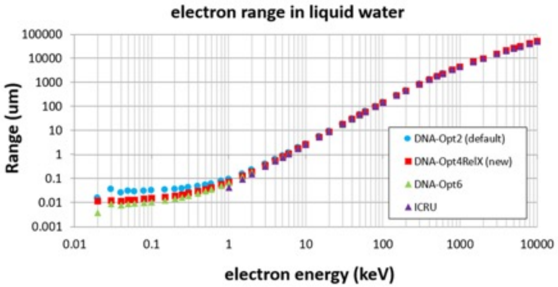


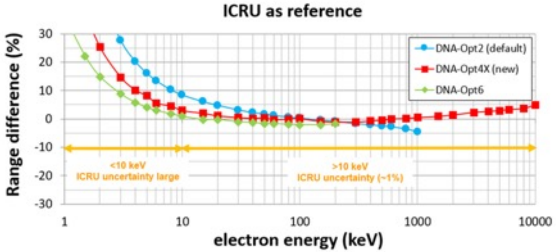
(Electronic) stopping power





Range





Coming soon!

Courtesy of Jose Ramos-Mendez and J. Naoki D-Kondo (UCSF)

Physics: lithium Ions Cross-Sections for Geant4-DNA (1)

- Context of **BNCT therapy**: $^{10}B(n,\alpha)^{7}Li$
  - New classes are required in Geant4-DNA for using new XS for **ionization, excitation and charge exchange** processes.
  - New particles are needed for the different states of Li. **A particle template might help** to create these new states.
- Data was obtained for all the charge states of lithium ions
  - **Ionization and excitation** were obtained by weighting the Li^{3+} cross-sections by effective charge factors[1]
  - **Charge exchange** was obtained using the Classical Trajectory Monte Carlo Method (CTMC) [2]

Cross-Section	Based on	Energy Ranges	Applicable to
Ionization	G4DNARuddIonizationExtended	700 eV – 7 GeV	Li^{3+}, Li^{2+}, Li^{1+}, Li^{0}
Excitation	G4DNAMillerGreenExcitationModel	70 eV – 3.5 MeV	Li^{3+}, Li^{2+}, Li^{1+}, Li^{0}
	G4DNABornExcitationModel	3.5 MeV – 700 MeV	Li^{3+}, Li^{2+}, Li^{1+}, Li^{0}
Charge Increase	CTMC	7 keV – 70 MeV	Li^{2+}, Li^{1+}, Li^{0}
Charge Decrease	CTMC	7 keV – 70 MeV	Li^{3+}, Li^{2+}, Li^{1+}

[1] R.H. Garvey, C. H. J. and A. E. S. G. (1975). Independent-particle-model potentials for atoms and ions with 36 < Z <= 54 and a modified Thomas-Fermi atomic energy formula*. *Physical Review A*, *12*(4), 1144–1152, https://doi.org/10.1080/00431672.1975.9931783

[2] Olson, R. E., & Salop, A. (1977). Charge-transfer and impact-ionization cross sections for fully and partially stripped positive ions colliding with atomic hydrogen. *Physical Review A*, *16*(2), 531–541, https://doi.org/10.1103/PhysRevA.16.531

Coming soon!

Phys. Med. Biol. 70 (2025) 165019

Ioannina U. et al.

Beyond liquid water: new model for electrons in solid gold

- Provides an **alternative and more accurate set of inelastic cross sections** for track structures simulations in solid gold
  - Existing one:
    - Relativistic binary encounter Bethe Vriens cross section formula for ionizations, Quinn's expression for collective (plasmon) excitation, and various theoretical and experimental data for the main electronic excitation channels
  - New set:
    - **Dielectric response function for**malism, same approach as option4 inelastic models for liquid water
    - Includes improved plasmon dampling, relativistic extension and various corrections to (R)PWBA
      - Coulomb (CO), Exchange (EX), and asymptotic (ASY)
- **Larger energy range, better accuracy**
  - E.g. stopping power plot
- Domain of applications:
  - **Use of GNP in radiation therapy** to boost energy deposition
    - Demonstrated on the AuNP extended example
    - Includes the possibility to simulate resulting water radiolysis

Stopping power

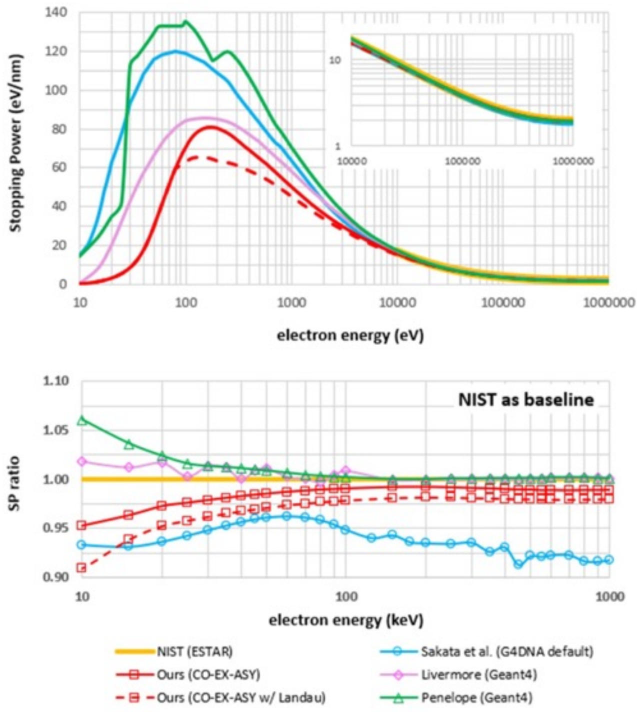


Figure 9. Top panel: the electronic stopping power of solid gold calculated by the present model with Coulomb (CO), Exchange (EX), and asymptotic (ASY) corrections but without Landau plasmon damping (red line) and with Landau plasmon damping (dashed red line). Also included for comparison are the Geant4-DNA default model for gold (blue line), the Geant4 Livermore model (purple line), the Geant4 Penelope model (green line), and the NIST ESTAR data (yellow line). The inset focuses on the high-energy range (10 keV–1 MeV). Bottom panel: the electronic stopping power ratios with NIST data used as baseline.

Coming soon!

Beyond liquid water: new models for atmospheric simulations

Phys. Med. 128 (2024) 104838
Phys. Med. 114 (2023) 102661

- Cross sections for **electron impact on N_2, O_2, CO_2** molecules have been implemented in Geant4-DNA (energy range: 10 eV – 10 MeV) for track-structure simulations in atmospheres

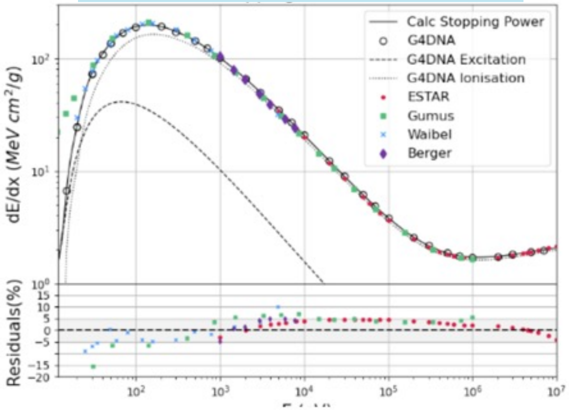
- 3 physics model classes:
  - **Elastic** scattering (Independent Atomic Model with Screening Coefficients)
  - **Ionisation** (Relativistic Binary Encounter Bethe Model)
  - **Excitation** (Porter's formula with fitted parameters)

- Ranges and stopping powers have been verified vs NIST

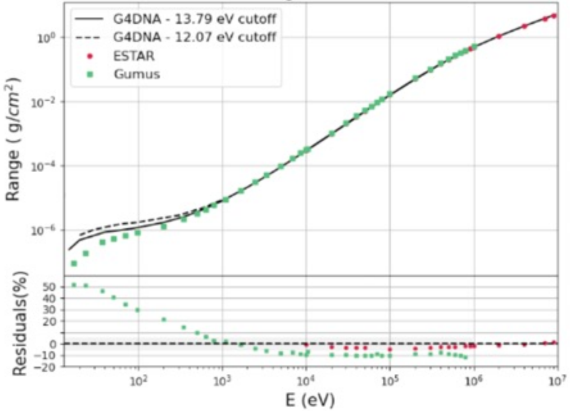
- Work in progress & future
  - A draft **physico-chemistry dissociation process** has been developed through the dissociation branching ratios for N_2 and O_2
  - Extension of cross sections to positrons (10 eV – 10 MeV)

Roma U. et al.

Stopping power in CO2

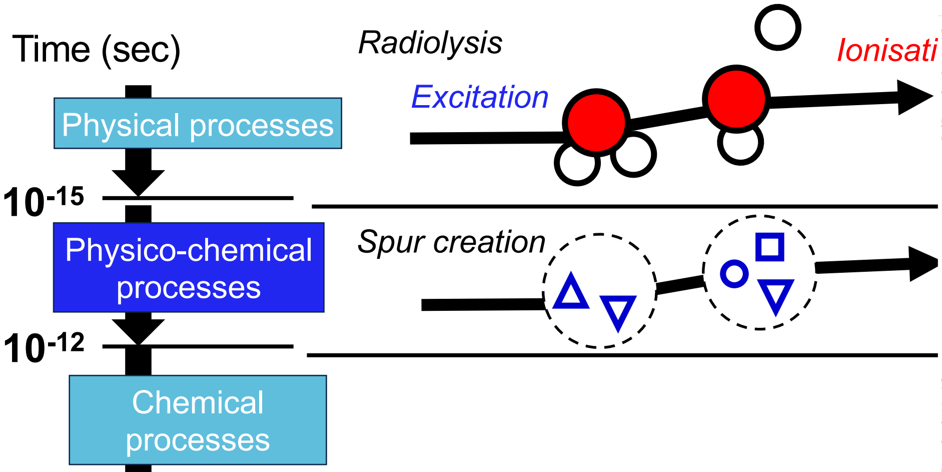


Range in CO2

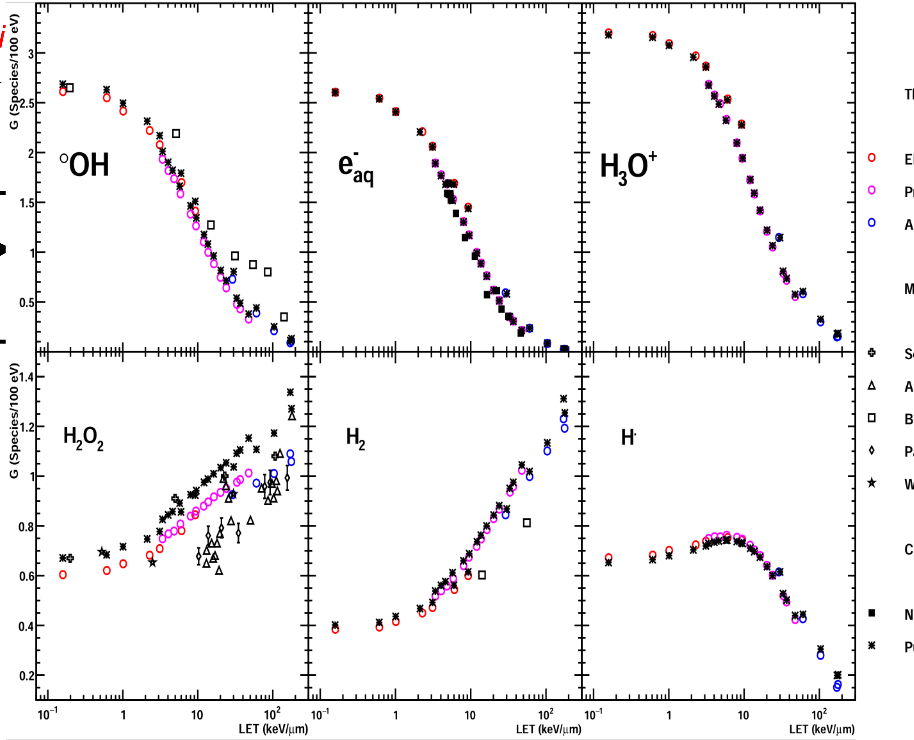


Satisfactory agreement on stopping power and ranges for incident energies exceeding 200 eV

Chemistry / Physico-chemical stage



- Geant4-DNA starts from **altered water molecules** which underwent changes in their electronic configuration from physical processes (excitation & ionisation) occuring during the **physical stage**.
- Dissociation of water molecules by ionising radiation **during physico-chemical stage**, **creating molecules** in **« spur »**.



Ref: J. Comput. Phys. 274, 841-882 (2014)

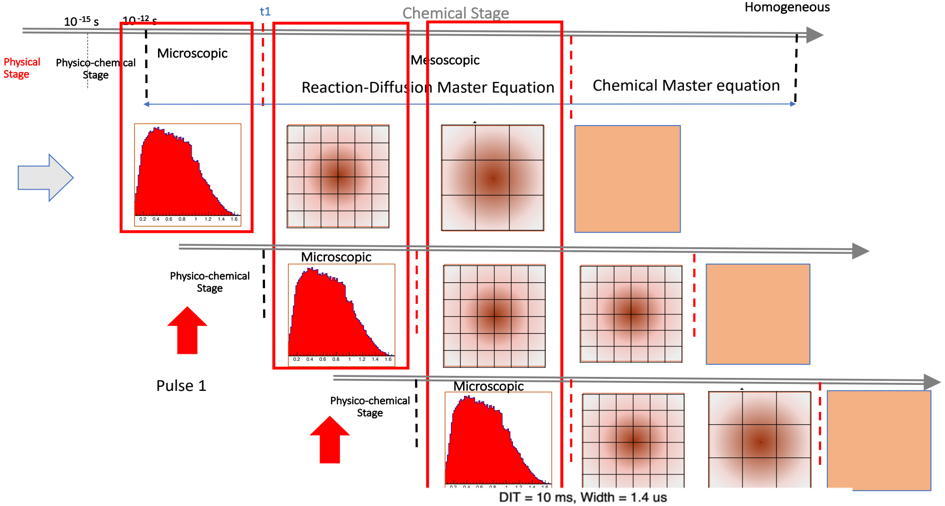
Ref.: Phys. Med. 88, 86-90 (2021)

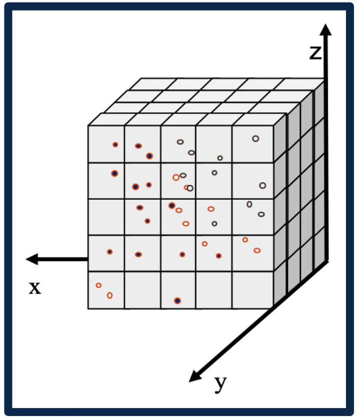
Coming soon!

New « mesoscopic » approach

Tran et al., Int. J. Mol. Sci. (2021) 22 (link)

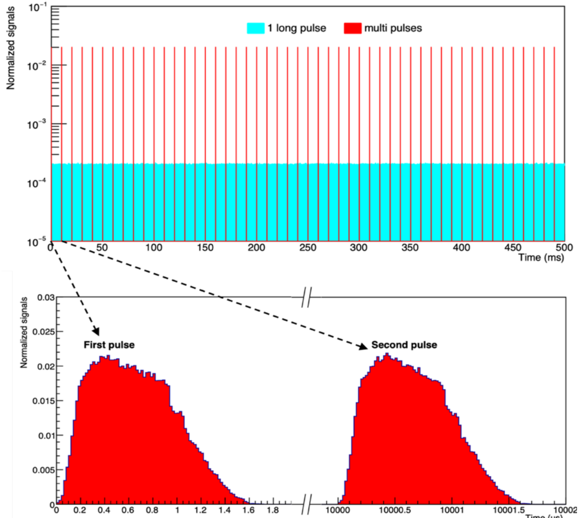
- Use a new « mesoscopic » approach to study the production and evolution of reactive oxygen species generated under irradiation with different dose rate conditions, such as in FLASH RT
- Coarse-grained model: "compartment-based"
- Simulation from heterogeneous (microsecond) to homogeneous states (beyond)
- Multiple pulses simulation





1. *Well mixed species in voxels*
2. *Species can react with each other in the voxels*
3. *Diffusion is modelled by jumps between adjacent voxels*

Voxelization of the simulation volume into smaller sub-volumes. Species are represented by different types of circles

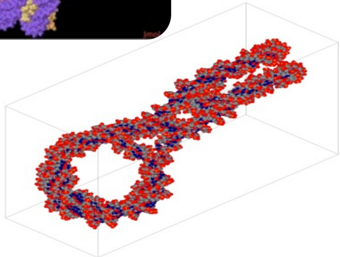


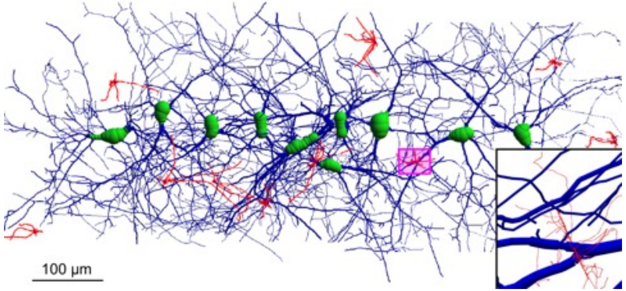
GEANT4-DNA

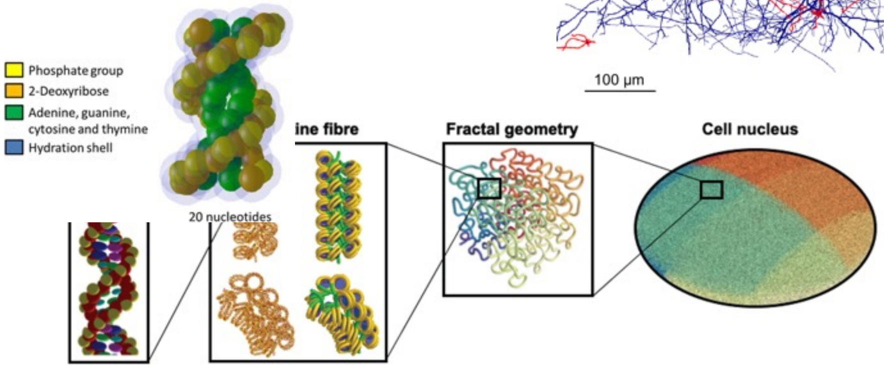
Geometries / Geant4-DNA models (available in examples)

10^{-10} — 10^{-9} — 10^{-6} — [m]

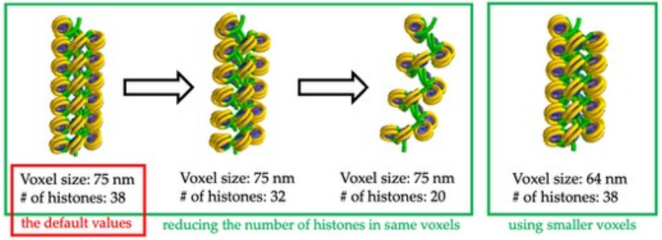
- **Atomic scale**
  - pdb4dna
- **Molecular scale**
  - wholeNuclearDNA
  - dnadamage1,2
  - dsbandrepair
  - molecularDNA
- **Cellular scale or larger**
  - microbeam
  - neuron







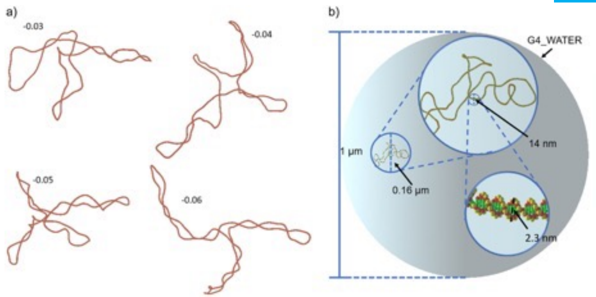
Geometries: library

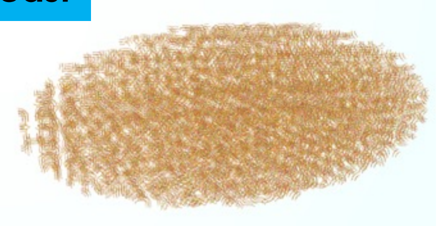


Phage DNA & plasmids

Yeast

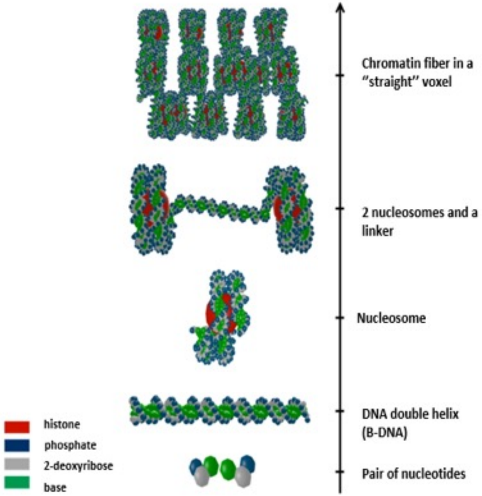
E. coli bacterium

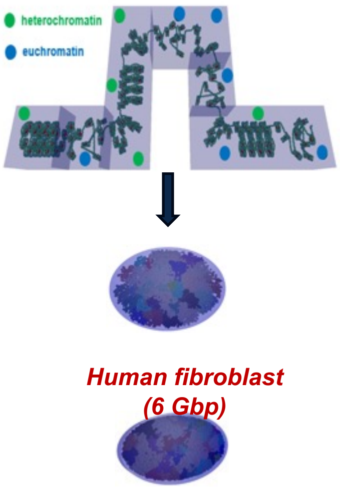




Available in the "moleculardna" and "dsbandrepair" simulation chains

Voxels of chromatin

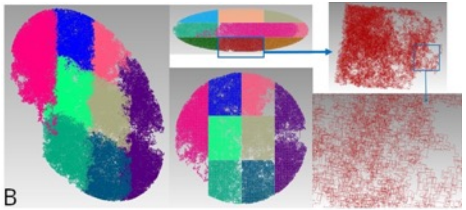


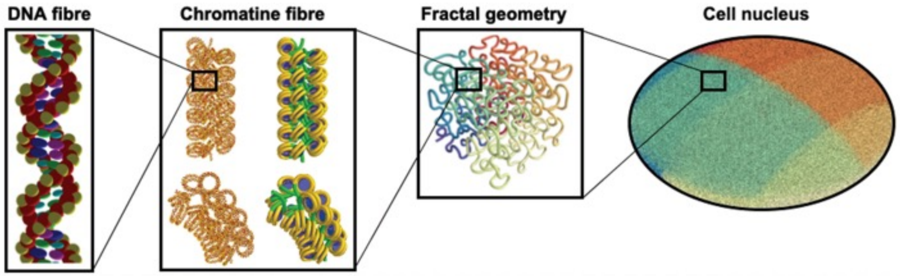


Human fibroblast (6 Gbp)

Human endothelium (6 Gbp)

Various cell nuclei





GEANT4-DNA

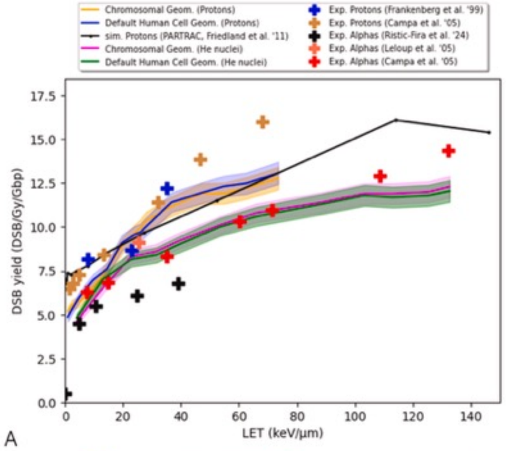
Examples of verification & validation

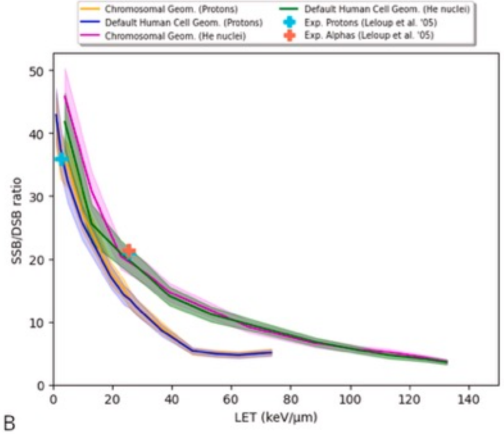
[K. P. Chatzipapas, et al., Prec. Radiat. Oncol. 2023; 7: 4–14]

DSB & SSB/DSB vs LET:

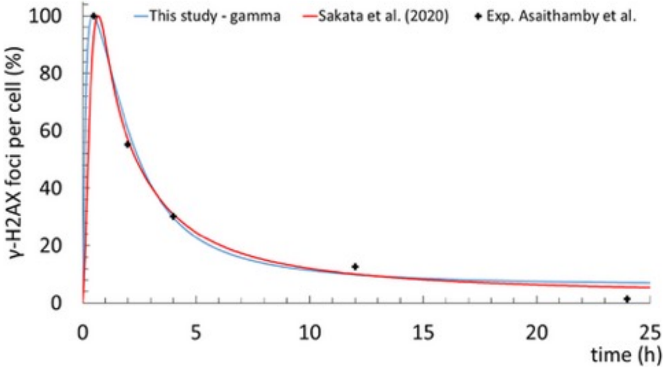
moleculardna & measurements

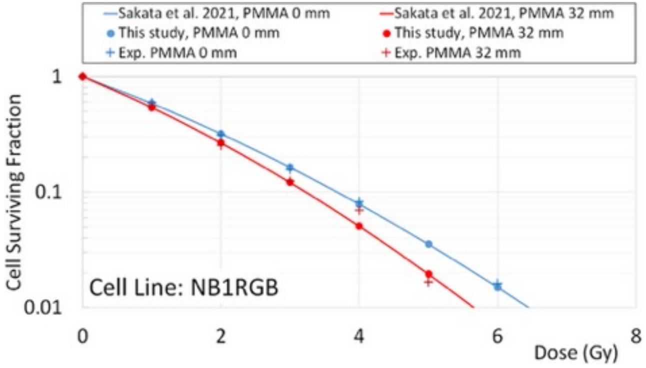
[K. P. Chatzipapas, et al., Phys. Med. 127, 104839, 2024]





Damage repair & cell survival: moleculardna & measurements





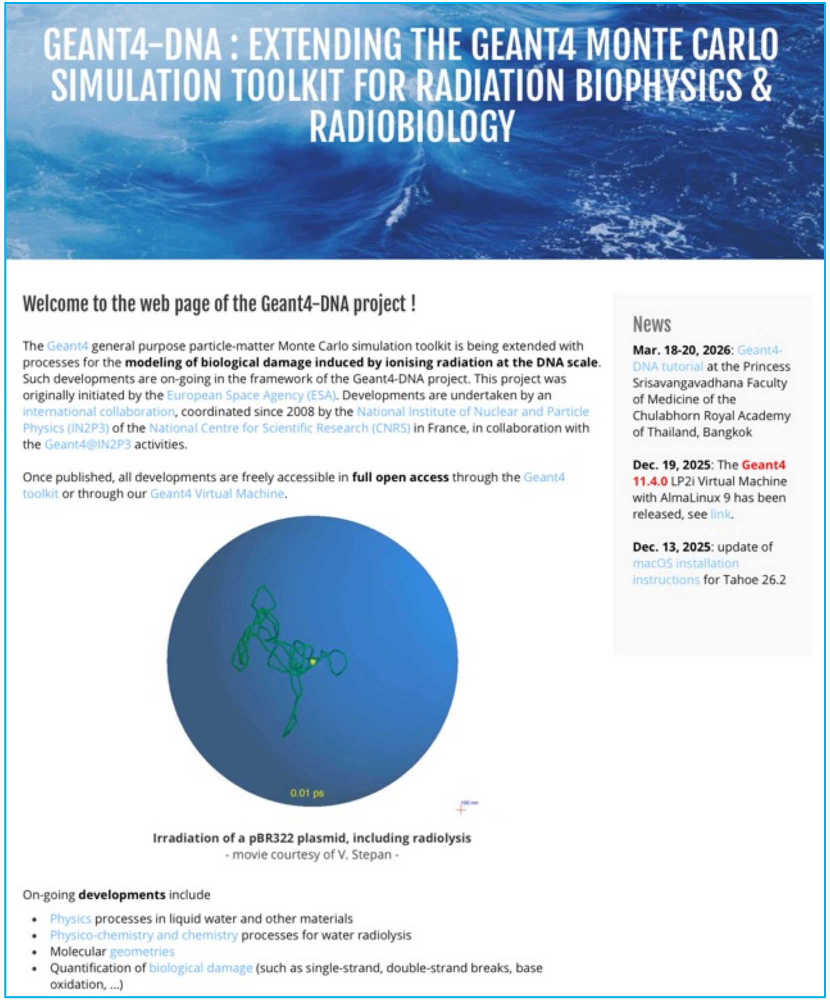
Geant4-DNA: What to expect in the coming years

- Physics
  - Delivery of recently published physics models:
    - **e-** models in **liquid water up to 10 MeV** in option4 constructor (coll. with Ioannina U. et al.)
    - **e-** in **gold** - version 2 in option4 constructor (coll. with Ioannina U. et al.)
    - **e-** in **O2** & **N2** & **CO2** (coll. with Roma U. et al.)
    - **Li** in liquid water (coll. with UCSF, ASNR, CNRS/LP2i et al.)
  - New « **option 7 / cosmicDNA** » constructor (e-, p, ions) (coll. with Wollongong U. et al.)
  - New discrete cross section models for **C in liquid water** ions are under development (coll. UCSF + ASNR + CNRS/LP2i)
  - New discrete e- cross section models for **ice water** under development (coll. with Weizman I. et al.)
  - New set of **physics models from LPCHEM software** (coll. CNRS/IP2i + LP2i + B. Gervais)
  - Removal of older physics constructors
- Chemistry
  - Prototype testing and experimental validation of **multi-pulse radiolysis** (UHDR example) from CONV to UHDR irradiation (coll. CNRS/LP2i & LPCA, VINATOM, INFN, Subatech/Arronax, CHUV)
- Damage prediction
  - Convergence of « dsbandrepair » and « moleculardna » **simulation chains**: common geometries, compatibility with UHDR radiolysis (coll. CNRS/LP2i & ASNR & VINATOM)
  - Additional **geometries of biological models** compatible with the simulation chains (e.g., new cell lines) (coll. with Swinburne U. et al.)
  - Extension of the above chains to **use cases in medical physics** (e.g. new radionuclides, BNCT, hadrons, VHEE, Flash…) (open)
  - Additional **biological repair models** (coll. with D. Sakata et al.)
- Computing
  - We will follow Geant4 strategy (GPU, AI) – under investigation
- **Message: development takes time; e.g., after 20 years, we are still improving Geant4-DNA physics for liquid water! Thank you for your patience.**

Where to find more information ?

https://geant4-dna.org/

Thank you for your attention!



GEANT4-DNA : EXTENDING THE GEANT4 MONTE CARLO SIMULATION TOOLKIT FOR RADIATION BIOPHYSICS & RADIOBIOLOGY

Welcome to the web page of the Geant4-DNA project !

The Geant4 general purpose particle-matter Monte Carlo simulation toolkit is being extended with processes for the **modeling of biological damage induced by ionising radiation at the DNA scale**. Such developments are on-going in the framework of the Geant4-DNA project. This project was originally initiated by the European Space Agency (ESA). Developments are undertaken by an international collaboration, coordinated since 2008 by the National Institute of Nuclear and Particle Physics (IN2P3) of the National Centre for Scientific Research (CNRS) in France, in collaboration with the Geant4@IN2P3 activities.

Once published, all developments are freely accessible in **full open access** through the Geant4 toolkit or through our Geant4 Virtual Machine.

0.01 ps

Irradiation of a pBR322 plasmid, including radiolysis
- movie courtesy of V. Stepan -

On-going **developments** include

- Physics processes in liquid water and other materials
- Physico-chemistry and chemistry processes for water radiolysis
- Molecular geometries
- Quantification of biological damage (such as single-strand, double-strand breaks, base oxidation, ...)

News

Mar. 18-20, 2026: Geant4-DNA tutorial at the Princess Srisavangavadhana Faculty of Medicine of the Chulabhorn Royal Academy of Thailand, Bangkok

Dec. 19, 2025: The Geant4 11.4.0 LP2i Virtual Machine with AlmaLinux 9 has been released, see link.

Dec. 13, 2025: update of macOS installation instructions for Tahoe 26.2