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Heavy-Ion Track Structure and Target Dose Deposition Simulations Using Geant4-DNA

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Heavy ions within the Galactic Cosmic Ray (GCR) spectrum present a primary challenge for radiation risk assessment in deep-space exploration and astroparticle physics. Accurate description of their biological effectiveness requires multi-scale Monte Carlo simulations that account for both nanoscale stochastic ionization patterns and macroscopic energy deposition in target volumes.

In this work, we investigate the performance and applicability of the Geant4 and Geant4-DNA toolkits for modeling the track structure of charged particles, ranging from light ions to intermediate-mass nuclei. Benchmark calculations were conducted for critical physical and nanodosimetric endpoints, specifically Radial Dose Distributions (RDD) and Ionisation Cluster Size Distributions (ICSD), across different particle energies and physics constructors.

In addition, we examine a multi-scale simulation framework to evaluate absorbed dose distributions in target geometries, accounting for particle transport through surrounding structural materials. The impact of the secondary radiation field generated along the beam path on the resulting spatial dose profile is assessed. This study demonstrates the connection between validated nanoscale track-structure metrics and macroscopic dose calculations, providing a robust methodological foundation for radiation transport modeling in space radiobiology.

Primary author(s) : VOLOGZHIN, Matvey (Tomsk State University); IVANTCHENKO, Vladimir (Tomsk State Research University); BATMUNKH, Munkhbaatar (LRB JINR)

Presenter(s) : VOLOGZHIN, Matvey (Tomsk State University)

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