Monte Carlo simulations of biological samples irradiation using a new setup at the 3 MV Tandetron™ of IFIN-HH

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IFIN-HH

Charged particle accelerated beam-based cancer therapy is an accurate radiotherapy technique, very effective in delivering the desired (or expected) doses to target volumes. The improved local control of the beam allows a more efficient sparing of the healthy tissue.

The 3 MV (*I. Burducea et al., 2015*) facility at IFIN-HH has been adapted to be used for charged particle irradiation of biological samples in in vitro radiobiology studies.

To optimize the irradiation protocols, we employed a Monte Carlo object-oriented particle tracking strategy, implemented with the Geant4 simulation toolkit (*Geant4 Collaboration, 2017*).

Subsequent improvements and adaptations were implemented to the Geant4 application *TD3MV@IFIN-HH* in order to ensure a better emulation to the experimental conditions of the radiobiology setup.

Aim of the study

Implementation of a Geant4 application that accurately emulates the radiobiology experimental setup from the 3 MV Tandetron^{TM} of IFIN-HH.

Past implementations and present features of the Geant4 simulation code for the Tandetron 3MV (*TD3MV@IFIN-HH*)

TD3MV@IFIN-HH Version I

Base code: Geant4 example B1

Primary source: built using
G4GeneralParticleSource
Disc shaped source with an intrinsic Gaussian distribution
Scoring volume:
Supports energy distribution calculations at the surface of the target volume and beam profiling along diameter

TD3MV@IFIN-HH Version II

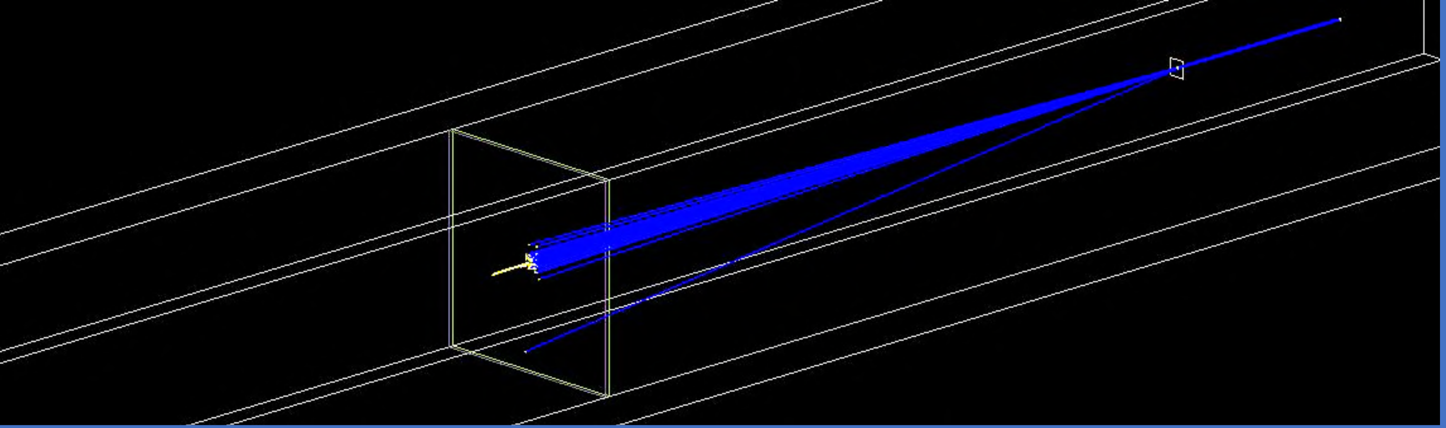
Base code: Geant4 TestEm7

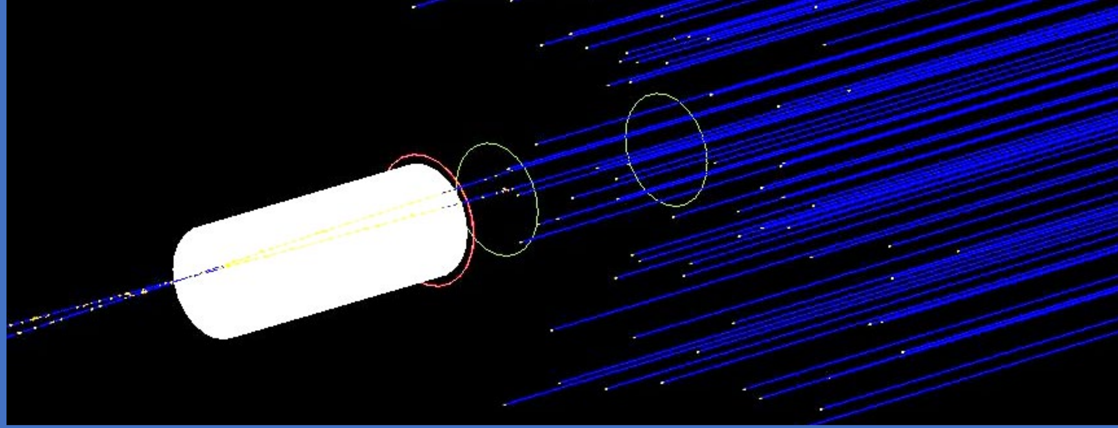
Scoring volume:
Consists of replicas along the beam propagation axis in which the Bragg peak can be determined
Provides advanced control of the in-depth scoring resolution.
Physics list:
Electromagnetic option 4 physics lists, (V. Beaudoux et al., 2019; Y. Wang et al., 2019).

TD3MV@IFIN-HH Version III *(present version)*

Base code: original code

Primary source: reverted to
G4ParticleGun
Disc shaped randomized source distribution weighted by a Gaussian distribution
Scoring volume:
Added intertwined test volumes for fluence scoring, used to compute the LET inside the target volume
Physics list: modular (user set)
Supports more Geant4 physics lists





3 MV Tandetron^{TM} simulation parameters

Two envelope volumes representing – vacuum tube and air section

Vacuum tube

- **Particle source – G4ParticleGun**
  Disc shaped randomized source distribution weighted by a Gaussian distribution
  Mono energetic channel energy of 3 MeV for protons (8.5 MeV for alpha)
  Energy spread of 5 keV for protons (15 keV for alpha)
- **Thin gold/aluminum foil** *used to scatter the protons along the beam propagation axis with a high/low fluence.*

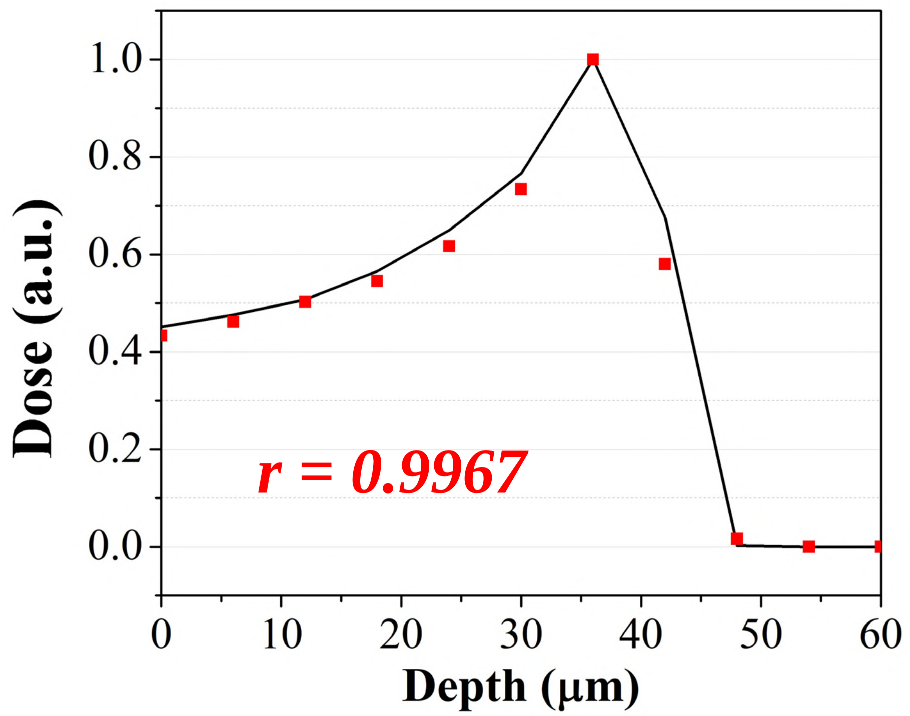
Thick graphite *collimator with a 6 mm in diameter circular window*
1 µm thick Si_3N_4 window

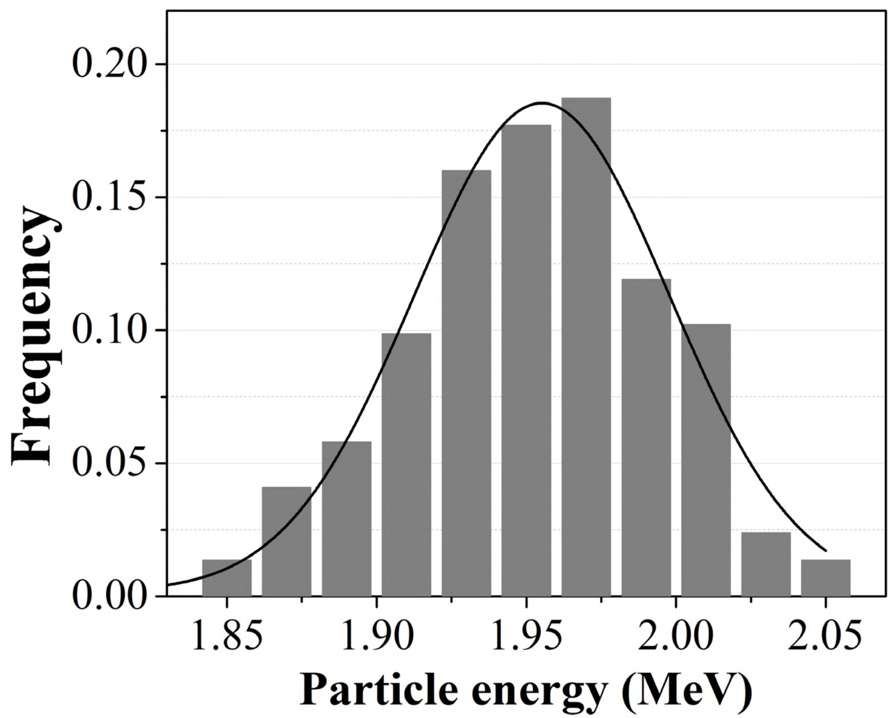
Material compositions and physical parameters were obtained from the NIST material database. The **physical processes** inside the volumes were described using the **electromagnetic option 4** physics lists constructor with default parameters. It is classified as the most accurate model for standard and low-energy simulations (*V. Beaudoux et al., 2019; Y. Wang et al., 2019*).

Air section

- **Mylar layer**
  6 µm thickness and 7 mm diameter as support for cell culture
- **1 µm thick water scoring volume**
  Diameter of 6 mm.
  LET in replicas of volume, generated horizontally along the beam line up to 100 times (1 µm Bragg peak resolution).
- **0.1 µm thick intertwined test volumes** *for fluence scoring.*
  Diameter of 6 mm.

Simulation of proton beam irradiation at 3 MV Tandetron™ facility

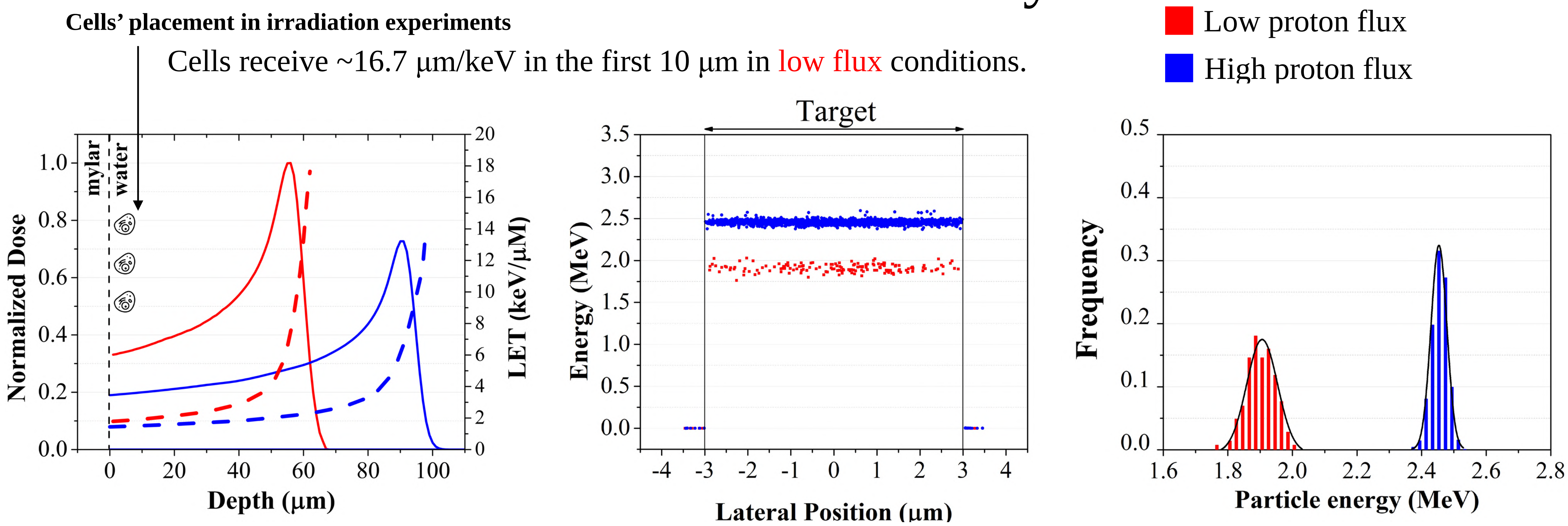




GEANT4 simulation of the proton beam Bragg peak in water against experimental data acquired using the Markus detector and the energy distribution of the alpha particles beam at the mylar-water interface (mean energy = 1.95 MeV, FWHM = 104.2 keV)

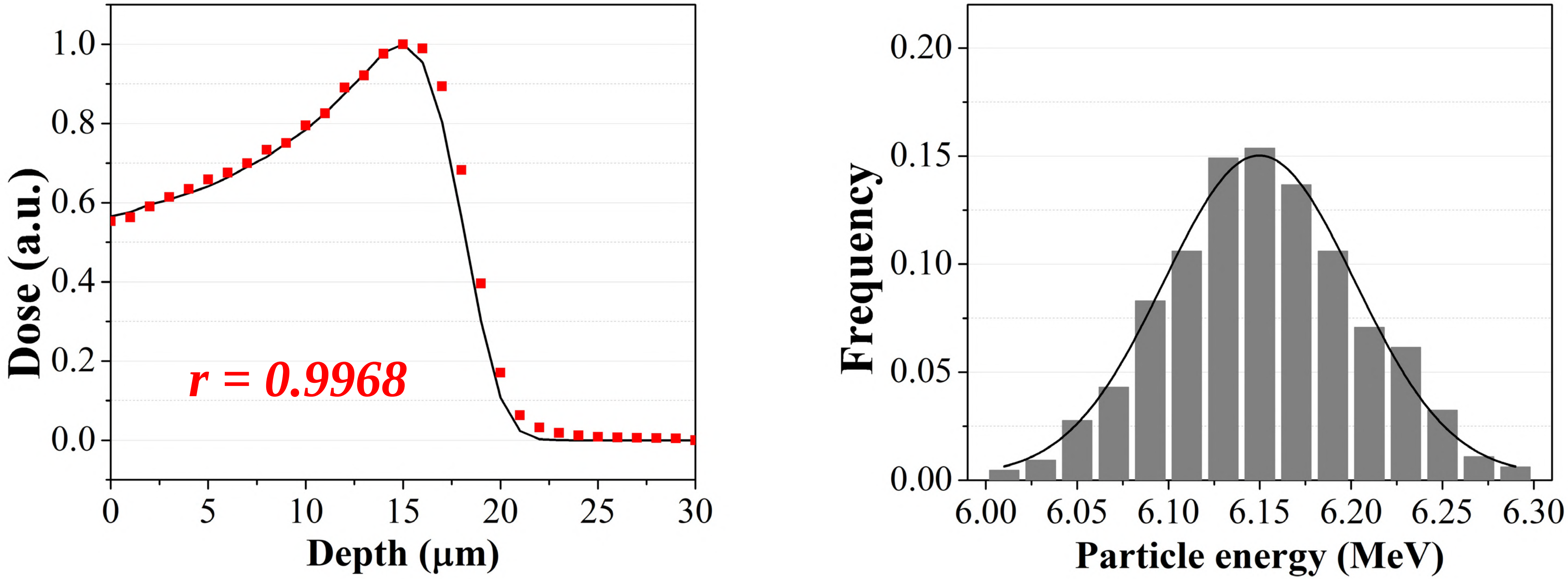
Simulation of high and low flux proton irradiation at 3 MV Tandetron^{TM} facility

Cells receive ~16.7 µm/keV in the first 10 µm in low flux conditions.



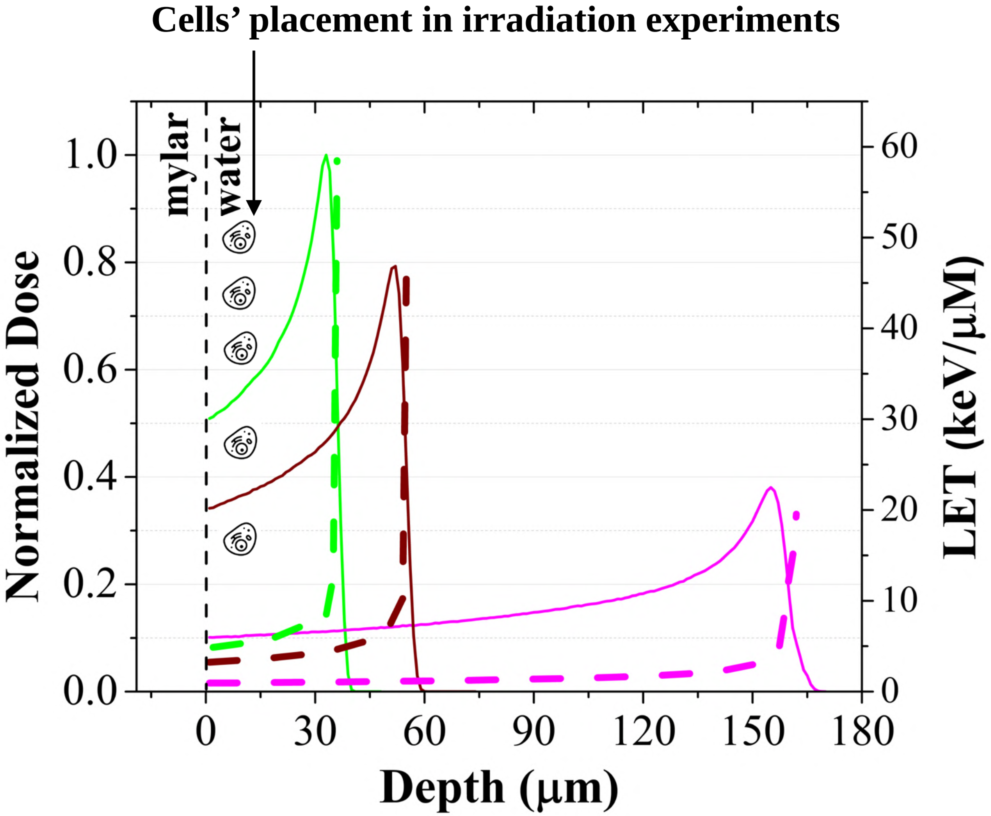
GEANT4 simulation of Bragg peaks and LET profiles in water, simulated energy profiles along the diameter at the air target interface and energy distributions of the high and low flux proton beams at the mylar-water interface. (mean energy = 1.9 MeV – low flux, 2.45 MeV – high flux, FWHM = 104.02 keV – low flux, 56.18 keV – high flux)

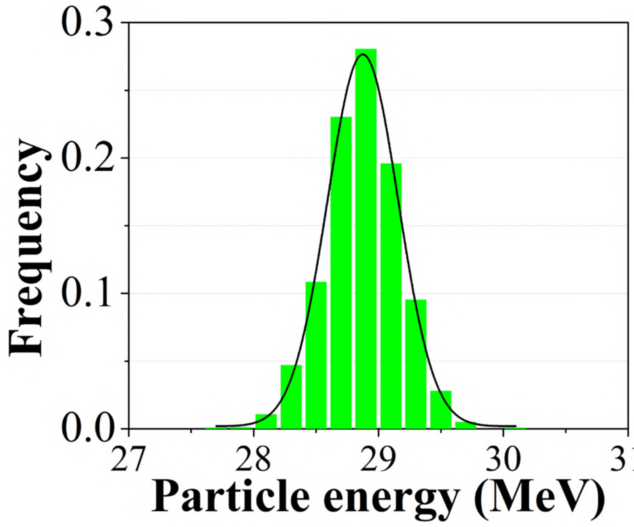
Simulation of alpha particle beam irradiation at 3 MV Tandetron^{TM} facility

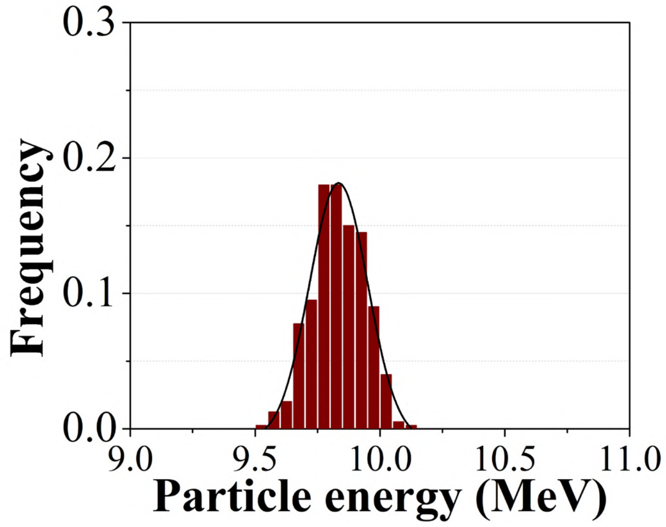


GEANT4 simulation of alpha particles Bragg peak in water against experimental data acquired using the Markus detector and the energy distribution of the alpha particles beam at the mylar-water interface (mean energy = 6.15 MeV, FWHM = 123 keV)

Simulation of heavy ion beams irradiation at a future radiobiology setup for the 9 MV Van de Graaff Tandem from IFIN-HH



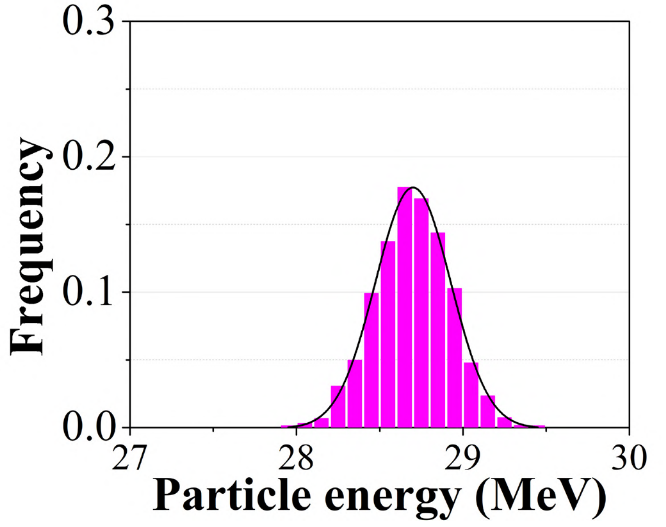




56 MeV $^{12}C^{6+}$

48 MeV $^{11}B^{5+}$

32 MeV $^{7}Li^{3+}$



GEANT4 simulation of heavy ion beams Bragg peaks and LET in water and the energy distributions at the mylar-water interface

mean energy = 28.75 MeV – $^{7}Li^{3+}$, 9.8 MeV – $^{11}B^{5+}$, 28.9 MeV – $^{12}C^{6+}$

FWHM = 523.62 keV – $^{7}Li^{3+}$, 245.14 – $^{11}B^{5+}$, 679.63 – $^{12}C^{6+}$

Conclusions and perspectives

- Geant4 simulations proved to be useful in validating the feasibility of heavy ions irradiation experiments from 3 MV accelerator.
- The Geant4 simulations also assisted us in calculating the energy ranges of heavy ion beams. The heavy ion beams simulation will be helpful when the entire setup will be moved to the 9 MV Van de Graaff Tandem accelerator of IFIN-HH.
- The *TD3MV@IFIN-HH* simulation code provides a high-fidelity representation of the geometry, source parameters and physical processes, as well as flexible dose, LET and energy estimations.
- Future implementation of the application should feature an option for a user-defined modular physics list, providing a more detailed description of physical processes