

# Optimization of GEANT4/GATE hadronic models for in-beam PET dose monitoring in carbon ion therapy



Charlotte Robert<sup>1</sup>, Loïc Lestand<sup>2</sup>, Gérard Montarou<sup>2</sup>, Paul Force<sup>2</sup>, Nicoleta Pauna<sup>2</sup> and Irène Buvat<sup>1</sup>  
<sup>1</sup> Unité Imagerie et Modélisation en Neurobiologie et Cancérologie, CNRS UMR 8165, F-91406, Orsay Cedex France  
<sup>2</sup> Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, BP 10448, F-63000 Clermont-Ferrand



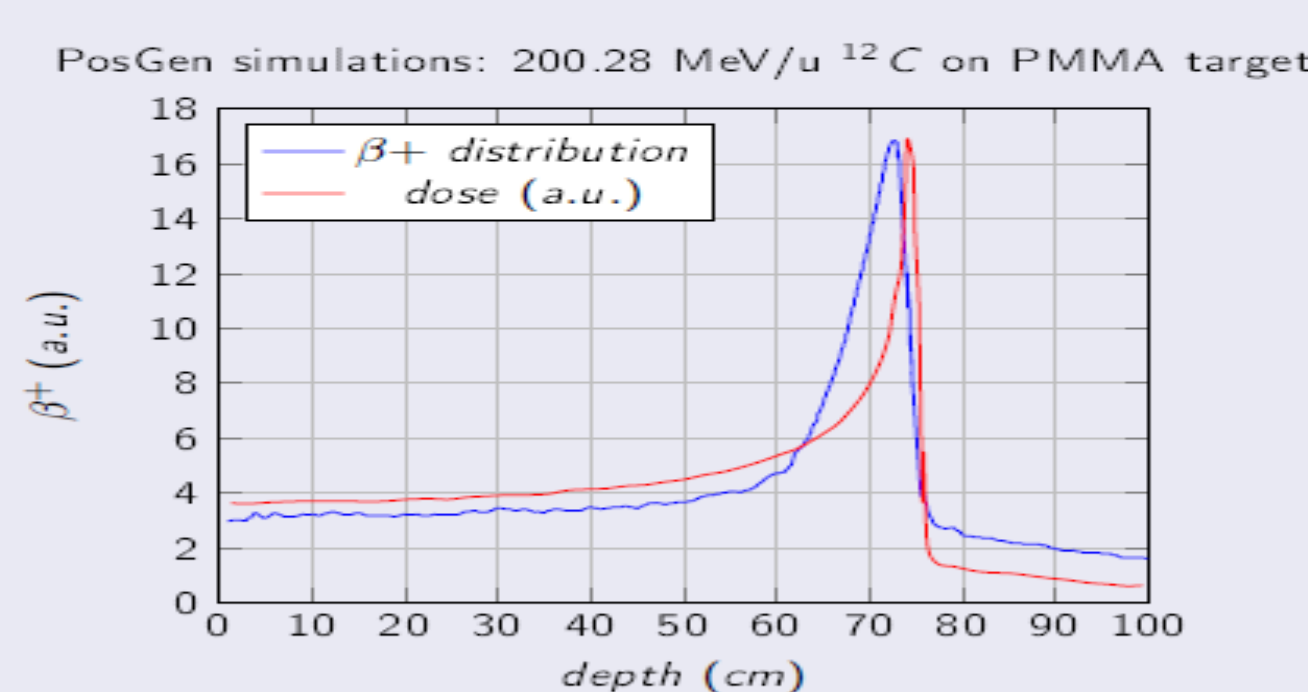
The GATE simulation toolkit (GATE v6) based on GEANT4 v9.4 has all the necessary features to model in-beam Positron Emission Tomography (PET). In this work, we characterize the accuracy of the physics models included in GEANT4 v9.4 to describe  $\beta^+$  emissions induced by  $^{12}\text{C}$  ion beam that give rise to the detected signal in in-beam PET monitoring of carbon ion therapy.

## Carbon ion therapy

Carbon ion therapy is a new type of radiotherapy treatment for cancer using Carbon ion beams. It is especially appealing for radioresistant tumors or tumors close to organs at risk.

## Principle of in-beam PET monitoring

- Primary ions interact through nuclear collisions with the target
- Among the secondary particles resulting from these interactions,  $\beta^+$  emitters are produced ( $^{10}\text{C}$  ( $T_{1/2} \sim 20$  s),  $^{11}\text{C}$  ( $T_{1/2} \sim 20$  min) and  $^{15}\text{O}$  ( $T_{1/2} \sim 2$  min) mostly)
- The  $\beta^+$  activity spatial distribution is closely correlated to the dose distribution



- Treatment monitoring: beam induced  $\beta^+$  activity map is measured using PET
- 📄 P.CRESPO PhD Thesis 2005

## GEANT4 and GATE toolkits

- GEometry ANd Tracking (GEANT4) is a toolkit dedicated to the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, and studies in medical and space science.
- GEANT4 Application for Emission Tomography (GATE) is an advanced open-source software developed by the international OpenGATE collaboration and dedicated to numerical simulations in medical imaging and radiotherapy.
  - ⇒ It encapsulates the Geant4 libraries in a modular versatile, scripted simulation software

- 📄 Agostinelli *et al.* GEANT4, a simulation toolkit. NIM A 506 (2003) 250-303
- 📄 Allison *et al.* Geant4 developments and applications. IEEE Trans. Nucl. Sci 53 (2006) 270-278
- 📄 Jan *et al.* GATE V6: a major enhancement of the GATE simulation platform enabling modelling of CT and radiotherapy. Phys. Med. Biol. 56 (2011) 881-901
- 📄 Jan *et al.* GATE: a simulation toolkit for PET and SPECT. Phys. Med. Biol. 49 (2004) 4543-4561
- 📄 <http://www.opengatecollaboration.org>

## Hadronic models

Two models suitable for nuclear collision description are available in GEANT4 v9.4: Binary Cascade (BiC) and Quantum Molecular Dynamics (QMD) models.

## Methods

Experimental and simulated production rates were compared considering a  $^{12}\text{C}$  beam in a  $30 \times 10 \times 10 \times \text{cm}^3$  PMMA target, with beam energy of 212.12 MeV/u, 259.5 MeV/u and 343.46 MeV/u. The relative deviation between experimental yield  $\mathcal{Y}$  and simulated yield  $\mathcal{Y}_{model}$  was calculated as  $\epsilon_{model} = \frac{|\mathcal{Y} - \mathcal{Y}_{model}|}{\mathcal{Y}}$ .

- green values correspond to relative deviation  $< 20\%$
- orange values correspond to relative deviation between 20% and 40%
- red values correspond to relative deviation  $> 40\%$

Experimental and simulated production rates as a function of depth were compared considering a  $^{12}\text{C}$  beam in a  $30 \times 10 \times 10 \times \text{cm}^3$  PMMA target, with beam energy of 215 MeV/u, 260 MeV/u and 337 MeV/u. Only shapes of the profiles were considered.

## $\beta^+$ production rate

The table below shows the integrated production rates over the whole PMMA target

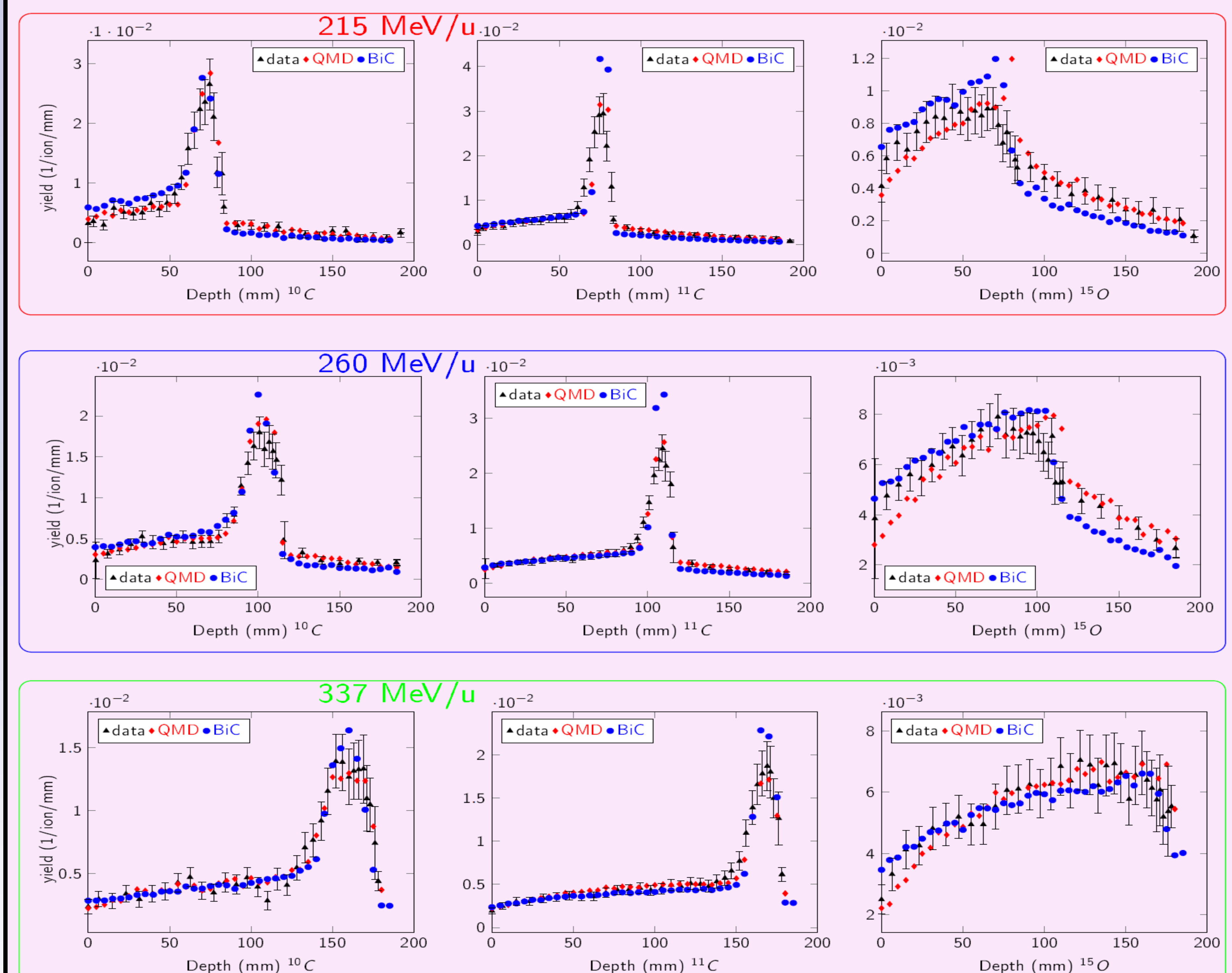
Beam Energy [MeV/u]	$\mathcal{Y}$ [ $10^{-2}$ /ion][1]	$\epsilon_{QMD}$ [%]	$\epsilon_{BiC}$ [%]
212.12 MeV/u	$(0.8 \pm 0.03)$	25	200
$^{10}\text{C}$			
$^{11}\text{C}$	$(10.5 \pm 1.3)$	15	18
$^{15}\text{O}$	$(2.1 \pm 0.3)$	5	22
259.5 MeV/u	$\mathcal{Y}$ [ $10^{-2}$ /ion][1]	$\epsilon_{QMD}$ [%]	$\epsilon_{BiC}$ [%]
$^{10}\text{C}$	$(1.2 \pm 0.3)$	16	46
$^{11}\text{C}$	$(14.7 \pm 1.6)$	12	20
$^{15}\text{O}$	$(3.1 \pm 0.4)$	6	35
343.46 MeV/u	$\mathcal{Y}$ [ $10^{-2}$ /ion][1]	$\epsilon_{QMD}$ [%]	$\epsilon_{BiC}$ [%]
$^{10}\text{C}$	$(1.5 \pm 0.3)$	53	46
$^{11}\text{C}$	$(19.9 \pm 2.4)$	5	12
$^{15}\text{O}$	$(5 \pm 0.4)$	18	16

⇒ For most experimental data, QMD model yields more accurate results than BiC model

📄 [1] K.Parodi *et al.* PhD Thesis 2004.

## $\beta^+$ emitter yields as a function of depth in a PMMA target

The plots below show the production rate as a function of depth in a PMMA target



⇒ For most profiles QMD model better reproduces the experimental data than the BiC model

📄 Data shared in the framework of WP6 ENVISSION European project.

## Conclusions

- The QMD nuclear collision model included in GEANT4 v9.4 accurately reproduces the  $\beta^+$  production rates experimentally measured as a function of depth for different  $^{12}\text{C}$  beam energies
- GATE/GEANT4 appears as a promising tool to accurately model in-beam PET monitoring of carbon ion treatment and to study the potential of this innovative treatment monitoring approach