vpgTLE GATE Actor:

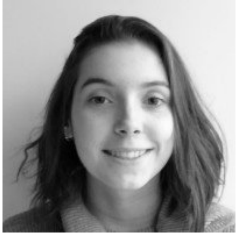
Track-Length Estimator for MC simulations of the Prompt-Gamma emission sources in proton therapy

Jean Michel Létang

Ion Imaging Workshop 2025, Firenze

Disclaimer

Part of this presentation is based on the work of **Violette Guittet** during her MSc internship at CREATIS, and co-supervised by Étienne Testa.



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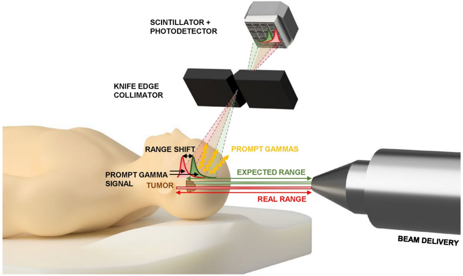
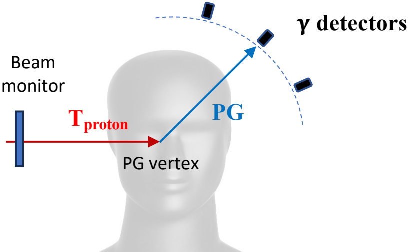
(MSc)

Étienne Testa
(Associate Professor)

Radiation therapy

Range monitoring with Prompt Gamma[3]





⇒ Need of MC simulations to design detection stages:

- Prompt-Gamma Time-of-flight Imaging ARrAy (TIARA)[1], PbF_2, 100ps RMS
- Prompt-Gamma Energy Integration (PGEI)[2], $PbWO_4$

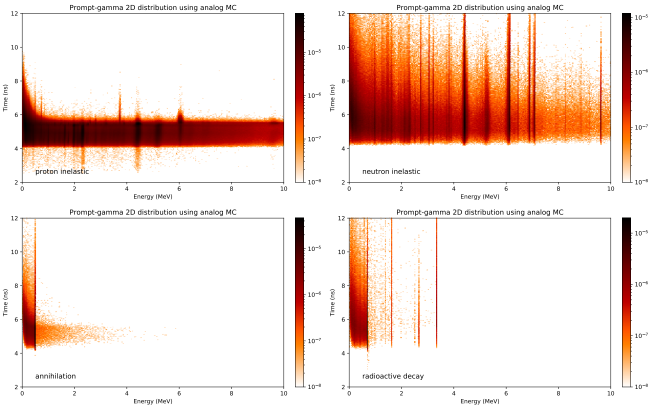
[1] M Jacquet et al. "A high sensitivity Cherenkov detector for prompt gamma timing and time imaging". In: Scientific Reports 13.1 (Mar. 2023). DOI: 10.1038/s41598-023-30712-x.

[2] P Everaere et al. "Prompt gamma energy integration: a new method for online-range verification in proton therapy with pulsed-beams". In: Frontiers in Physics 12 (June 2024). ISSN: 2296-424X. DOI: 10.3389/fphy.2024.1371015.

[3] A B Idrissi et al. "First experimental verification of prompt gamma imaging with carbon ion irradiation". In: Scientific Reports 14.1 (Oct. 2024). ISSN: 2045-2322. DOI: 10.1038/s41598-024-72870-6.

Gamma sources

Origins: protontherapy example from H & N treatment plan[4]

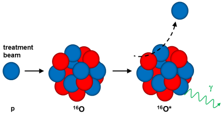


⇒ Mainly from **nuclear inelastic** interaction of **proton** and **neutron**

[4] J M Létang, O Allegrini, and É Testa. "Prompt-gamma timing with a track-length estimator in proton therapy". In: XXth International Conference on the use of Computers in Radiation therapy. 2024, pp. 584–587.

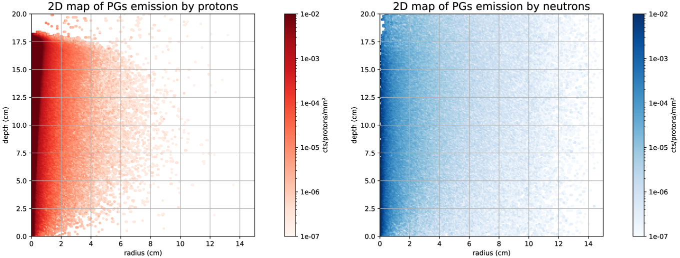
Prompt-Gamma sources

Protontherapy: Proton *vs* Neutron[5]



Nuclear inelastic interaction of **proton** and **neutron**
NB: other projectiles and their product species for hadron therapy with heavier ions (He-, C-ion).

PG spatial distribution (radial slice) with protons at 160MeV in a water tank from proton and neutron:

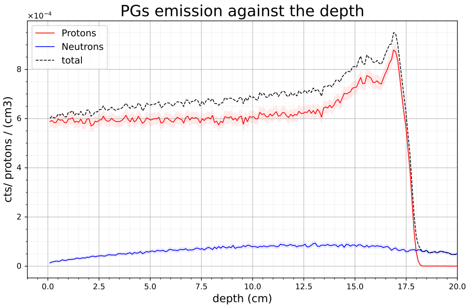


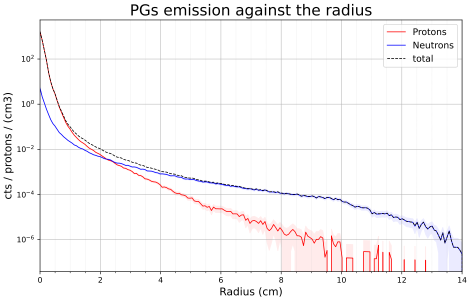
[5] V Guittet. "**Extension du module hybride d'émission des rayons γ prompts en protonthérapie dans le code Monte Carlo GATE pour prendre en compte les neutrons secondaires**". MSc Report (Med. Phys.) Université de Rennes, 2025.

Prompt-Gamma sources

Protontherapy: Proton *vs* Neutron[6]

Depth (left) and radial (right) PG emission distribution from proton and neutron in a water tank:





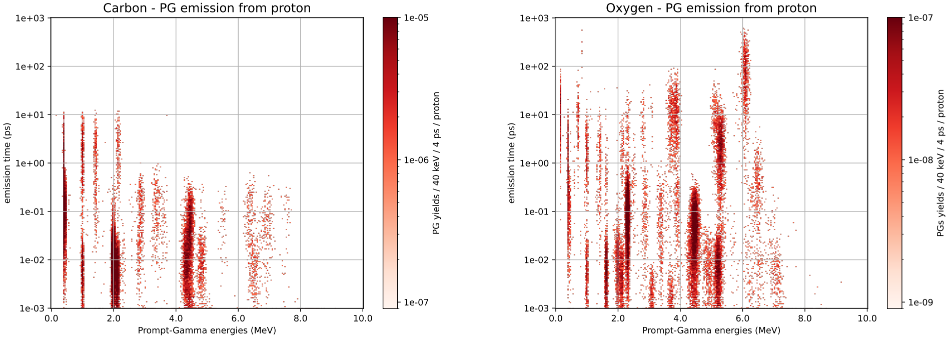
⇒ Neutron-induced PG becomes predominant:

- after the BP along the beam
- and a few cm away from the beam

[6] V Guittet. "**Extension du module hybride d'émission des rayons γ prompts en protonthérapie dans le code Monte Carlo GATE pour prendre en compte les neutrons secondaires**". MSc Report (Med. Phys.) Université de Rennes, 2025.

Prompt-Gamma sources
Decay Promptness[7]

Nuclear de-excitation gamma-ray lines from proton processes



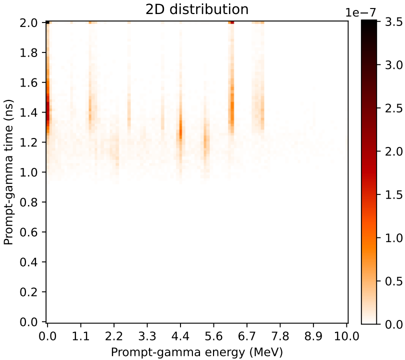
⇒ Negligible decay-time but correlated to gamma-ray energy

[7] V Guittet. "Extension du module hybride d'émission des rayons γ prompts en protonthérapie dans le code Monte Carlo GATE pour prendre en compte les neutrons secondaires". MSc Report (Med. Phys.) Université de Rennes, 2025.

Prompt-Gamma sources

2D (energy & time) distribution: p@130MeV in water[8]

2D PG yield in a $(2\text{mm})^3$ voxel at BP depth in water, but 2 cm away from it laterally.



⇒ Is it necessary/possible to store a 2D PG yield distribution at each voxel?

[8] V Guittet. "**Extension du module hybride d'émission des rayons γ prompts en protonthérapie dans le code Monte Carlo GATE pour prendre en compte les neutrons secondaires**". MSc Report (Med. Phys.) Université de Rennes, 2025.

Prompt-Gamma sources

2D representation: energy & time distribution sampling[9]

Prompt-Gamma source sampling:

- space: 10cm $\times$ 10cm $\times$ 20cm with a $(2\text{mm})^3$ sampling: **250 000** voxels
- time: 10ns time range at 10ps: **1000** time samples
- energy: 10MeV energy range at 10keV: **1000** energy samples

Two solutions:

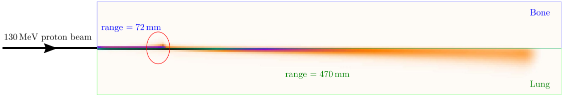
- **5D** PG distributions at each voxel: 3D space $\times$ 1D energy $\times$ 1D time:
  $\rightarrow$ 250×10^9 samples at double precision: **2TB** file
- Two **4D** PG distributions at each voxel: 3D space $\times$ (1D energy $+$ 1D time):
  $\rightarrow$ $2 \times 250 \times 10^6$ samples at double precision: **4GB** file

$\Rightarrow$ Check separability between PG emission time and energy

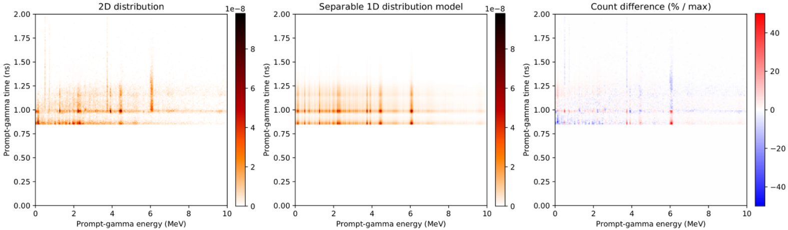
[9] V Guittet. "**Extension du module hybride d'émission des rayons γ prompts en protonthérapie dans le code Monte Carlo GATE pour prendre en compte les neutrons secondaires**". MSc Report (Med. Phys.) Université de Rennes, 2025.

Prompt-Gamma sources

Separability PG emission time *vs* energy[10]



For a $(2\text{mm})^3$ bone voxel at 70mm depth:

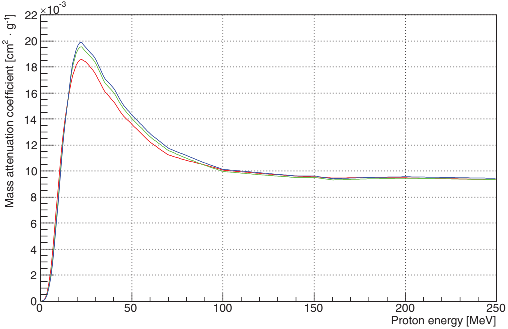


⇒ **Acceptable separability** of PG emission time and energy (except for some γ lines)

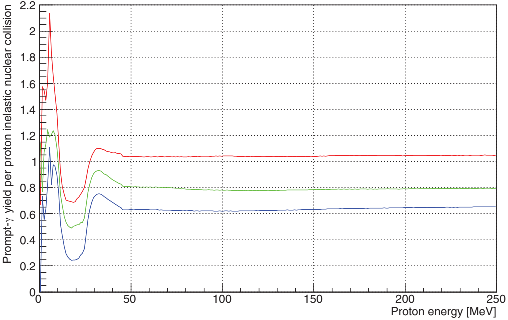
[10] J M Létang, O Allegrini, and É Testa. "**Prompt-gamma track-length estimator with time tagging from proton tracking**". In: Physics in Medicine and Biology 69.11 (2024), 115052:1–10. DOI: 10.1088/1361-6560/ad4a01.

Monte Carlo simulation

Computation of the 2 × 4D PG source[11]



Mass attenuation coefficient
Bone – Lung – Muscle



Total PG yield
Bone – Lung – Muscle

1% PG / proton / cm ⇒ Rare event: VRT necessary

[11] W El Kanawati et al. "Monte Carlo simulation of prompt γ-ray emission in proton therapy using a specific track length estimator". In: Physics in Medicine and Biology 60.20 (2015), pp. 8067–8086. DOI: 10.1088/0031-9155/60/20/8067.

Sidestep: Dose calculation
TLE for Kerma approximation[14]

Dose (monoenergetic x-ray beam E) at pixel $\mathbf{x}$:

$$D(\mathbf{x}) = \underbrace{\Phi(\mathbf{x})}_{\text{Fluence}} \times E \times \underbrace{\mu_{en}(E, \mathbf{x})}_{\to\text{DataBase}} \times \frac{1}{\rho(\mathbf{x})}$$

where

- the linear energy-absorption coefficient μ_{en} must be computed via MC calculations (or approximated from NIST database[12])
- and the particle fluence $\Phi \equiv$[13] the total particle path length $\sum_k L_k$ per volume V

$$\Phi(\mathbf{x}) = \frac{\sum_k L_k(\mathbf{x})}{V(\mathbf{x})}$$

$\Rightarrow$

- Linear **Track Length Estimator** (TLE) for fluence
- Need to build a **PG yield database**

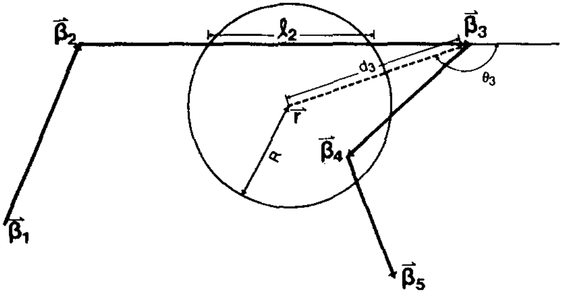
[12] https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

[13] G A Carlsson. "The dosimetry of ionizing radiation". In: vol. 1. Academic Pr, 1986. Chap. Theoretical Basis for Dosimetry. ISBN: 978-0-12-400401-6.

[14] Jeffrey F Williamson. "Monte Carlo evaluation of kerma at a point for photon transport problems". In: Medical Physics 14.4 (1987), pp. 567–576.

Track-Length Estimator (TLE)

Kerma estimation[15]



- Analog MC: discrete process attached to particle interactions
- TLE: continuous process attached to particle in transportation

[15] Jeffrey F Williamson. "Monte Carlo evaluation of kerma at a point for photon transport problems". In: Medical Physics 14.4 (1987), pp. 567–576.

Track-Length Estimator (TLE)

vpgTLE: voxellized Prompt-Gamma TLE[16]

The TLE variation for Prompt-Gamma energy source computation at voxel $\mathbf{x}$:

$$\mathbf{E}_{pg}(\mathbf{x}) = \sum_{i=1}^{N_{\text{steps}}} \sum_{p=1}^{N_{\text{energies}}} L_i(E_p, \mathbf{x}) \times \mathbf{\Gamma}_{m(\mathbf{x})}(E_p)$$

where

- $L_i(E_p, \mathbf{x})$ is the length of the step i in voxel $\mathbf{x}$ et particle energy E_p.
- $\mathbf{\Gamma}_{m(\mathbf{x})}(E_p)$ is the 1D PG energy distribution per unit length for material $m(\mathbf{x})$ and particle energy E_j,

Nota Bene: the PG database $\mathbf{\Gamma}_m$ is not scene dependent and can be built **offline** for each material m and each particle type (proton, neutron...).

$$\mathbf{\Gamma}_m(E_p) = \mathbf{N}_{m,\gamma}(E_p) \frac{\kappa_{m,\text{inel}}(E_p)}{N_{m,\text{inel}}(E_p)}$$

[16] W El Kanawati et al. "Monte Carlo simulation of prompt γ-ray emission in proton therapy using a specific track length estimator". In: Physics in Medicine and Biology 60.20 (2015), pp. 8067–8086. DOI: 10.1088/0031-9155/60/20/8067.

vpgTLE

PG database $\mathbf{\Gamma}_{\mathrm{m(x)}}(E_p)$: error analysis[17]

$$\mathbf{E}_{pg}(\mathbf{x}) = \sum_{i=1}^{N_{\mathbf{steps}}} \sum_{p=1}^{N_{\mathbf{energies}}} L_i(E_p, \mathbf{x}) \times \mathbf{\Gamma}_{m(\mathbf{x})}(E_p)$$

Error types and sources:

$L_i(E_j, \mathbf{x})$: **statistical** error

$$\text{statistical relative variance} \propto \frac{\sigma^2(L(\mathbf{x}))}{n(\mathbf{x})\ \bar{L}_n^2(\mathbf{x})}$$

$\Rightarrow$ fast convergence (on the primary particle track), low stat sufficient

$\mathbf{\Gamma}_{m(\mathbf{x})}(E_j)$: **systematic** error

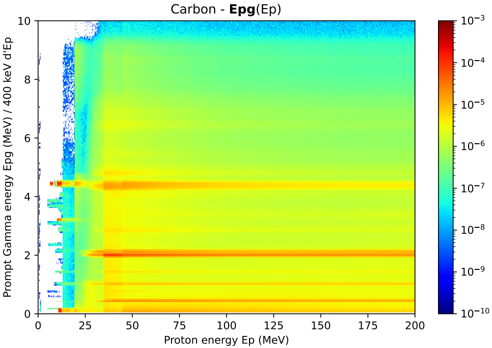
$$\text{systematic relative variance} \propto \frac{1}{N_{m(\mathbf{x}),\gamma}(E_p, E_\gamma)}$$

with $N_{m(\mathbf{x})}(E_p, E_\gamma)$ the nr of PG scored for particle energy E_p in the PG energy bin E_γ for material $m(\mathbf{x})$ $\Rightarrow$ high stat required.

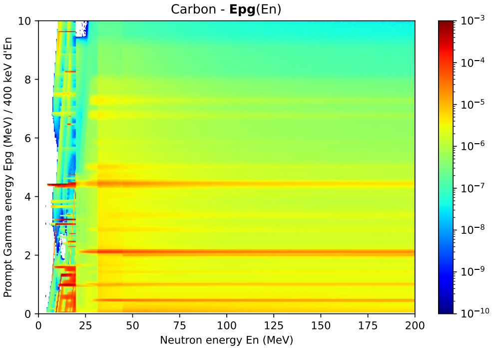
[17] W El Kanawati et al. "Monte Carlo simulation of prompt γ-ray emission in proton therapy using a specific track length estimator". In: Physics in Medicine and Biology 60.20 (2015), pp. 8067–8086. DOI: 10.1088/0031-9155/60/20/8067.

vpgTLE

PG database $\boldsymbol{\Gamma}_{\mathbf{m(x)}}(E_p)$: examples[18]



proton



neutron (HP)

Each column of $\boldsymbol{\Gamma}_{\mathbf{m(x)}}(E_p)$ (indexed by the particle energy E_p) is the **1D PG-energy emission yield**.

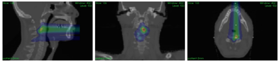
$\Rightarrow$ Root file format (JSON too large)

[18] V Guittet. "**Extension du module hybride d'émission des rayons γ prompts en protonthérapie dans le code Monte Carlo GATE pour prendre en compte les neutrons secondaires**". MSc Report (Med. Phys.) Université de Rennes, 2025.

vpgTLE

PG source calculation: online protocol[19]

For a given scene: (eg from a TPS)



Computation of the two 4D PG yield sources: At **each step** i

Energy: Increment the 1D PG energy distribution at voxel $\mathbf{x}$ with

$$\mathbf{E_{pg}}(\mathbf{x}) \mathrel{+}= L_i(E_p, \mathbf{x}) \times \mathbf{\Gamma_{m(x)}}(E_p)$$

where E_p is the particle energy, sampled randomly along its step.

Time: Increment 1 sample of the 1D PG time distribution at voxel $\mathbf{x}$ with

$$\mathbf{t_{pg}}(\mathbf{x}, t_p) \mathrel{+}= L_i(E_p, \mathbf{x}) \times \left(\sum_{E_{pg}} \Gamma_{m(\mathbf{x})}(E_p, E_{pg}) \right)$$

where t_p is the **particle** time, sampled randomly along its step.
($\Rightarrow$ Nuclear de-excitation time neglected)

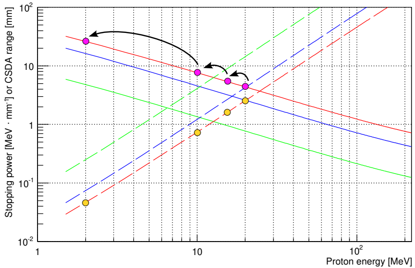
[19] W El Kanawati et al. "Monte Carlo simulation of prompt γ-ray emission in proton therapy using a specific track length estimator". In: Physics in Medicine and Biology 60.20 (2015), pp. 8067–8086. DOI: 10.1088/0031-9155/60/20/8067.

vpgTLE

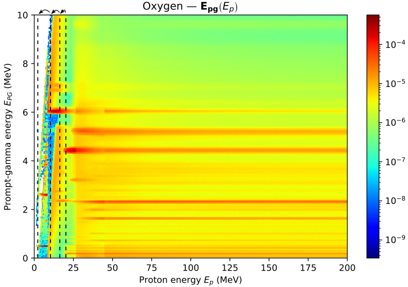
Aliasing in PG database reading[20]

With a 1mm-step for protons at 20MeV in bone:

- dE/dx(p@20MeV) = 4.5 MeV/mm,
- CSDA(p@20MeV) = 2.5 mm in bone.



SP (solid) and CSDA (dashed) for bone, muscle and lung



PG database $\mathbf{\Gamma}_{\text{oxygen}}(E_p)$ (45% in bone)

⇒ Discontinuities in PG production: possible **aliasing** in DB reading: ⚠ step limiter).

[20] W El Kanawati et al. "Monte Carlo simulation of prompt γ-ray emission in proton therapy using a specific track length estimator". In: Physics in Medicine and Biology 60.20 (2015), pp. 8067–8086. DOI: 10.1088/0031-9155/60/20/8067.

vpgELE
Energy-Loss variant[21]

Instead of the standard vpgTLE

$$\mathbf{E_{pg}}(\mathbf{x}) \mathrel{+}= \int_{r=r_{\mathbf{in}}(\mathbf{x})}^{r_{\mathbf{out}}(\mathbf{x})} \mathbf{\Gamma}_{\mathbf{m}(\mathbf{x})}\left(E_p(r)\right) \mathrm{d}r$$

an Energy-Loss Estimator can be derived (vpgELE)

$$\mathbf{E_{pg}}(\mathbf{x}) \mathrel{+}= \int_{E_p=E_{\mathbf{in}}(\mathbf{x})}^{E_{\mathbf{out}}(\mathbf{x})} \frac{\mathbf{\Gamma}_{\mathbf{m}(\mathbf{x})}\left(E_p\right)}{S(E_p)} \mathrm{d}E_p$$

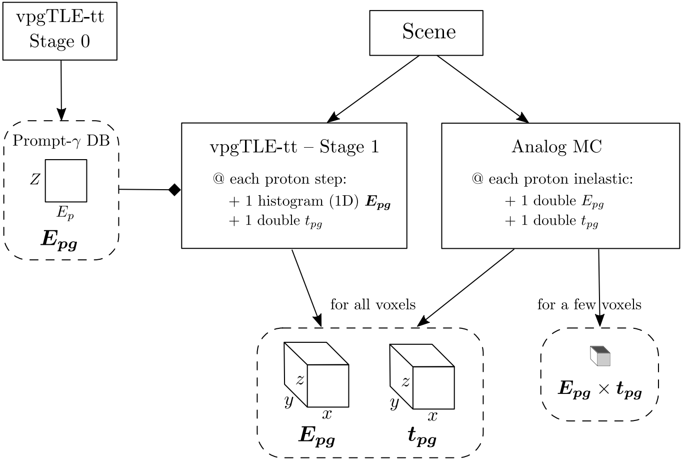
where $S(E_p)$ is the stopping power of the incident particle.

$\Rightarrow$ Another **cumulative** PG database could be introduced to tackle energy aliasing with this new estimator **vpgELE**.

[21] W El Kanawati et al. "Monte Carlo simulation of prompt γ-ray emission in proton therapy using a specific track length estimator". In: Physics in Medicine and Biology 60.20 (2015), pp. 8067–8086. DOI: 10.1088/0031-9155/60/20/8067.

vpgTLE

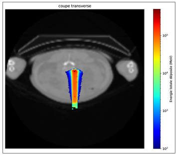
Diagram[22]



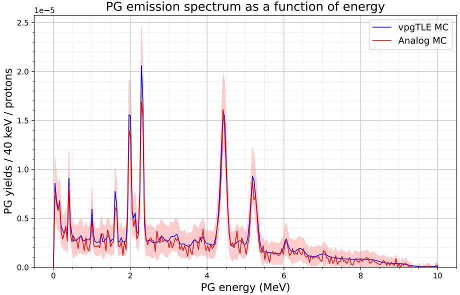
[22] J M Létang, O Allegrini, and É Testa. “Prompt-gamma track-length estimator with time tagging from proton tracking”. In: Physics in Medicine and Biology 69.11 (2024), 115052:1–10. DOI: 10.1088/1361-6560/ad4a01.

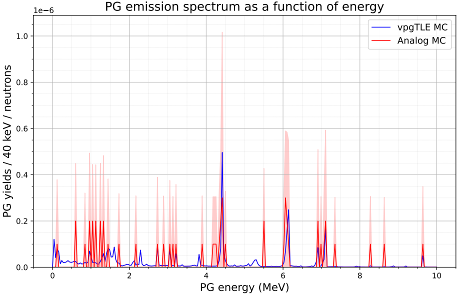
vpgTLE

PG energy distribution at VOI (Gate 10): proton *vs* neutron[23]



- Beam: proton@130MeV
- VOI: $(4\text{mm})^3$ voxel
- Stats: 10^6 vpgTLE *vs* 10^7 analog MC

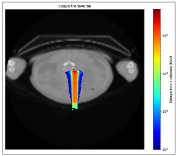




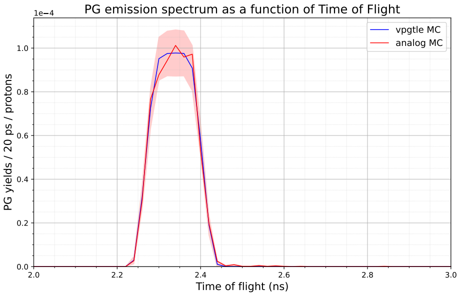
[23] V Guittet. "**Extension du module hybride d'émission des rayons γ prompts en protonthérapie dans le code Monte Carlo GATE pour prendre en compte les neutrons secondaires**". MSc Report (Med. Phys.) Université de Rennes, 2025.

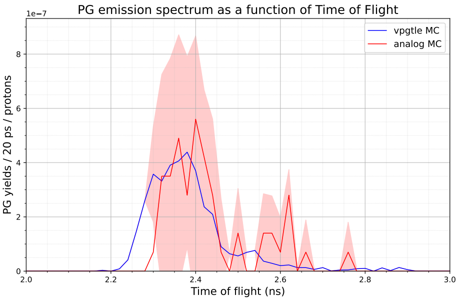
vpgTLE

PG time distribution at VOI (Gate 10): proton *vs* neutron[24]



- Beam: proton@130MeV
- VOI: $(4\text{mm})^3$ voxel
- Stats: 10^6 vpgTLE *vs* 10^7 analog MC

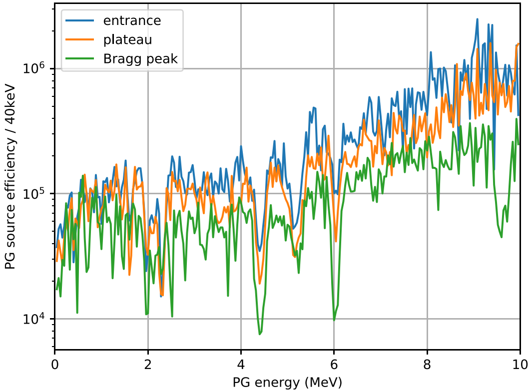




[24] V Guittet. "**Extension du module hybride d'émission des rayons γ prompts en protonthérapie dans le code Monte Carlo GATE pour prendre en compte les neutrons secondaires**". MSc Report (Med. Phys.) Université de Rennes, 2025.

vpgTLE

Efficiency gain wrt Analog MC (Gate 9.4)[25]



$\Rightarrow$ Efficiency gain wrt Analog MC of about $\mathbf{10^5}$: $\dfrac{1}{1\%\ \text{PG/cm}} \times 5\ \text{voxels/cm} \times 10^3\ \text{PG energy bins} = 5 \times 10^5$

[25] J M Létang, O Allegrini, and É Testa. "Prompt-gamma track-length estimator with time tagging from proton tracking". In: Physics in Medicine and Biology 69.11 (2024), 115052:1–10. DOI: 10.1088/1361-6560/ad4a01.

Conclusions

Achievements:

- vpgTLE ported to Gate 10
- expansion to neutron

To be done:

- implement vpgTLE ($2 \times 4D$) PG source in Gate 10
- extend to heavier ions (He, C)
- improve PG database construction (compatibility with G4 *Physics List Builder*)
- implement vpgELE (Energy-Loss Estimator)

GATE
opengatecollaboration.org