A fast - Monte Carlo toolkit on GPU for treatment plan dose recalculation in proton therapy

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Particle therapy (PT)

Cancer treatment technique using accelerated beams of protons or positive ions to treat solid tumor volumes.

\[ D = \frac{dE}{dm} \quad \text{Gy [J/kg]} \]
Particle therapy (PT)

Cancer treatment technique using accelerated beams of protons or positive ions to treat solid tumor volumes.

Dose \[ D = \frac{dE}{dm} \text{ Gy [J/kg]} \]

Radiotherapy vs particle therapy

Concentrated energy release at the end of path

Sharp decrease in energy after the Bragg Peak

Better dose distribution to preserve critical organs and surrounding healthy tissues
Cancer irradiation techniques goal:

**Conformal dose distribution**

concentrate all the dose to tumor and spare healthy tissues

- Standard radiotherapy ➞ **Intensity Modulated Radiation Therapy (IMRT)**
  - Different beam directions (fields)
  - Dynamic delivery (Different beams fluences, tissue compensator)

- Particle therapy ➞ **Spread Out Bragg Peak (SOBP)**
  - Active tumor volume scanning
  - Superposition of beams with different energies

![Graph showing dose-depth profile for different beam types: X-ray, Proton Beam, and Spread Out Bragg Peak (SOBP)]
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- Particle therapy
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PT exhibits a better conformal capability
The high **selectivity** in energy release asks for an high level of **accuracy** in the computation of beams to be sent to the patient.

**Treatment Planning System (TPS)**

**Patient anatomic data (CT, MRI, PET)**

<table>
<thead>
<tr>
<th>Volume of interest</th>
<th>% of Volume</th>
<th>Prescription/tolerance dose (Gy)</th>
<th>Relative importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate PTV</td>
<td>100</td>
<td>74.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td></td>
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<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Radiotherapist prescriptions**

<table>
<thead>
<tr>
<th></th>
<th>% of Volume</th>
<th>Prescription/tolerance dose (Gy)</th>
<th>Relative importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bladder</td>
<td>50.0</td>
<td>20.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Bladder</td>
<td>10.0</td>
<td>30.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Femoral heads</td>
<td>90.0</td>
<td>10.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Femoral heads</td>
<td>50.0</td>
<td>20.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Femoral heads</td>
<td>10.0</td>
<td>40.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Accelerator parameters**

For each beam:

- Fluence $\Phi_i$
- Energy $E_i$
- Direction $\theta_i$
Nowadays one of the major issues related to the TPS in Particle therapy is the **large CPU time** needed.

Options:

- FULL-MC recalculation using standard codes ~ 72 h/core
- Commercial TPS using analytical pencil beam algorithm ~ 1 h/core

**FRED** is a fast MC able to perform a complete recalculation of proton TP in **less than 1 minute**

How?!?

- Low budget
- Redundancy
- In-house maintenance
Both **carbons ions** and **protons** beam
One of the 10 worldwide centers using carbon ions beams to treat tumor
First patient treated in 2014
~ 900 patients treated
- Both **carbons ions** and **protons** beam
- One of the 10 worldwide centers using carbon ions beams to treat tumor
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CNAO clinical protocol
- Both **carbons ions** and **protons** beam
- One of the 10 worldwide centers using carbon ions beams to treat tumor
- First patient treated in 2014
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Physics models

Physics models implemented in the code are:

• Stopping Power

• Energy Fluctuations

• Multiple Coulombs Scattering (MCS)

• Nuclear interactions (elastic and inelastic)
Stopping power and energy fluctuations

Bethe formula\textsuperscript{[1]} \[ \frac{dE}{dx}(x, N_e, \nu, E, \beta, \gamma, I) \]

**Mean** energy loss per travelled distance

<table>
<thead>
<tr>
<th>Thick absorber</th>
<th>Gaussian distribution of energy loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin absorber</td>
<td>Landau-Vavilov distribution of energy loss</td>
</tr>
<tr>
<td></td>
<td>Approximation with logarithmic normal function</td>
</tr>
</tbody>
</table>

Multiple coulomb scattering

Distributions of projected angles $\theta_x$ and $\theta_y$ of the angle $\theta$ have been studied and modelized.

Small angles approximation: $\sin(\theta) \sim \theta$:

$$\theta = \sqrt{\theta_x^2 + \theta_y^2}$$

Three different models implemented:

**Single Gaussian**

**Double Gaussian**

(used in clinical analytic TPS)

**Gauss- Rutherford like**

$$f_{GR}(\theta_x, \theta_y) = (1 - w)G(\theta_x, \theta_y, \sigma) + w \frac{b^c}{(\theta_x^2 + \theta_y^2)^c}$$

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[Graphs showing distributions for Single, Double Gaussian, and Gauss-Rutherford models with Energy = 151 MeV and step = 10^(-1.0) cm]
Nuclear interaction

Nuclear cross sections from ICRU report of 2003

Secondary fragments computed:

✓ Protons, tracked
✓ Deuterons, tracked
✗ Neutrons, neglected
● Heavier ions, locally deposited

Single PB dose profiles

150 MeV protons in water (FWHM=0.0)

Bragg curve

Lateral dose line profile at 90% BP

Full Monte Carlo (FLUKA)
Fast Monte Carlo (FRED)
Clinical case: Glioblastoma

HU conversion in voxel density $\rho$ and elemental composition from “The Calibration of CT of CT Hounsfield units for radiotherapy treatment planning”, Schneider, Pedroni, Lomax, 1996 Phys. Med. Biol. 41 111

6400 pencil beams, 5000 primary each
Dose scoring volume resolution 2 x 2 x 2 mm

DVH

MCTP

FRED
Hardware and performance

Under sustained raytracing workload, in order to keep temperature of all GPU cads below 70°, we obtain:

- **AIR-COOLED 2X NVIDIA GTX TITAN** 30% duty cycle
- **WATER-COOLED 4X NVIDIA GTX 980** 100% duty cycle

<table>
<thead>
<tr>
<th>THREADS</th>
<th>primary/s</th>
<th>μs/primary</th>
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</thead>
<tbody>
<tr>
<td><strong>CPU</strong></td>
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</tr>
<tr>
<td></td>
<td>FRED</td>
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</tr>
<tr>
<td></td>
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<td>16</td>
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<tr>
<td></td>
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<tr>
<td><strong>GPU</strong></td>
<td>FRED</td>
<td>1 GPU*</td>
</tr>
<tr>
<td></td>
<td>FRED</td>
<td>2 GPU**</td>
</tr>
<tr>
<td></td>
<td>FRED</td>
<td>4 GPU***</td>
</tr>
</tbody>
</table>

*LAPTOP: MacBookPro(AMD Radeon R9 M370X)

** DESKTOP: Mac Pro (AMD FirePro D300)

***LINUX WorkStation with 4 NVIDIA GTX 980 GPUs
Synchronous/asynchronous execution

WATER-COOLED 4X NVIDIA GTX 980

1 DEVICE
1 QUEUE

Host→ Device
Device→ Host
Calculation

Time
Synchronous/asynchronous execution

WATER-COoled 4X NVIDIA GTX 980

1 DEVICE
2 QUEUES
Synchronous/asynchronous execution

WATER-COOLED 4X NVIDIA GTX 980

2 DEVICES
2 QUEUES

Host -> Device
Device -> Host
Calculation

<table>
<thead>
<tr>
<th>time</th>
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</thead>
<tbody>
<tr>
<td>0.00</td>
</tr>
<tr>
<td>0.05</td>
</tr>
<tr>
<td>0.10</td>
</tr>
<tr>
<td>0.15</td>
</tr>
<tr>
<td>0.20</td>
</tr>
<tr>
<td>0.25</td>
</tr>
<tr>
<td>0.30</td>
</tr>
<tr>
<td>0.35</td>
</tr>
<tr>
<td>0.40</td>
</tr>
<tr>
<td>0.45</td>
</tr>
</tbody>
</table>
Synchronous/asynchronous execution

WATER-COOLED 4X NVIDIA GTX 980

4 DEVICES
2 QUEUES

Host→ Device
Device→ Host
Calculation

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45

time
Synchronous/asynchronous execution

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4 DEVICES
2 QUEUES
Conclusions and future developments

- Good dose maps agreement with TPS data and Full-MC simulations

- Time computing expense > 1000 times less than a full MC tool
Conclusions and future developments

- Good dose maps agreement with TPS data and Full-MC simulations
- Time computing expense ~ 1000 times less than a full MC tool
- Clinical validation of fast-recalculation tool
  - Applications to clinical routine
  - Extensions to include other ions (Carbon, Helium)
  - Improvement of radiobiological models (RBE)
  - Dose monitoring using secondary particles
Thank you for your attention!

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Patient statistic
Bragg Peaks

Nuclear Interactions

- ALL OFF
- elastic interaction ONLY
- inelastic interaction ONLY

Graph showing GeV/cm vs. cm with bands for different nuclear interactions:
- FULL-MC
- E100NucAllOff
- E150NucElOnly
- E200NucAllOn
- E250NucInOnly
Gamma Index pass rate\[^{[3]}\]

\[
\Gamma(\vec{r}_e, \vec{r}_r) = \sqrt{\frac{|r_e - r_r|^2}{DTA^2} + \frac{[D_e(r_e) - D_r(r_r)]^2}{DD^2}}
\]

\[
\gamma(\vec{r}_r) = \min \{ \Gamma(\vec{r}_e, \vec{r}_r) \} \forall \{ \vec{r}_e \}
\]

If $\gamma < 1$, the reference point passes the $\gamma$-test; otherwise it fails.

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Quality assurance cube

SOBP 3 cm cube @ 20 cm depth
20000 primary protons per PB

- FRED
- TPS