A fast and accurate GPU-based proton transport Monte Carlo simulation for validating proton therapy treatment plans

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Motivation

• The gold standard for dose calculations in proton therapy is Monte Carlo simulation (e.g. FLUKA, MCNP, Geant4)

• Geant4 Monte Carlo calculations of a typical proton treatment plan take several hours on a large CPU cluster

• Our goal is to be able to perform MC calculations of proton plans with <2% statistical error on the prescribed dose in around 1 minute, with comparable accuracy to Geant4

• This tool will be used for:

  (1) Fast and relatively inexpensive dose verification system (this talk)
  
  (2) MC-based optimizer for treatment planning (see poster #P146)
  
  (3) Other applications
Development hardware

Gaming PC with two NVIDIA GTX680 cards
Development language: CUDA C

$500 x 2
Simulation Components

Particle phase space

GPU kernel

Geant4 (TOPAS) PBS nozzle simulation

Host CPU

Energy loss, multiple scattering, nuclear elastic scattering

GPU kernel

Nuclear evaporation

GPU kernel

Bertini cascade

GPU kernel

CT image

NB: kernel = piece of code that runs on the GPU but can be called from the CPU
Sequence of GPU kernel calls

1. **Random no. initialization**
2. **Phase space kernel**
3. **Transport kernel**
4. **Sort nuclear interactions on GPU**
5. **Bertini cascade kernel**
6. **Evaporation kernel**
7. **Collect proton secondaries on GPU**

Loop until all batches processed

Load phase space data on GPU

Loop until no more secondary protons

Transfer results to CPU

**start**

**end**
GPU kernels for simulating non-elastic proton-nucleus interactions

- First-ever detailed simulation of nuclear interactions on a GPU
- Two kernels to handle Bertini cascade and subsequent evaporation stage
- Ability to handle proton collisions with any therapeutically relevant nucleus
- Predictions of secondary proton and neutron properties following nuclear collisions in good agreement with Geant4

More details: Poster #P181
H. Wan Chan Tseung & C. Beltran, Computer Physics Communications, 185 (2014) 2029
GPU kernels for simulating non-elastic proton-nucleus interactions: results

Time taken to compute 260k nuclear interactions:

<table>
<thead>
<tr>
<th></th>
<th>70 MeV protons on Carbon</th>
<th>70 MeV protons on Calcium</th>
<th>200 MeV protons on Carbon</th>
<th>200 MeV protons on Calcium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our GPU MC</td>
<td>0.97 s</td>
<td>1.5 s</td>
<td>1.14 s</td>
<td>1.89 s</td>
</tr>
<tr>
<td>Geant4</td>
<td>173.69 s</td>
<td>317.53 s</td>
<td>202.28 s</td>
<td>461.54 s</td>
</tr>
</tbody>
</table>

×200 speedup
Benchmarking our Monte Carlo

We performed extensive comparisons with Geant4. Example:

- 230 MeV pencil beam of protons in water
- 200 MeV pencil beam of protons in titanium

3-D gamma pass rate (2%-2mm) : 100%
Complex Head and Neck plan 1

3-D gamma (2%-2mm) pass rate: 98.2%

Comparisons of DVHs for various structures

60 million proton histories
Geant4/TOPAS on a CPU cluster: 650 CPU-hours
Our GPU MC: 3.5 minutes on one NVIDIA GTX680 card
Complex Head and Neck plan 2

3-D gamma (2%-2mm) pass rate: 97.8%

- 60 million proton histories
- Geant4/TOPAS on a CPU cluster: **650 CPU-hours**
- Our GPU MC: **2.7 minutes** on one NVIDIA GTX680 card
Summary

• We have developed a very fast and accurate GPU-based Monte Carlo for proton therapy, incorporating detailed modeling of non-elastic nuclear interactions

• Detailed nuclear modeling allows us to calculate dose with more confidence, especially in cases where significant hardware is present

• Compared to a 100-node CPU cluster, proton treatment plans are simulated ~100 times faster using one single graphics gaming card

• A dosimetric verification system is currently being deployed at Mayo Clinic, using a dual GPU server

• We will obtain routine, near real-time Monte Carlo feedback on pencil-beam plan accuracy
Acknowledgements
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Further reading

Thank you for your attention