gPMC: GPU-Based Monte Carlo Dose Calculation for Proton Radiotherapy

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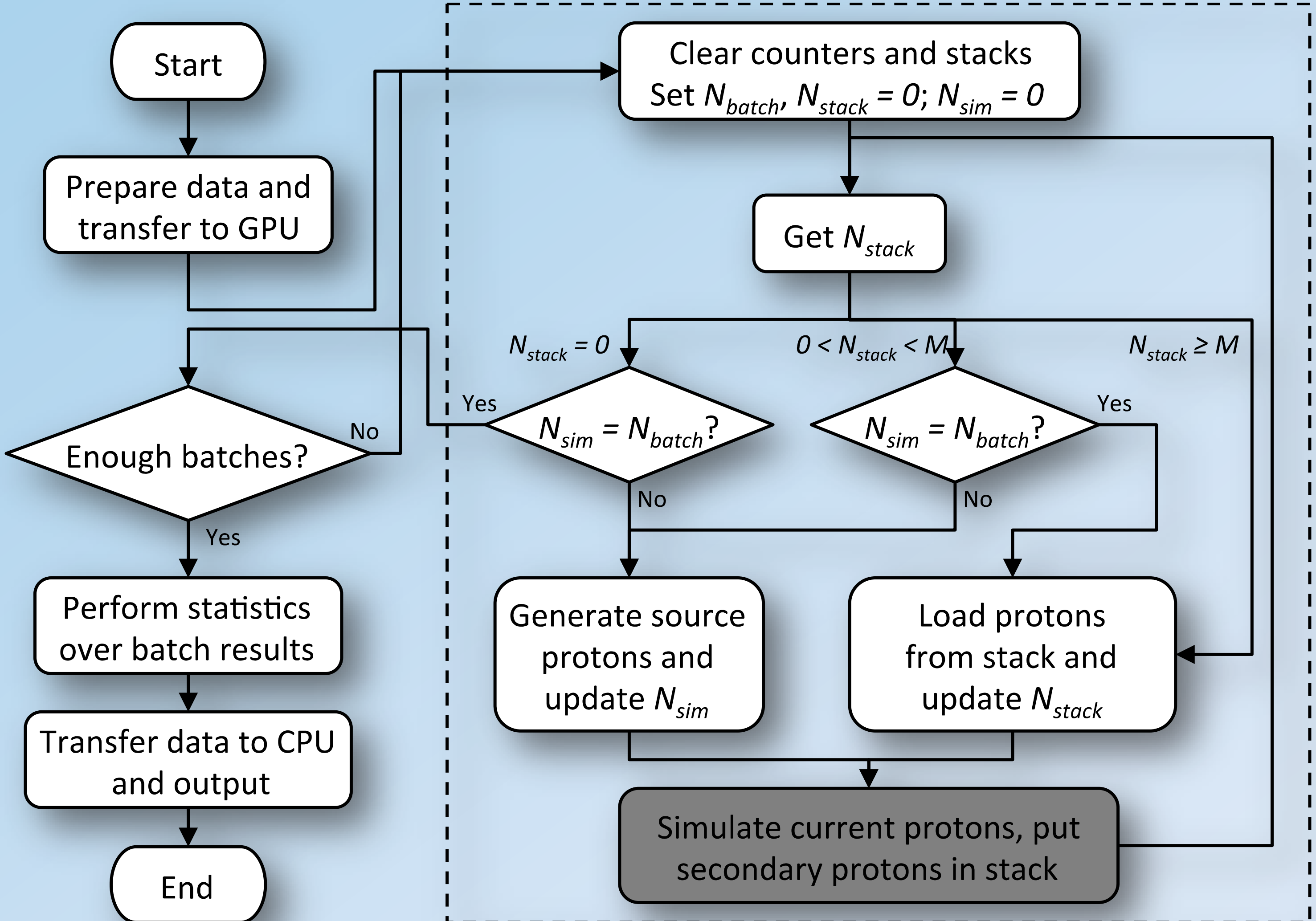
gPMC project

- Proton therapy dose calculation
  - Pencil beam method
  - Monte Carlo method

- gPMC project
  - Started Jan 2012
  - Objective: speed up full MC dose calculations for proton therapy using Graphics Processing Units (GPU)
    - Develop an appropriate physics model to achieve sufficient accuracy for proton therapy
    - Design GPU-friendly implementations to achieve high computational efficiency

Jia et. al. PMB **57**, 7783 (2012)

gPMC flow chart



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Proton transport

- Proton transport physics
  - Combines the physics from various literatures

    Kawrakow, *Med Phys*, **27**, 485(2000), Fippel *et. al., Med Phys*, **31**, 2263 (2004), Penelope manual (2009), Geant4 physics manual (2011)
  - Energy range [0.5, 350.0] MeV
  - Class II condensed history simulation scheme with continuous slowing down approximation
  - Multiple scattering and energy straggling
  - Secondary electrons are not transported
  - Nuclear interaction is handled by an empirical strategy

    Fippel *et. al.*, *Med Phys*, **31**, 2263(2004)
- Support 25 materials that were defined in TOPAS/Geant4
- Voxelized patient geometry
  - CT to material conversion

Other issues

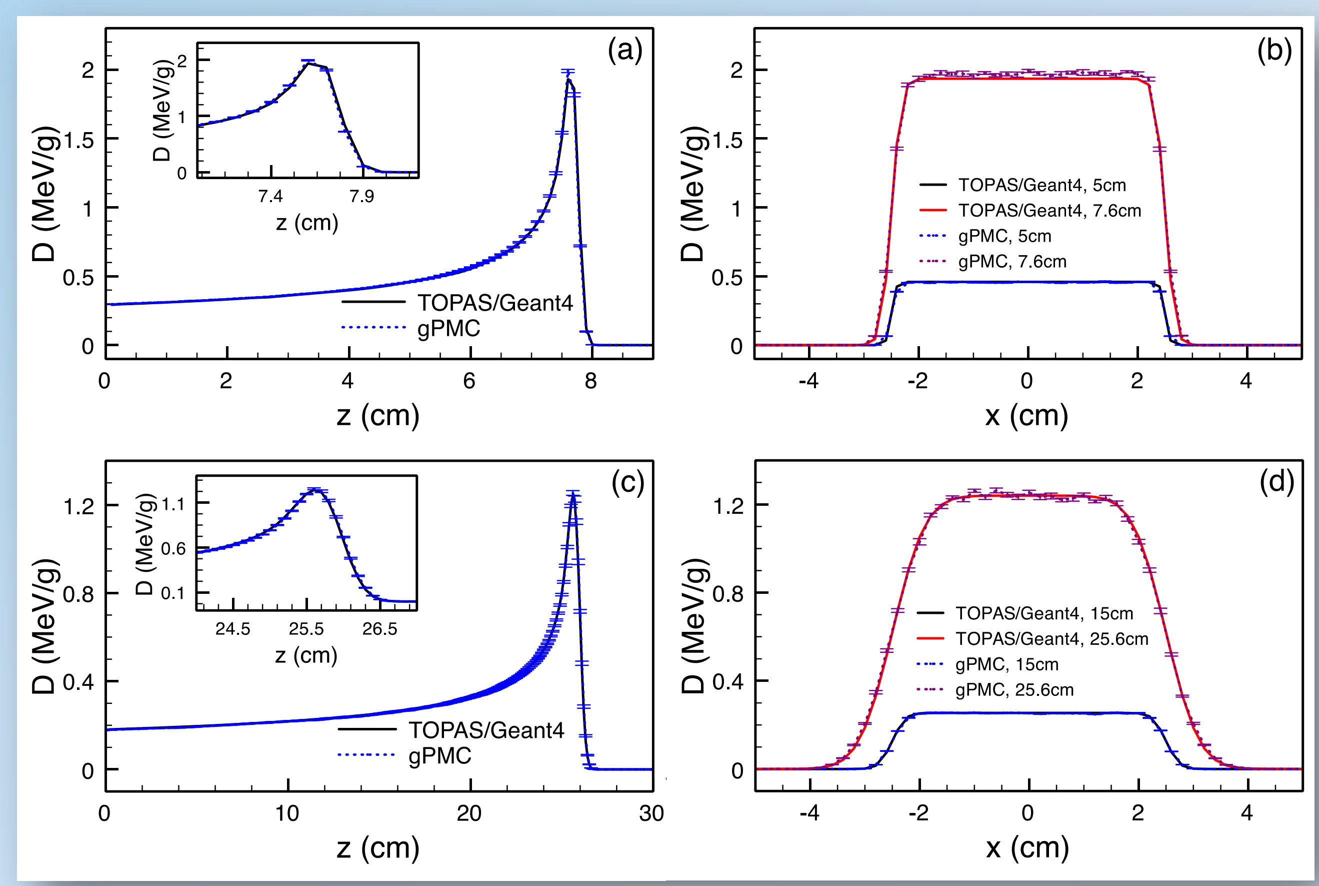
- Random number generator efficiency
  - Use CURAND, a light-weight RND generator provided by NVIDIA
- Interpolation of cross section data
  - Linear interpolation is used in gPMC
    - No loss of accuracy is observed
    - GPU support hardware interpolation
- Optimize GPU memory access
  - Use shared memory

Water phantom

- A phantom with pure water
- Electromagnetic channel only

100 MeV

200 MeV



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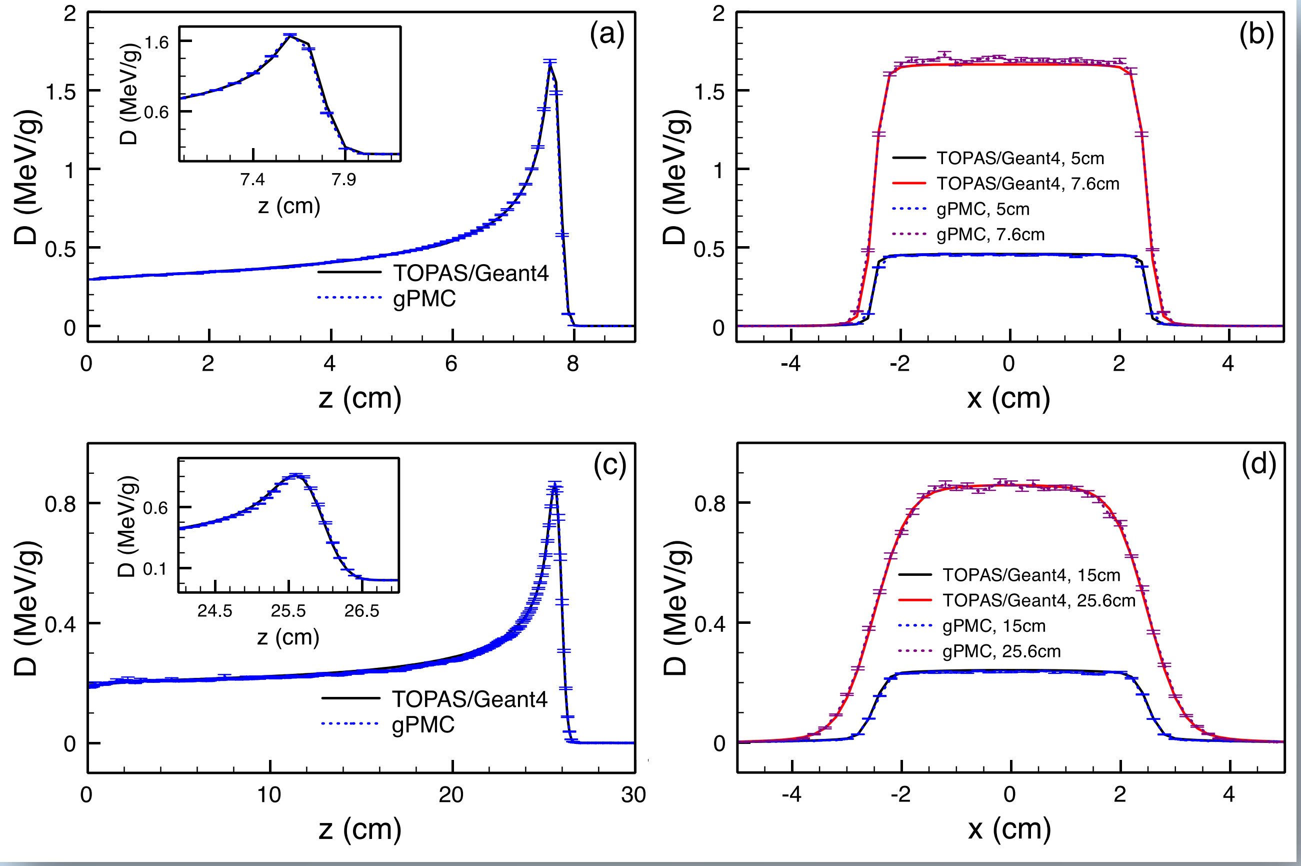
Water phantom

- A phantom with pure water
- Electromagnetic channel + nuclear channel

100 MeV

200 MeV



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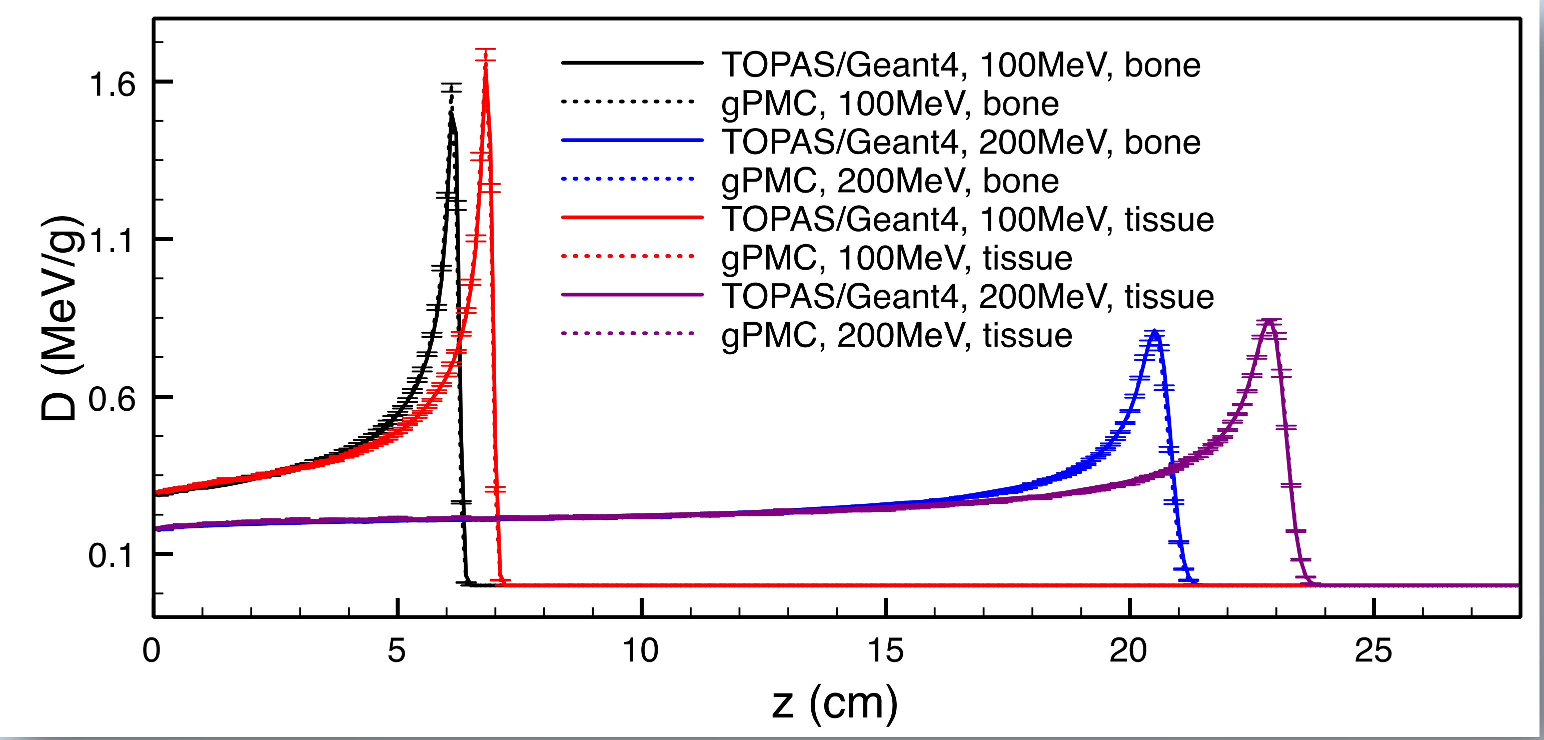
Other homogeneous phantoms

- Bone phantom (500 HU)
- Tissue phantom (200 HU)
- 100 MeV and 200 MeV sources



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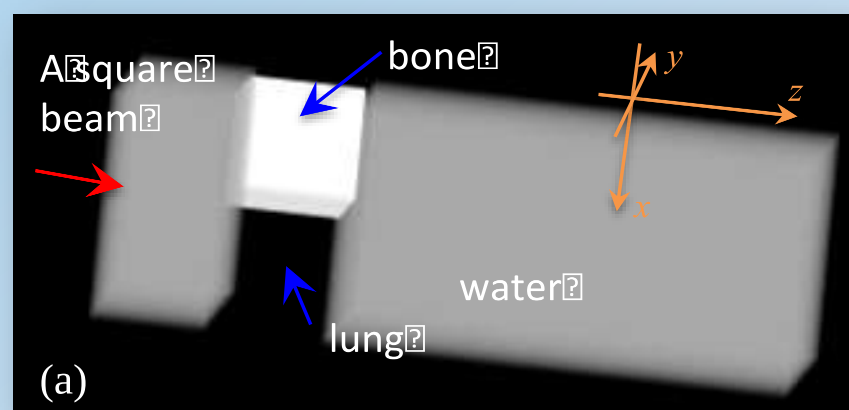
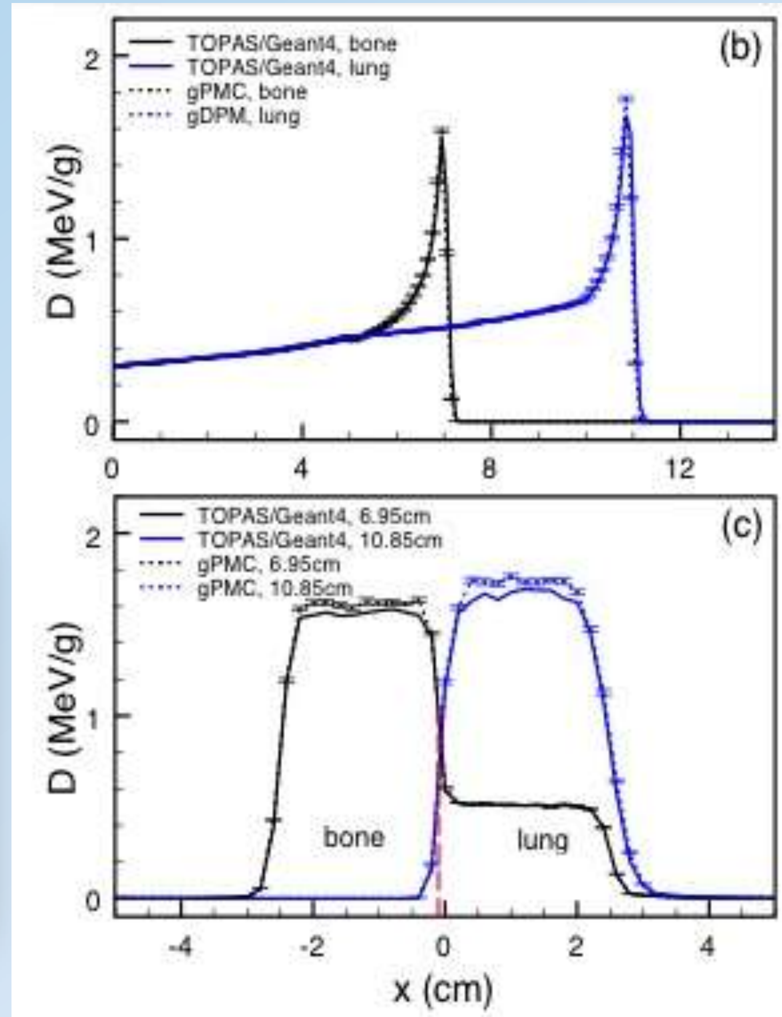
Inhomogeneous phantoms

- Materials
  - Water (0 HU)
  - Bone insert (500 HU)
  - Lung insert (-700 HU)





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Results

Average relative uncertainty $\langle \sigma_D/D \rangle$ (computed in region where $D > 0.1D_{max}$), γ-test passing rates *P*, and computation time *t*.

Phantom	Source Energy (MeV)	$<\sigma/D>$ (%)	P_γ (1mm/1%)(%)	P_γ (2mm/2%)(%)	T (sec)
Water, EM	100	0.8	99.2	99.6	6.66
	200	0.8	99.9	99.9	19.12
Water	100	0.9	99.3	99.7	6.76
	200	1.1	97.3	99.9	21.14
Bone	100	0.9	98.6	98.7	6.68
	200	1.1	98.1	99.9	20.98
Tissue	100	0.9	99.0	99.4	7.08
	200	1.1	97.6	99.9	22.29
Inhomogeneous phantom	100	0.9	99.9	99.9	9.44

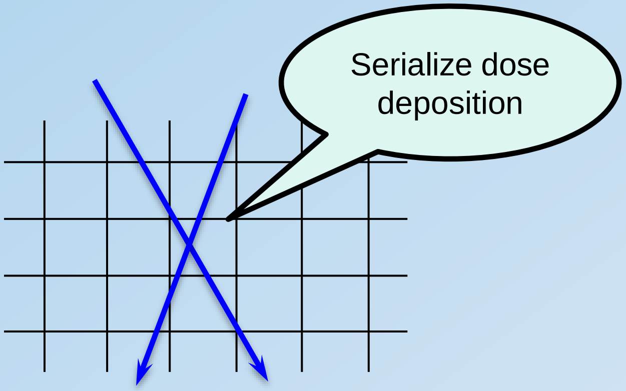
GPU: NVIDIA Tesla C2050

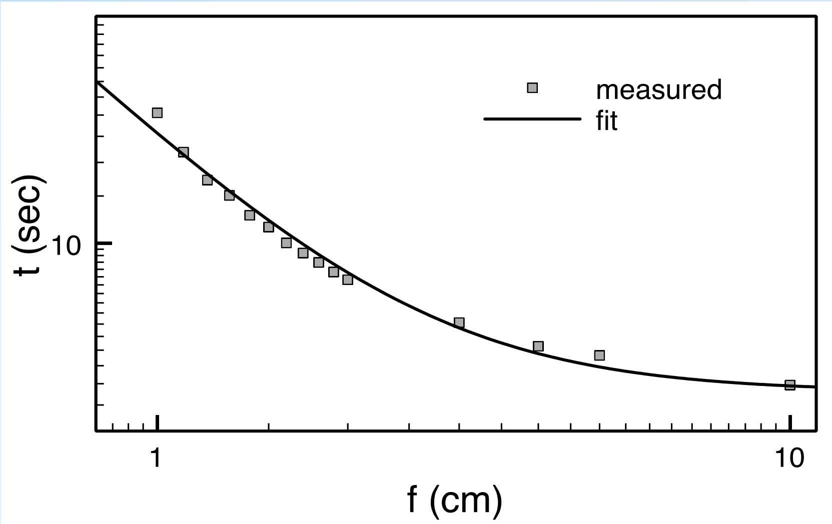
CPU computation time is 2~80 CPU hrs

Memory writing conflict

- When two GPU threads write to the same voxel
- An example of efficiency reduction
  - Square beams with different sizes

$$t \sim \frac{\alpha N \Delta t}{f^2} + \frac{N \Delta t}{N_{\text{thread}}}(1 - \frac{\alpha}{f^2})$$





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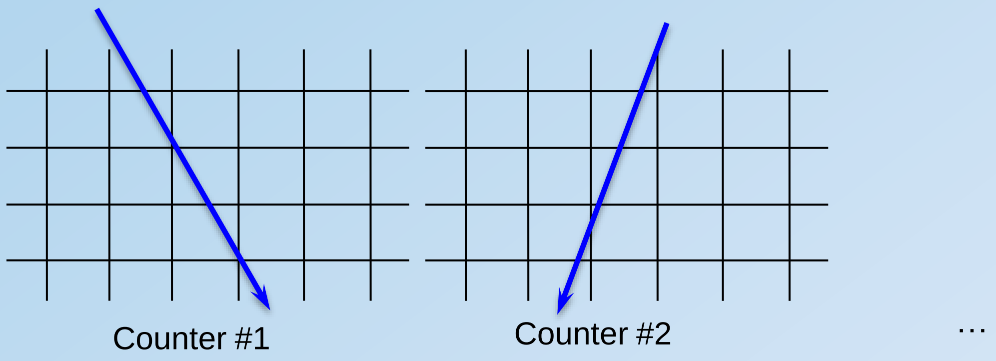
Memory writing conflict

- Multiple dose counter
  - Allocate multiple dose counters
  - Assign each deposition event randomly to a counter



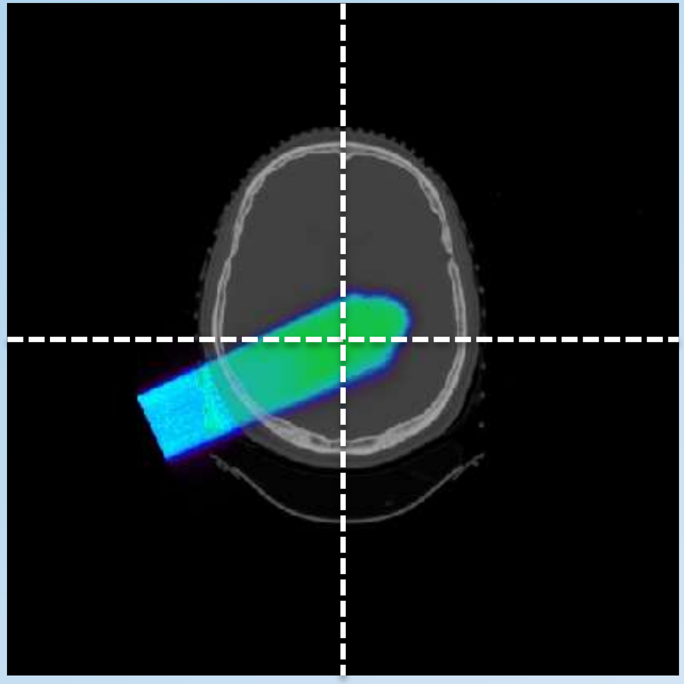
  - Collect data from all counters at the end
  - Uncertainty estimation based on results at all counters
  - Require a large memory

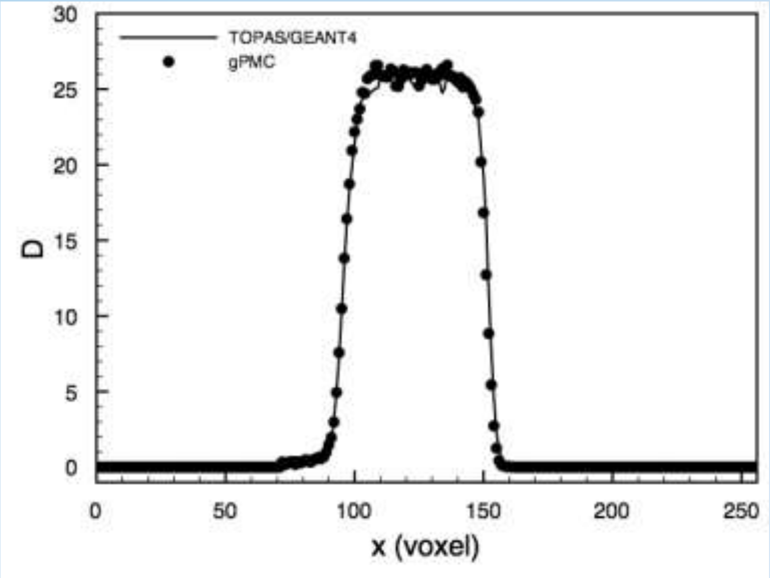
Other modules

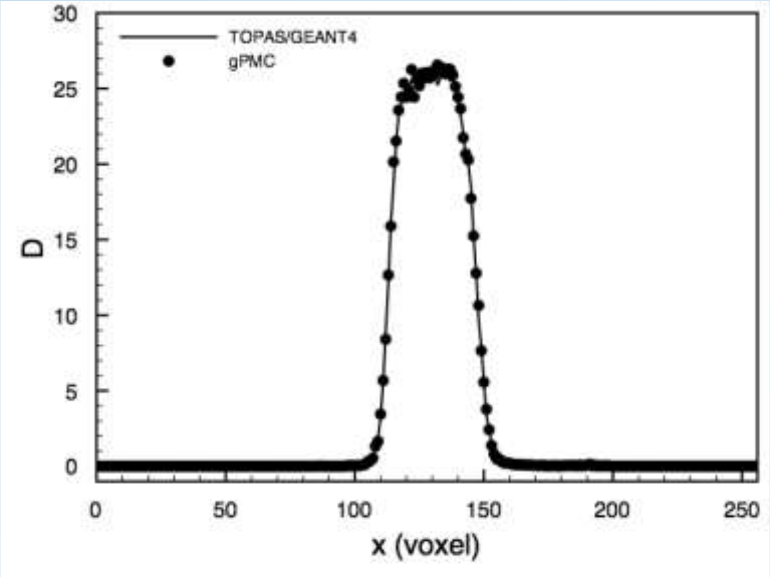
- Phase space file input generated by TOPAS/Geant4
  - Load particles from hard drive to CPU memory
  - Sort the particles into bins according to energy
  - Loop over each energy bin to transfer particles of similar energy
  - Avoid efficiency loss due to a long-lived thread
- Realistic treatment geometry
  - Translations and gantry/couch rotations
- Score dose-to-water if needed
- Score to a dose grid different from patient CT grid if needed
  - Reinterpolation of the results from CT grid to dose grid at the end of calculations

Patient Cases

- One beam in a realistic treatment plan
  - Resolution: 256×256×128
  - Voxel size: 1.5×1.5×1.25 mm^3
  - Dose to medium







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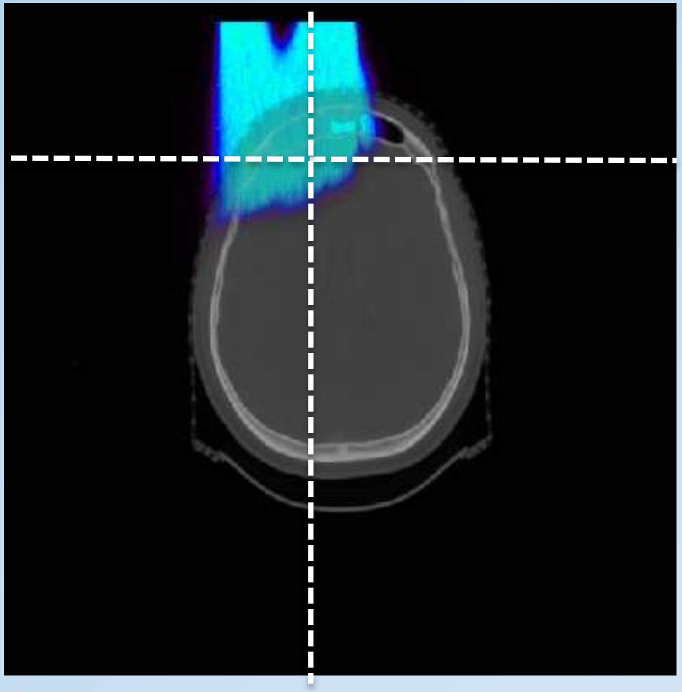
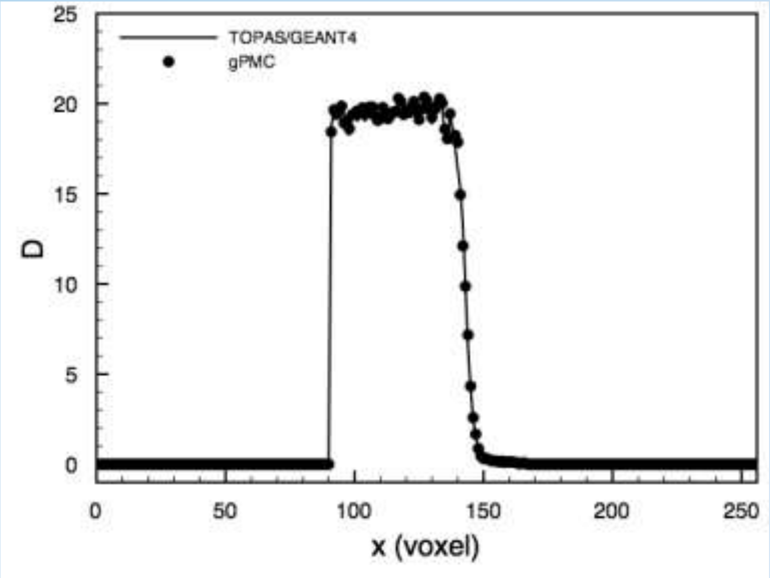
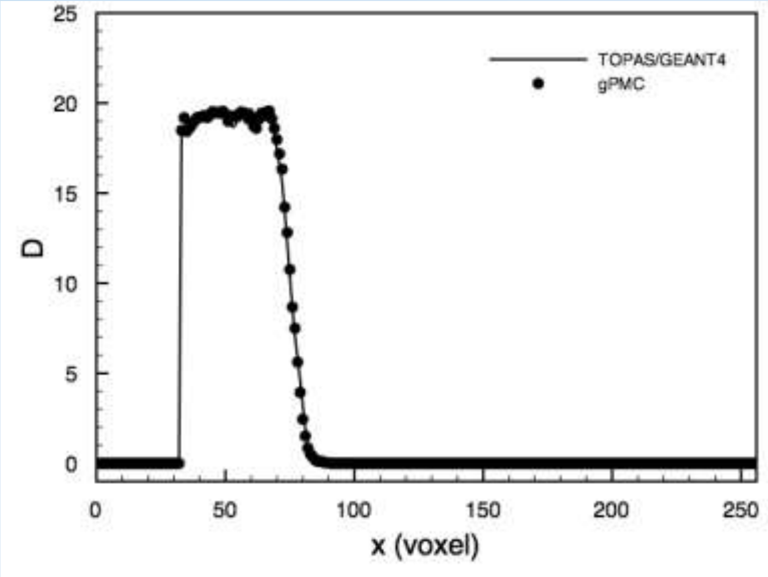
Patient Cases

- One beam in a realistic treatment plan
  - Resolution: 256×256×137
  - Voxel size: 1.39×1.39×2.5 mm^3
  - Dose to water







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Results

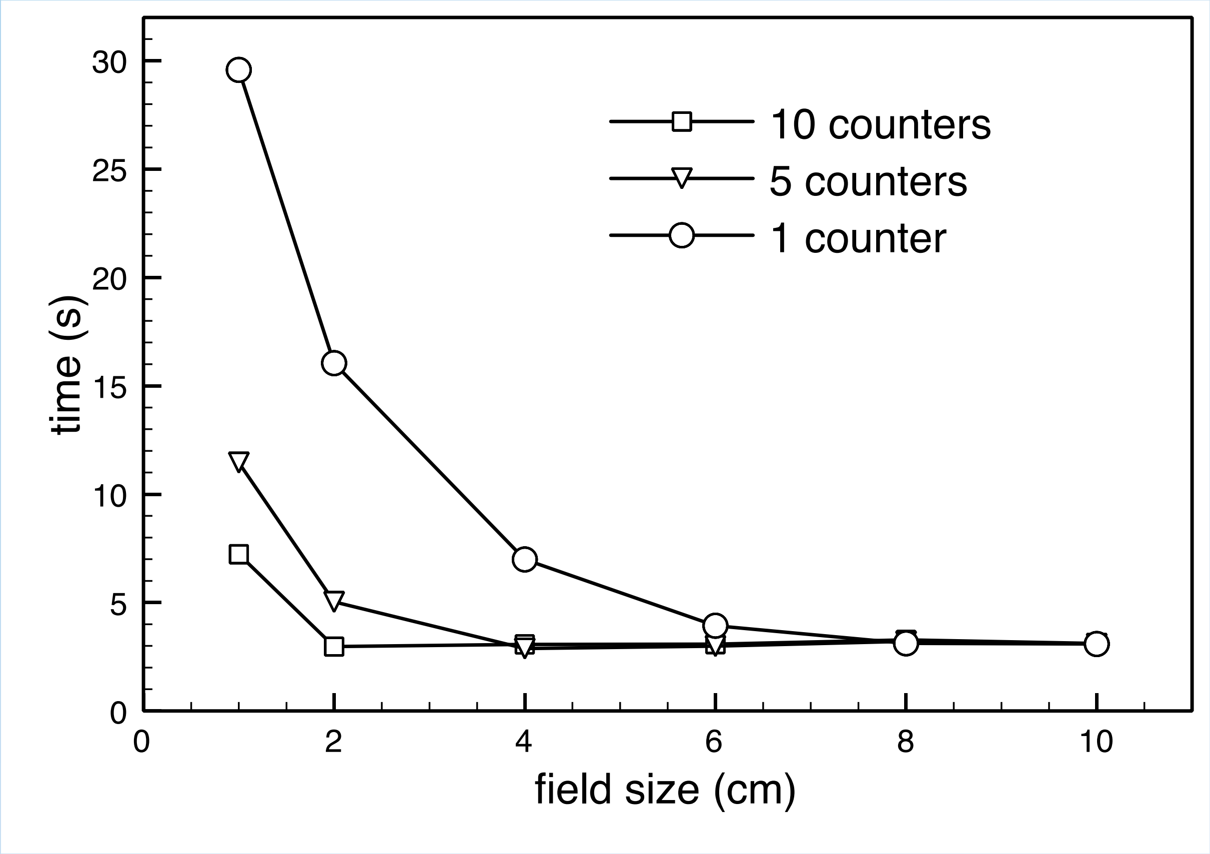
Computation time (data loading and simulation) and gamma passing rate compared to ground truth (TOPAS/Geant4)

Patient #	Beam #	N_{part} (M)	T_{load} (sec)	T_{sim} (sec)	P_{γ} (2%/2mm)(%)
1	1	10.8	15.5	16.2	97.5
	2	10.7	15.2	13.3	98.0
	3	7.6	11.2	10.8	97.4
	4	8.4	12.5	12.6	97.7
	5	5.6	9.2	8.6	97.4
2	1	6.8	10.6	5.5	99.2
	2	7.1	10.5	5.7	99.4
	3	7.3	10.7	5.8	99.6

GPU: NVIDIA GTX580

Memory writing conflict

- The effect of memory conflict



Conclusions

- A GPU-based proton transport code has been developed for dose calculations
  - Accuracy validated against TOPAS/Geant4
  - Implementation is optimized for GPU platform
  - Computation time:
    - 10~20 sec for phantom cases
    - ~10+10 sec for patient cases
- In the progress of comprehensive evaluations in patient cases at MGH
- Future directions
  - Further improve efficiency for other applications
  - Other practical issues: source modeling, commission…
  - Clinical implementations

Acknowledgement

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