A CUDA Monte Carlo simulator for radiation therapy dosimetry based on Geant4

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Collaboration

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Geant4 @ KEK

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NVIDIA CUDA

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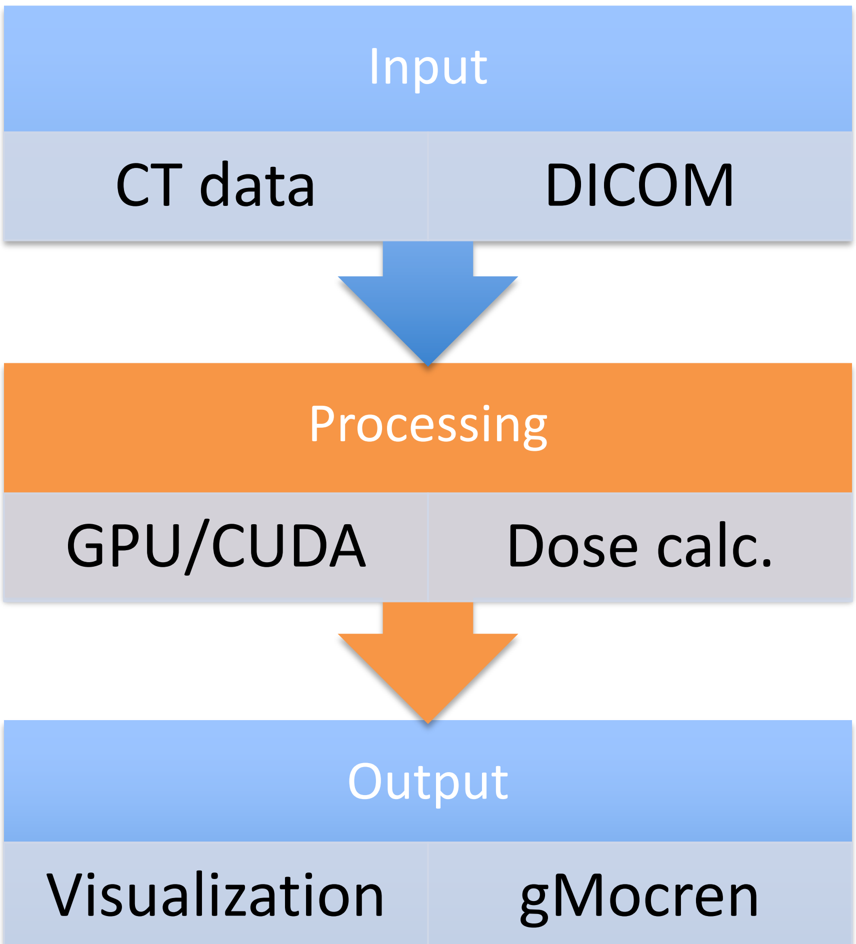
Outline

- Project overview
- Method / algorithm
- GPU implementation
- Performance and validation

Project overview

GPU based dose calculation for radiation therapy



Features

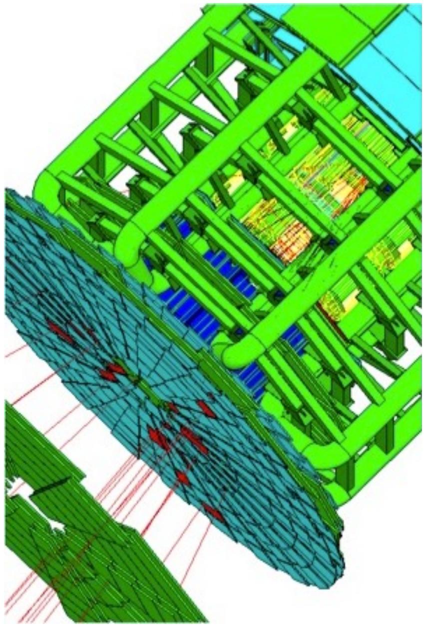
- GPU code based on Geant4
- Voxelized geometry
- DICOM interface
- Material is water with variable density
- Limited Geant4 EM physics: electron/positron/gamma
- Scoring of dose in each voxel
- Process secondary particles

Geant4 Toolkit

- Enables Monte Carlo simulation of particles travelling through and interacting with matter
- Allows modeling of complex geometries
- Covers all elementary particles and nuclei for a wide energy range

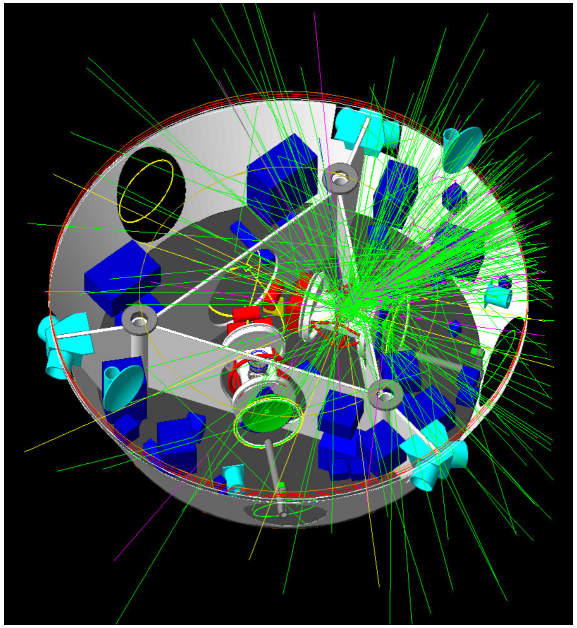
Geant4 Applications

High Energy Physics



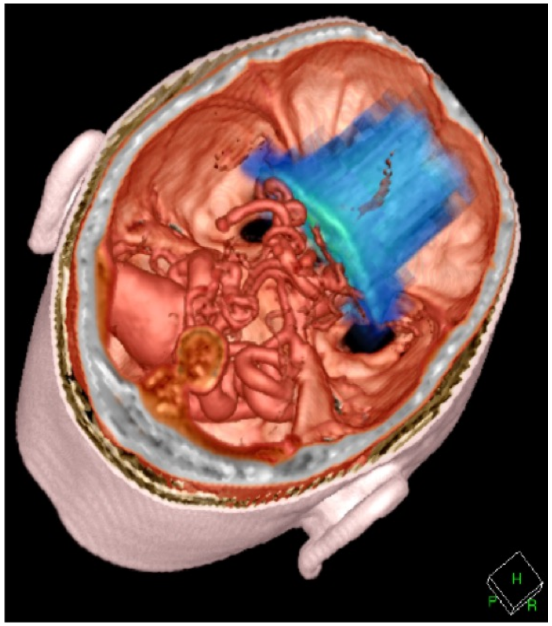
ATLAS

Space & Radiation



LISA

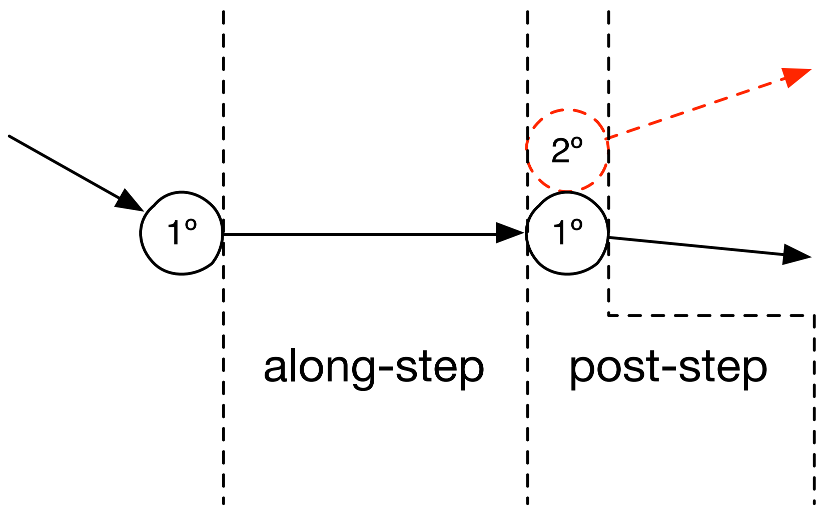
Medical Physics



gMocren

Images from: [Geant4 gallery](#)and [gMocren](#)

Geant4 algorithm summary



Each step can have:

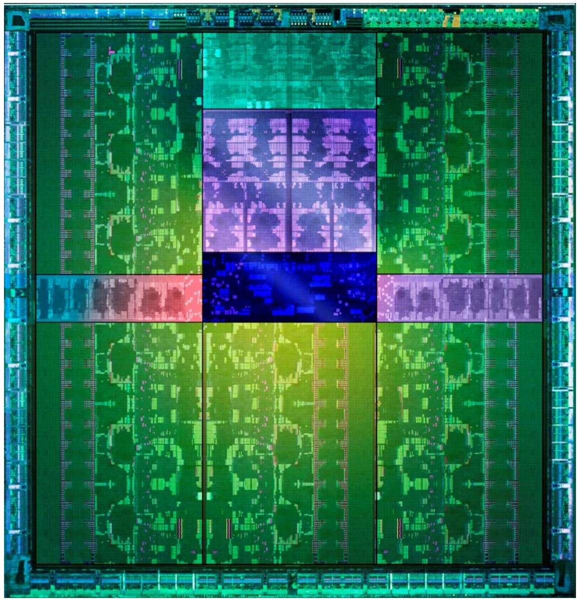
- along-step process
  - energy loss
  - multiple scattering
- post-step process
  - Compton scattering
  - Photoelectric effect
  - (several others)
  - May generate secondary particles

Parallelization challenges in Geant4

- Large and complex code base
  - object-oriented design
  - many inter-dependencies
- Sophisticated geometry and tracking management
- Elaborate physics models
- Branching, look-up tables, single-thread optimizations

GPU implementation strategy

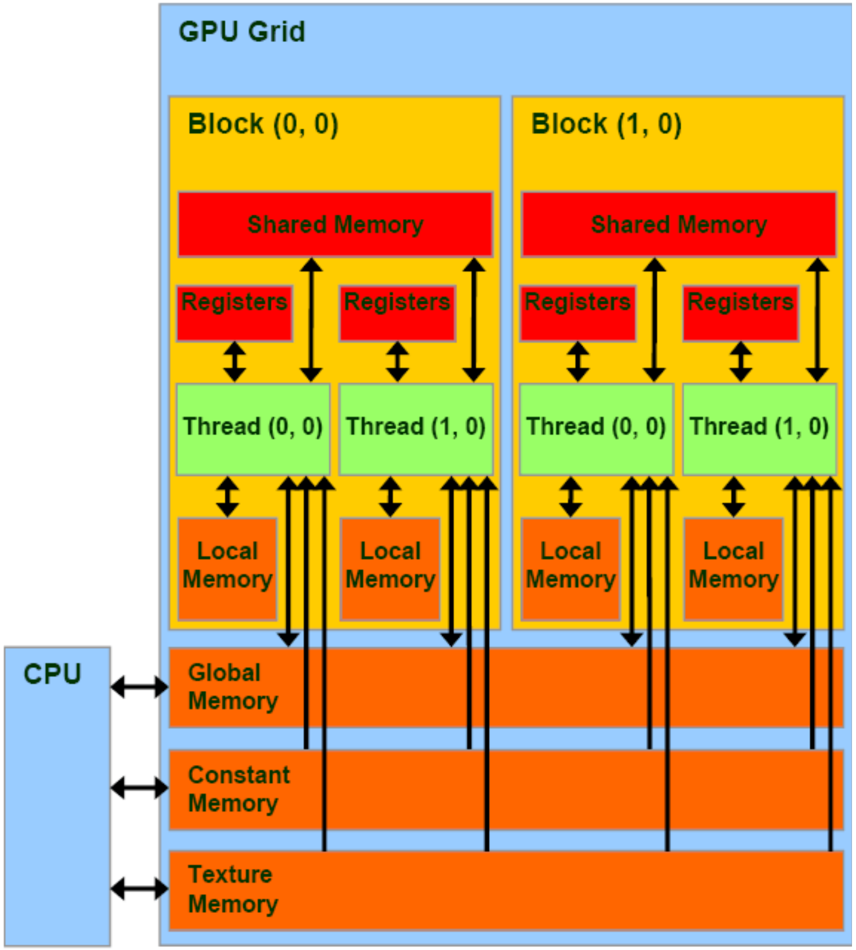
- Process many particles in parallel
- Limited geometry & material
  - voxelized region contained in a world volume
  - material is modeled as water with variable density
- Limited physics
  - low energy electro-magnetics
  - electron, positron, gamma
- Limited scoring
  - record energy dose in each voxel



NVidia Kepler

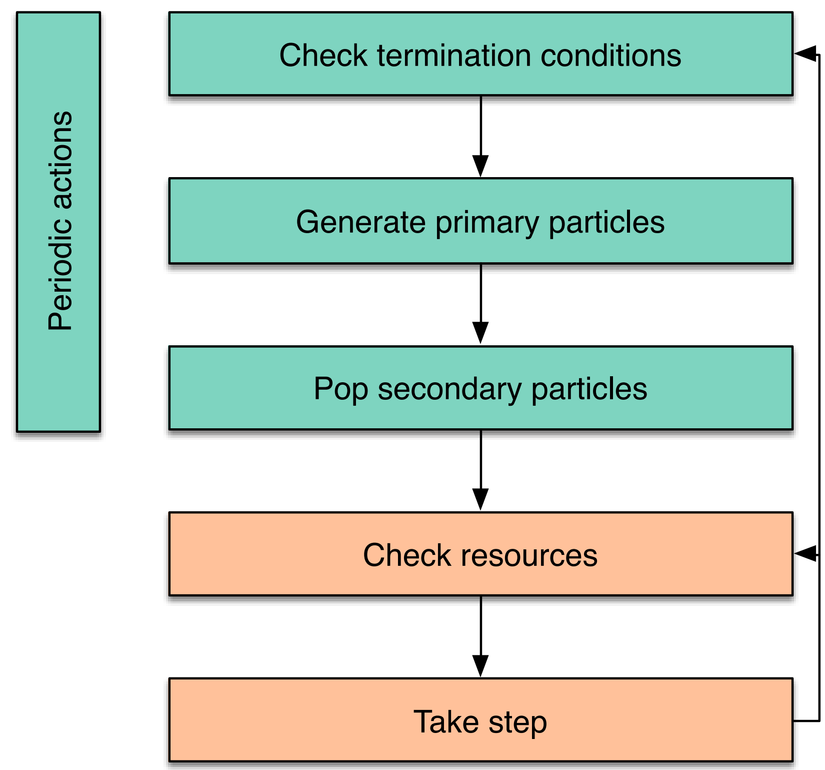
CUDA Basics

- "SIMD" architecture
  - ideal: same instruction on multiple pieces of data
- Memory hierarchy
  - global > cache > register
  - cache: {shared, constant, texture}
- Memory access pattern
  - want single read to satisfy many threads
- Race conditions
  - arise when multiple threads attempt to write to same location in global memory
  - may happen in dose accumulation
  - CUDA supports atomic operations

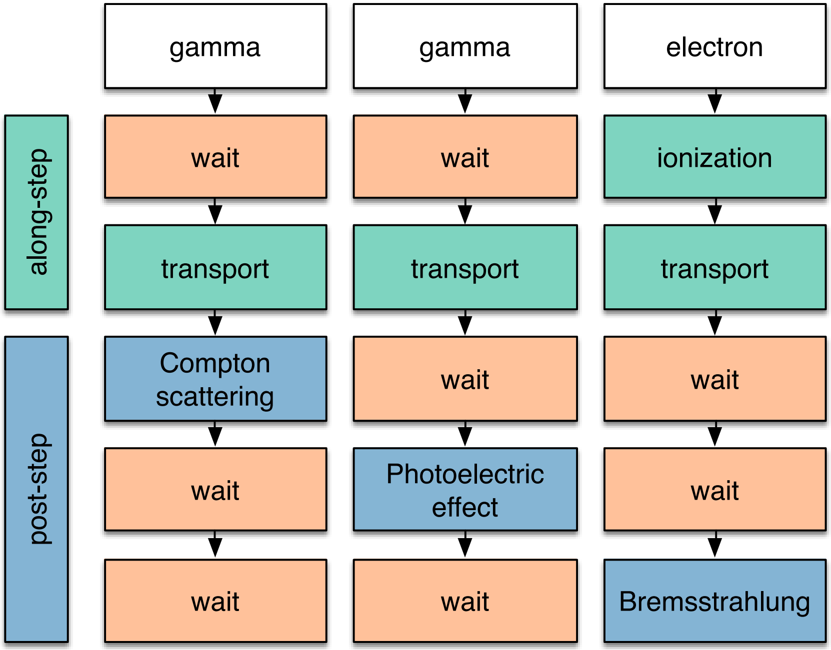


G4CU: CUDA implementation

- Each GPU thread processes a single track until the track exits the geometry
- Each thread has a stack for secondary particles
- Every thread takes a step in each iteration
- Algorithm is periodically interrupted for various actions



G4CU: parallel execution



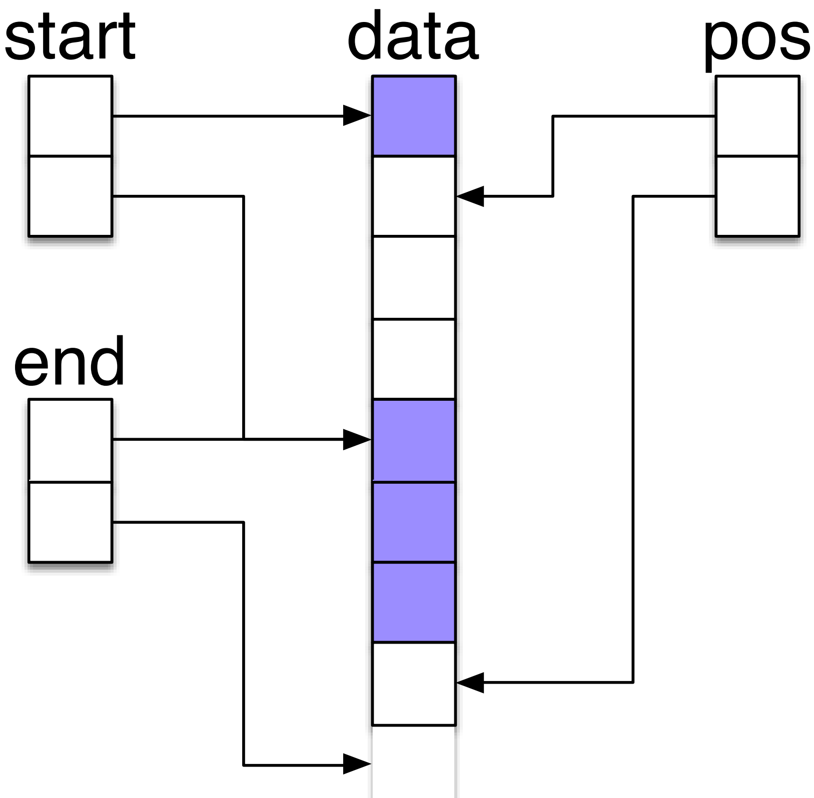
- CUDA kernels are applied to all particles
- Threads must wait if physics process does not apply to particle
- Parallel execution is achieved:
  - maintenance operations
  - transport process
  - same process on same particle

G4CU: struct of arrays

```
struct ParticleArray {
  // length of arrays
  int length;
  // kind of particle
  ParticleKind *kind;
  // position
  float *x, *y, *z;
  // direction
  float *dx, *dy, *dz;
  // particle energy
  float *energy;
};
```

- Common pattern in CUDA to allow for coalesced memory access
- Experiments with transport showed this to be 3-4x faster than an array of structs

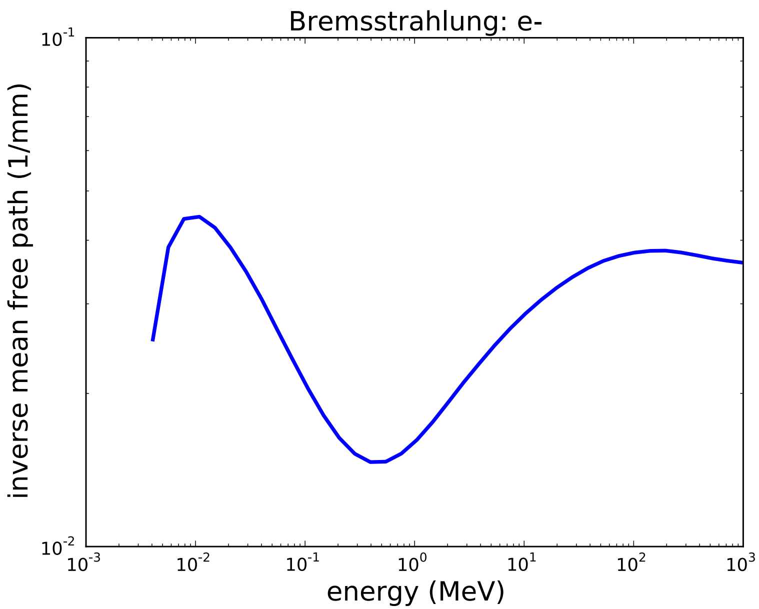
G4CU: parallel stack




```
template <typename T>
struct pstack {
   // number of stacks
   int stack_num;
   // size of each stack
   int stack_size;
   // stack ranges
   int *start, *end;
   // stack positions
   int *pos;
   // stack data array
   T *data;
};
```

G4CU: look-up tables

- Used for cross sections, dE/dx, (inverse-)ranges
  - 40 bins, log spaced (1keV – 1GeV)
  - linear and spline interpolation
  - retrieve data from G4 for a certain cut (1mm)
  - prepared for standard water
- Other tables: Bremsstrahlung uses 2D (surface) interpolation



G4CU: dose accumulation

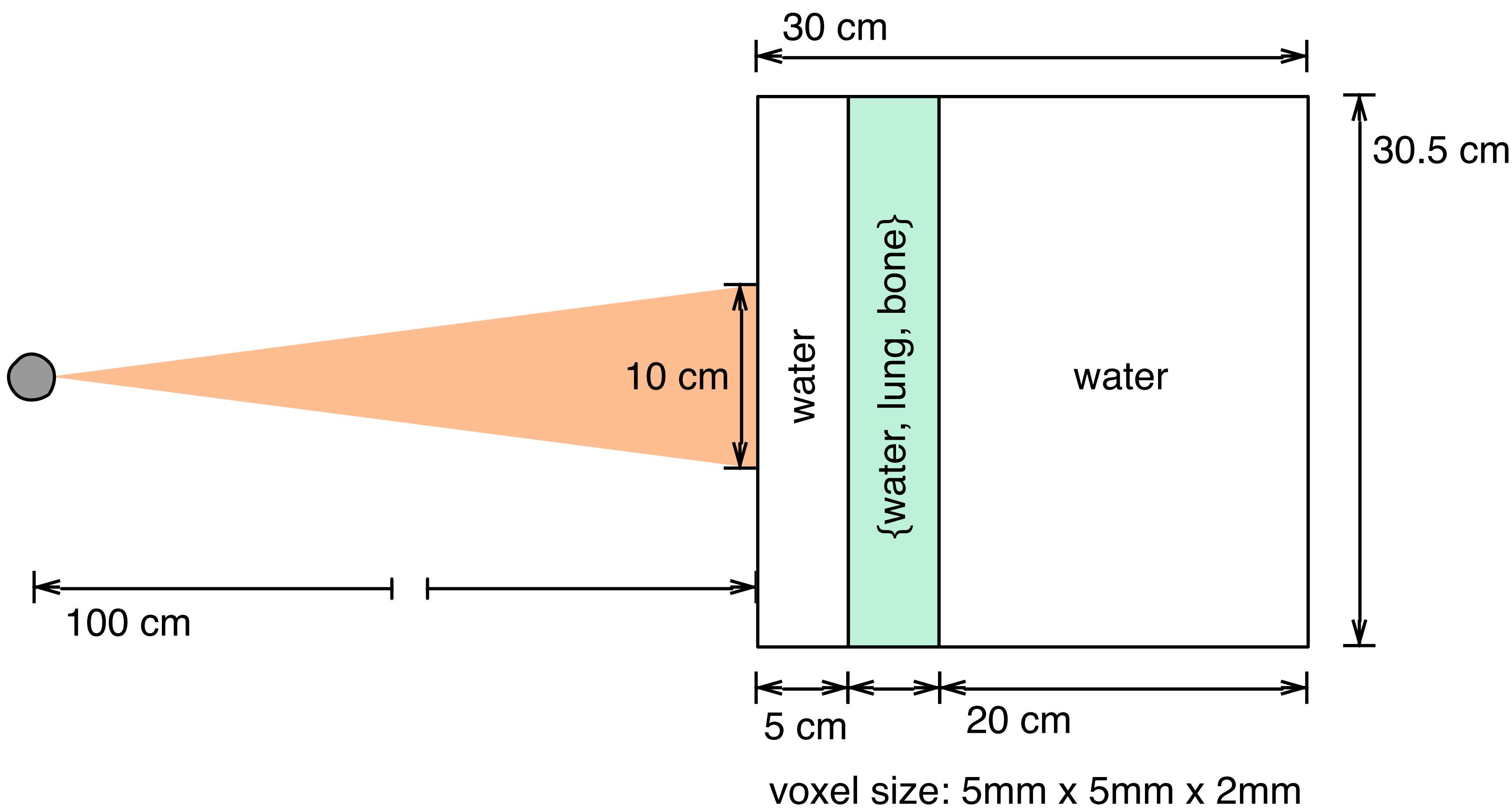
- Race conditions might arise when multiple CUDA threads attempt to write to the same location in global memory. We use CUDA's atomicAdd function
- Double precision is used for dose accumulation
  - single precision for everything else
  - prevents overflow in the case of small energy deposition to large accumulated dose

Performance and validation

Hardware and software:

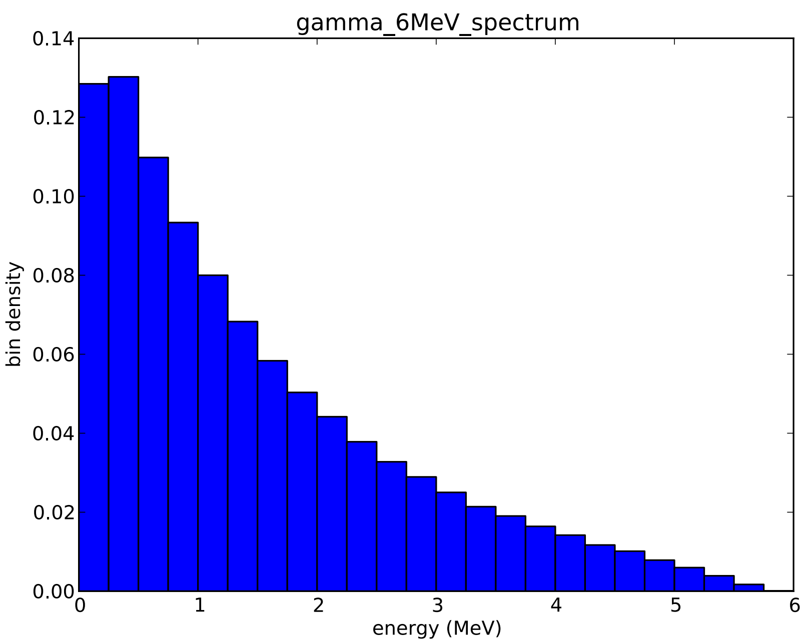
- GPU:
  - Tesla K20 Kepler
  - 2496 cores, 706 MHz, 5GB GDDR5 (ECC)
- CPU
  - Xeon X5680 (3.33GHz)
  - single thread operation
- SDK:
  - CUDA 5.5
  - Geant4 release 9.6 p2

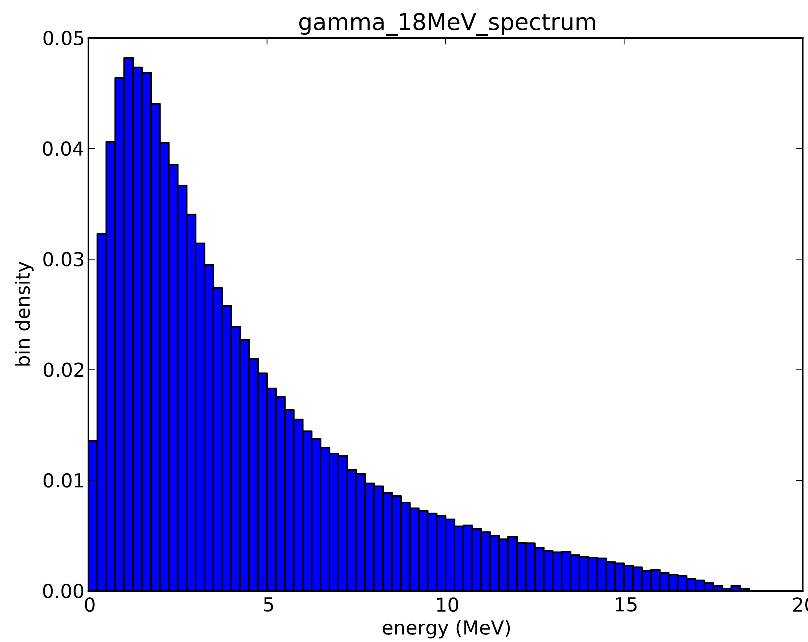
Phantom geometry



Particle sources

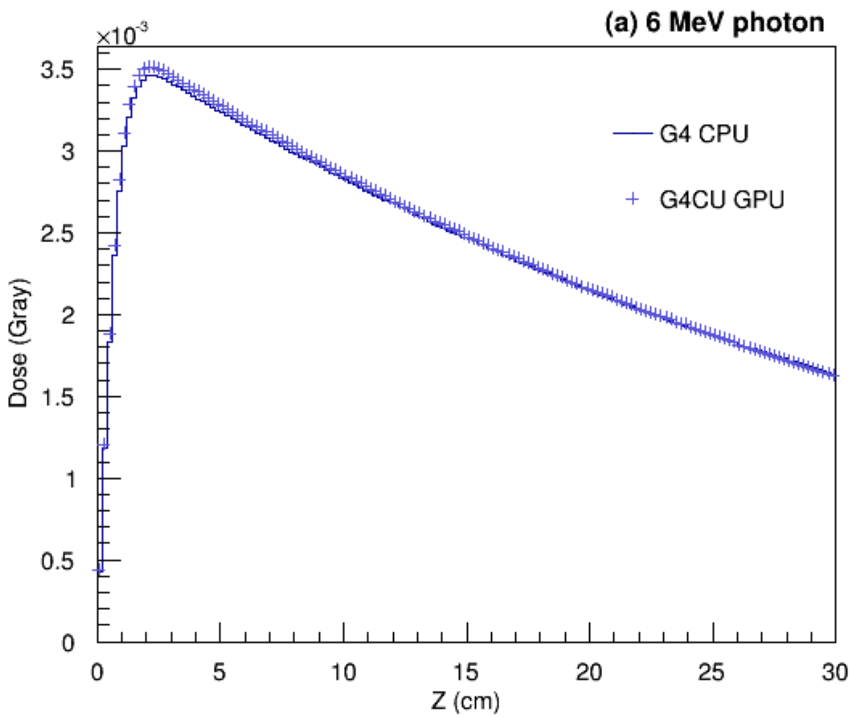
- 20 MeV electron / 6 MeV photons (mono-energy)
- 6 MV & 18 MV spectrum photons

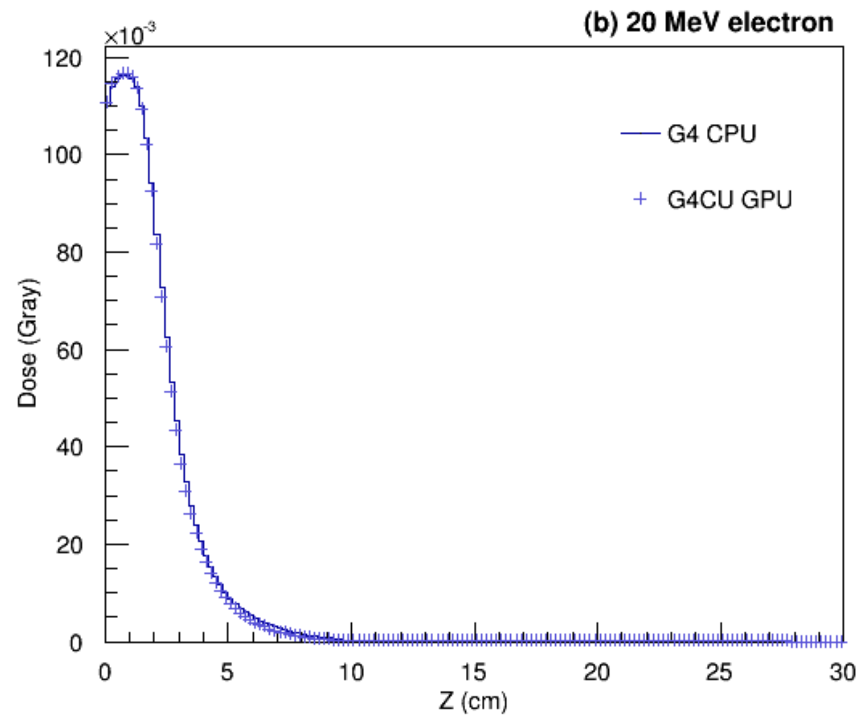




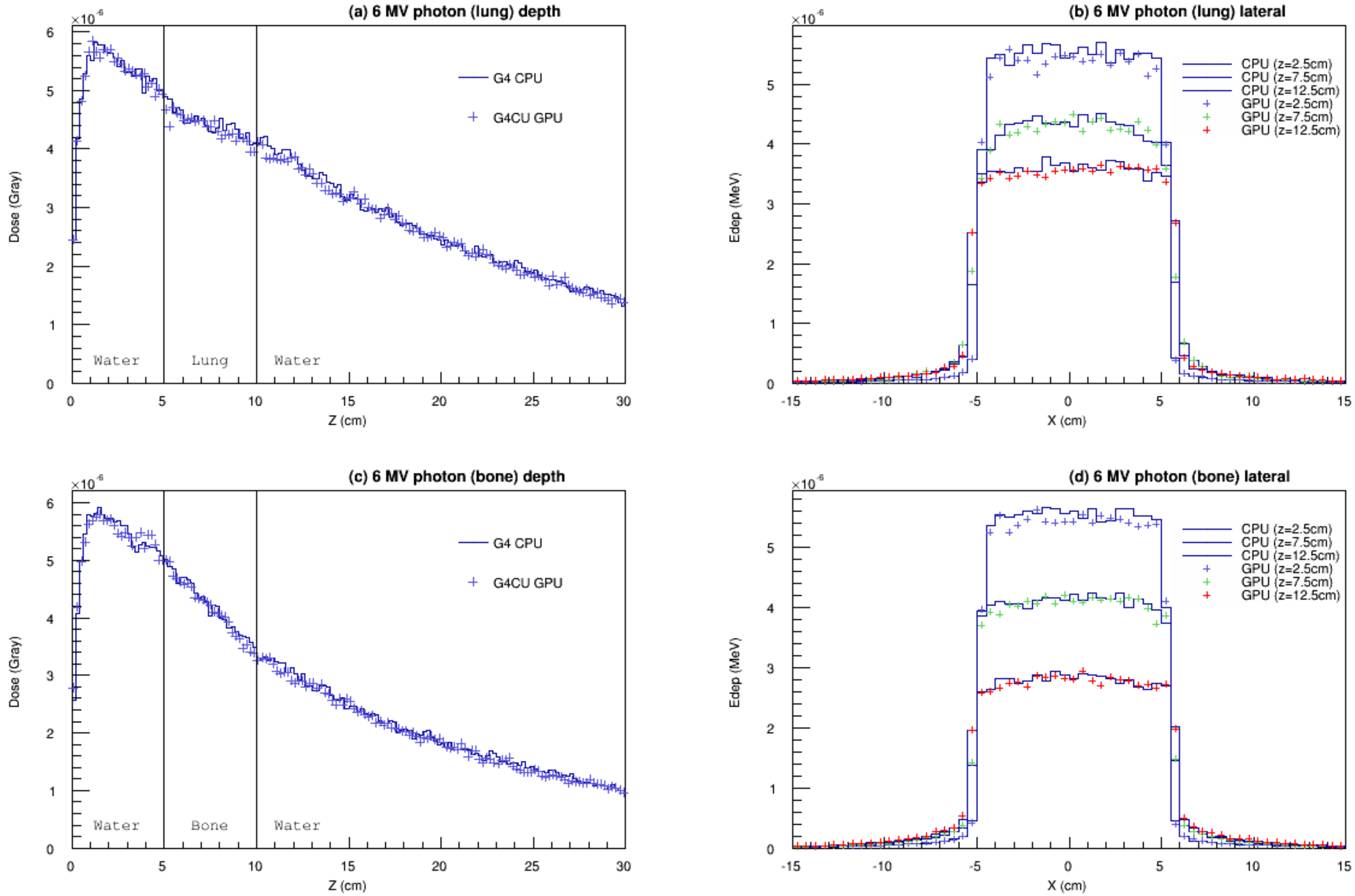
Depth dose distribution: water phantom

- 6MeV photon, 20 MeV electron
- dose along central axis





Comparisons for slab phantoms



6MV photon, Lung/Bone as inner slab material

Profile

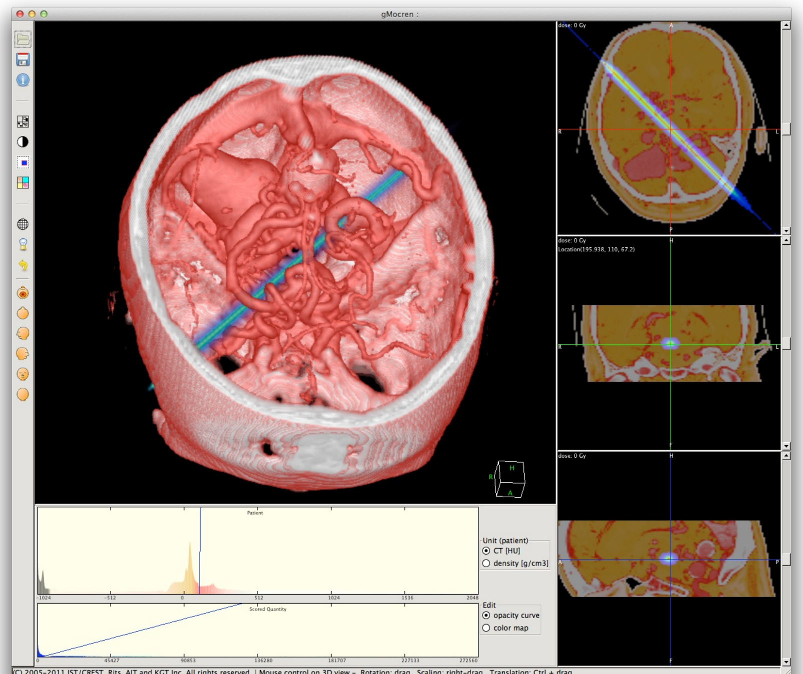
Process	Process total	Post step	PIL	Along step	Manag.	Init.	Step length	At-rest
Component total	**100.00**	**52.80**	**20.73**	**14.16**	**4.19**	**3.78**	**3.46**	**0.89**
Bremsstrahlung	**32.81**	29.83	2.23			0.75		
Ionization	**14.83**	1.70	3.50	8.84		0.79		
Photo-electric effect	**10.79**	8.80	1.57			0.41		
Gamma conversion	**10.67**	8.72	1.54			0.41		
Multiple scattering	**10.50**		3.43	4.58			2.49	
Transport	**8.67**	1.17	5.23	0.74		0.57	0.96	
Compton scattering	**4.20**	2.14	1.58			0.48		
Management	**4.19**				4.19			
Pair production	**2.56**	0.44	1.23			0.36		0.53
Electron deletion	**0.79**		0.43					0.36

Computation time comparison

Primary	Phantom	Time/History CPU (sec)	Time/History GPU (sec)	CPU/GPU
20 MeV electron (pencil)	Water	1.06E-03	2.52E-05	42.1
20 MeV electron (beam)	Lung	1.20E-03	2.67E-05	44.9
20 MeV electron (beam)	Bone	9.76E-4	2.54E-05	38.4
6 MeV photon (pencil)	Water	4.47E-04	1.12E-05	39.9
6 MV photon (beam)	Lung	3.52E-04	9.16E-06	38.4
6 MV photon (beam)	Bone	3.59E-04	9.00E-06	39.9
18 MV photon (beam)	Lung	4.05E-04	1.12E-05	36.2
18 MV photon (beam)	Bone	4.29E-04	1.17E-05	36.7

Observed GPU speed up over CPU: ~40x

Visualization with gMocren



- Image for demonstration purposes only!
- 50M 6MeV photons
- Pencil beam configuration

Future

- Performance improvement
  - texture memory usage for interpolation
  - different stack management for each particle type
- Physics performance
  - more detailed / statistical comparison and verification
  - energy deposition and msc, esp. for lower energy region
- Code design
  - dynamic physics table generation
  - class packaging
  - interfacing with peripheral components

Acknowledgements

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