Towards GPU Accelerated Simulation of Optical Calorimetry

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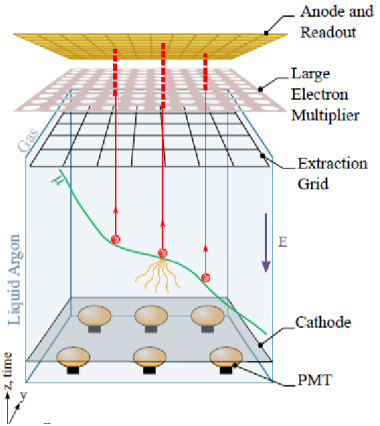
Coordination Panel for Advanced Detectors November 20th, 2024

Motivation

Detectors measuring **scintillation** and **Cerenkov** light are abundant!

- Liquid Argon TPCs (DUNE, SBND)
- Liquid Xenon TPCs (LZ)
- Gadolinium-Doped water Cerenkov detectors (ANNIE, Super-K)
- Dual readout calorimetry (CalVision)



LArTPC detector design principle [arxiv:2103.06395]

Problem: Optical Physics in Geant4

Geant4:

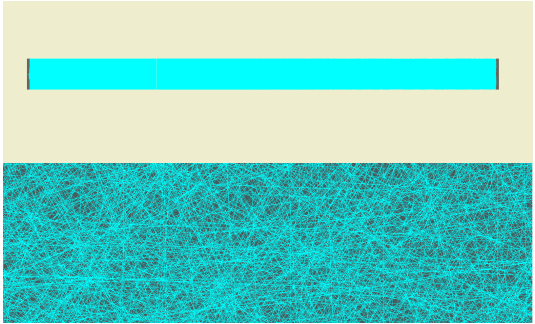
- Multithreaded on CPU
- Tracks evolve in independent threads
- Throughput scales with number of cores

HPC cluster available CPU cores: ~ 64

- $\sim 10,000$'s Cerenkov photons per event
- $\sim 100,000$'s scintillation photons per event

Doesn't scale well enough to run full optical simulations.

Example: 1 GeV muon incident on PWO_4



Zoomed: Geant4 optical photon tracks

- $\sim 20,000$ Cerenkov photons
- $\sim 100,000$ scintillation photons

Optical Physics Speed-Up Efforts

Fast Parameterizaitons

- Precompute detector response for single photons
- Scintillation well approximated (isotropic, constant spectrum)
- Cerenkov poorly approximated (highly velocity and direction dependent)
- Still need to simulate the initial parameterization

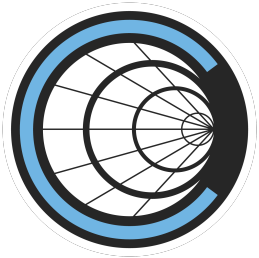
GPU Offloading

Pass initial photons to GPU simulations instead of a parameterization.

- Opticks: uses NVIDIA OptiX Engine
- Mitsuba3: just-in-time physics based renderer

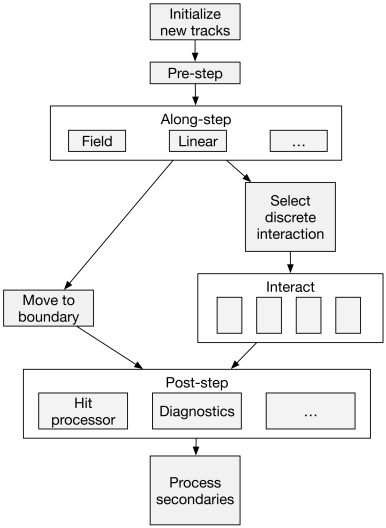
Celeritas: GPU Accelerated Detector Simulation

- **GPU accelerated**, CPU reproducible
- **Full fidelity** Monte Carlo detector simulation
- **Automated Geant4 integration** (geometry, physics, SD)
- **Open source** and actively seeking collaborators



Celeritas: Optical Physics

- Platform portable (CPU, NVIDIA, AMD, Intel)
- Separate main and optical tracking loop
  - Fine-tune optimizations for high count optical tracks
- Various integration methods
  - Standalone Celeritas full simulation
  - GPU offloading for Geant4 optical photons
  - Fast parameterization generation
  - Replace Geant4 optical physics



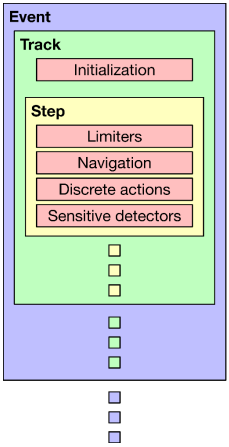
GPU Acceleration with “Actions”

Track independence allows loop reordering

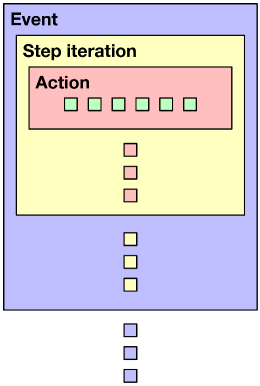
- Geant4: Event → Track → Steps
- Celeritas: Event → Steps → Tracks

Generalize steps to “actions” framework

- Loops over tracks on CPU or GPU
- Supports dynamic per-track state
- Customization point for GPU acceleration



CPU stepping loop

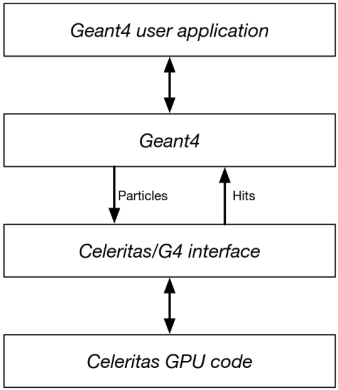


GPU stepping loop

Geant4 Integration

Goal: Drop Celeritas into existing Geant4 workflows with minimal users changes

- Directly import G4 data
- Geometry translation to VecGeom / ORANGE (Oak Ridge Advanced Nested Geometry Engine)
- Tracks offloaded to Celeritas
  - Hooks into G4's user managers
  - Selective offloading for mixed Celeritas / G4 runs
- Sensitive detector "hits" sent back to G4



Optical Physics Capabilities

Generators (implemented):

- Cerenkov and scintillation
- Runs in the main physics loop
- Create a small distribution struct
  - Pass to the optical loop
  - Generate photons from the distribution

Behavior looks like usual offloading!

- G4 and Celeritas distributions handled the same

Currently implemented:

- Absorption
- Rayleigh scattering

Planned:

- Wavelength shifting
- Mie scattering
- Surface optical physics

Proof-of-Concept: Photon Generation

- Single 10 MeV electron primary in a LAr sphere
  - Roughly **300 million** optical photons total
  - AMD EPYC 7532 (64 cores) vs Nvidia A100
- Only **generating** optical (scintillation and Cerenkov) photons, **not** tracking
  - `celer-sim` (standalone Celeritas): kill the optical photons immediately
  - `celer-g4` (Geant4 front-end): immediately kill optical photons via user tracking action

	CPU threads	Runtime (s)
Geant4	1	204.5
Celeritas CPU	1	99.3
Celeritas CPU (OMP)	64	5.7
Celeritas GPU	1	1.3

OMP: OpenMP Track level parallelism

150 CPU : 1 GPU performance tracks with previous results

Conclusion

- Celeritas is working towards full optical simulations
  - GPUs critical for performance
  - Platform portability
  - Geant4 compatability
- Still a work in progress
- Volumetric optical physics by end of year
- Surface physics by mid-2025
- Concurrent development of muon physics, neutrino physics, geometry, ...
- Actively coordinating with experiments to meet their simulation requirements and goals!

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- Code: github.com/celeritas-project/celeritas
- Documentation: celeritas-project.github.io/celeritas/dev/index.html
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