The TriForce Project: Progress and Plans

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Summary

- `TriForce` is a modular C++ framework for parallel GPU-accelerated particle-based hybrid fluid-kinetic 3D simulations
- The goal is to provide better predictive capability and access to advanced models for the benefit of the academic community.
- Student involvement: high school, undergraduate, and graduate

Why particles?

ALE meshes easily tangle

Particle and mesh-free approaches handle shear, eddies, and mix with higher accuracy and less dissipation…

… while reproducing standard hydro results

… and allowing fluid and kinetic descriptions to co-exist

Particle-based meshless fluid algorithms

Smoothed-particle hydrodynamics (SPH)

A meshless approach to CFD

Particle property P_i, Kernel W, Smoothing length h, Neighbors

MHDSPH

Impact in sand

Fragmenting ring

Liquid-solid interaction

ICF Implosion

Standard SPH vs RSPH: N_{neg}= 256

t = 8.55 ns

t = 9.2 ns

Mach 2 vs. Mach 6

All Materials

EOS(ρ,P,e)

Gas & fluids | Solids | Rigid (filled) | Rigid (plate)

Fully elastic | Plastic-elastic

Perfect plasticity | Plasticity limited by fracture | Porosity

Material models (fluids)

- Equation of state
  Analytic, tabular (FPEOS, LEOS, SESAME)
- Opacity and <Z>
  Analytic, tabular (Astrophys., FPEOS, etc)
- Electrical resistivity
  Spitzer, tabular (QLMD)
- Viscosity
  Real and artificial
- Surface tension
- Stress-strain and material strength
  Elastic-plastic, Steinberg-Guinan/-Lund

Other models and advanced structures

- Explicit or implicit particles & fields
- Adaptive particles and meshes
- Charged particle beams
- Ionization and excitation
- Magnetohydrodynamics
- Circuit model
- Nonlocal thermal conduction
- Nuclear fusion and α transport
- Neutron transport
- Photon transport
- Gravity
- Nonpolar geodesic polyhedral mesh
- Unstructured mesh (triangulated)
- Chaining cells
- KD-Trees
- RT and Tensor core GPU algorithms

Scientific motivation

Direct and indirect inertial confinement fusion (ICF)

Magneto-inertial fusion (MIF)

High-intensity lasers

Field-reversed configuration (FRC)

Pulsed power science

Modular multiphysics simulations

Architectural hierarchy

Driver — User-facing configuration directly via Python code or indirectly via Input Deck

Operation Sequencing — Specification and ordering of the core time-stepping loop

Data Management — Particle Data, Grid Data, Global Parameters

Physics Calculations — Field Integration, Particle EoM, Interpolation

More computational capability

More user flexibility

The software is being designed for
- development by multiple people
- use of abstract base classes
- modularity and extensibility
- compartmentalization of tasks
- alteration of simulation archetype
- rapid prototyping
- running in serial or parallel
- computing on CPUs or GPUs

MHD transport coefficient sensitivity studies

Impact of the choice on integrated modeling

Magnetized liner inertial fusion

Thermal conductivity and Nernst term

"2010 point design" →

Available models:
- Braginskii
- Epperlein-Haines
- Ji-Held-Davies
- Sadler

Longer-term goal:
- Compare MHD and XMHD to implicit E&M PIC

Coulomb collision models

$$\frac{\partial f_\alpha}{\partial t} + v \cdot \nabla f_\alpha + \frac{q_\alpha}{m_\alpha}\left(E + \frac{v \times B}{c}\right) \cdot \nabla_v f_\alpha = \left(\frac{\partial f_\alpha}{\partial t}\right)_{\text{col}}$$

- Drifting Maxwellian/thermal (fluid)
- Binary pairwise generalized (kinetic)

Equilibration test

First-principles stopping power

Electron slowing in cold ions

Electron beam in aluminum plasma

First-principles conductivity

Electrical conduction in copper plasma

Field-reversed configuration (FRC)

FRC fusion reactor

3D TriForce rendering

FRC rocket engine

Closed field lines confine the plasma

O-point, Seperatrix, X-point

Current

3D TriForce rendering

Laser propagation and absorption

- Standard ray tracing with inverse projection
- Complex ray tracing
- Wave-based launcher
- GPU-accelerated modeling

Direct drive ICF implosions

Supersonic turbulence

Crossed-beam energy transfer (CBET)

Field amplitude (eE/$m_e\omega_{0}c$)

Convergence ~ 2

P, ρ

Current density (-J_θ) in plasma

Reversed B_z field (from -J_θ)

Magnetized plasma physics

Plasma flow in pulsed-power transmission lines

Magnetically-driven implosions

DATA (X-RAYS)

SIMULATED

ρ > 4.9 g/cc

ρ > 4.2 g/cc

Low-noise "quiet" methods

Rays example: Smooth bundles (uses interpolation)

Ref: Schmitt

Particles examples: "quiet direct simulation" (QDS)

Sod shock tube using 4 p.p.c. (without artificial viscosity)

density, velocity, pressure

DS-MC/PIC vs QDS: Disassembly of 3D sphere, ρ_0 = 1, r_0 = 0.3

Density(x,y) @ z=0 | Density(x,z) @ y=0 | Density(y,z) @ x=0

DSMC (ppc = 125) | QDS (ppc = 64) | DSMC (ppc = 1000) | QDS (ppc = 64)

- QDS: Fewer particles, low noise, high dynamic range

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