Simulation of Interpenetrating Plasmas in 1D with a Multifluid Approach

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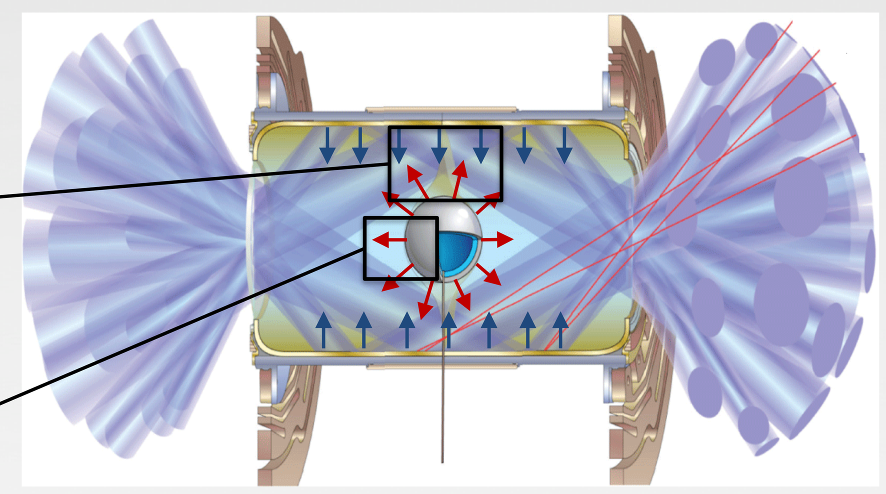
Motivation

Inertial Confinement Fusion: Colliding plasmas from hohlraum wall and capsule

Interpenetration of plasma flows from capsule and hohlraum wall

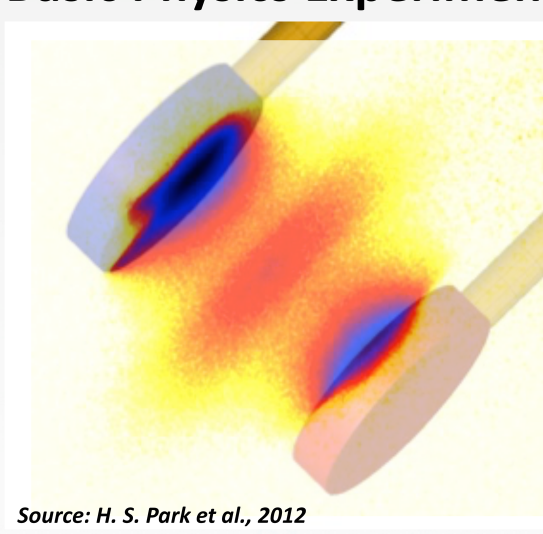
- Large range of Z: $2 \leq Z \leq 60$
- Supersonic flows ($\Delta u \approx 10^8$ cm/s)

Species separation inside target capsule



Source: https://csdl-images.computer.org/mags/cs/2014/06/figures/mcs20140600421.gif

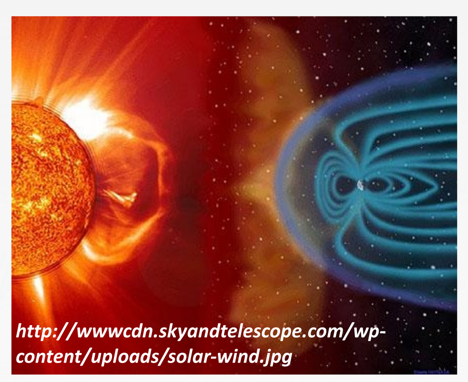
Basic Physics Experiments



Source: H. S. Park et al., 2012

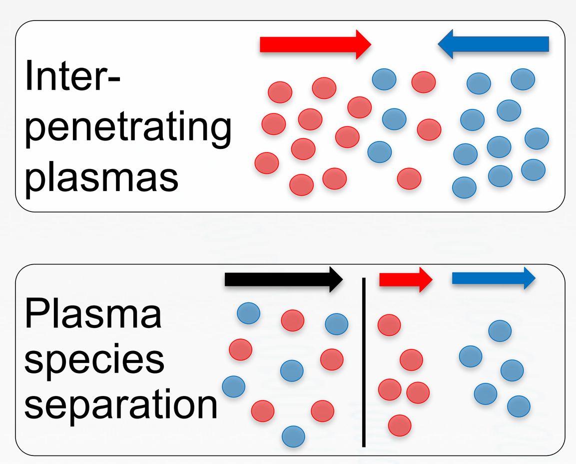
HED collisionless shock experiments

Astrophysics



Solar wind – collective kinetic effects slow counter-streaming plasmas

Multifluid phenomena that we want to model



Multifluid Model

- *Distinct flows* for each ion species and electrons
- All-species coupling via *friction* (collisions and kinetic processes) and *electric fields*
- Ion species can *separate* if friction weak & charge/mass ratios differ

Inviscid Euler equations for each species $\alpha = 1, \cdots, n_s$

$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot (\rho_\alpha \mathbf{u}_\alpha) = 0$$

$$\frac{\partial \rho_\alpha \mathbf{u}_\alpha}{\partial t} + \nabla (P_\alpha + \rho_\alpha \mathbf{u}_\alpha \otimes \mathbf{u}_\alpha) = -Z_\alpha e n_\alpha \nabla\phi + \sum_{\beta\neq\alpha} \mathbf{R}_{\alpha,\beta}$$

$$\frac{\partial \mathcal{E}_\alpha}{\partial t} + \nabla \cdot [(\mathcal{E}_\alpha + P_\alpha)\mathbf{u}_\alpha] = -Z_\alpha e n_\alpha \mathbf{u}_\alpha \cdot \nabla\phi + \sum_{\beta\neq\alpha} (\mathbf{R}_{\alpha,\beta}\cdot\mathbf{u}_\alpha + Q_{\alpha,\beta})$$

Interaction between species

Poisson equation for electrostatic potential

$$\nabla^2\phi = 4\pi e \left(n_e - \sum_\alpha Z_\alpha n_\alpha \right)$$

Frictional heating and thermal equilibration

$$Q_{\alpha,\beta} = Q^{\rm fric}_{\alpha,\beta} + Q^{\rm eq}_{\alpha,\beta}$$

$$Q^{\rm fric}_{\alpha,\beta} = m_{\alpha,\beta} n_\alpha \nu_{\alpha,\beta} (\mathbf{u}_\beta - \mathbf{u}_\alpha)^2$$

$$Q^{\rm eq}_{\alpha,\beta} = -3 m_\alpha n_\alpha \frac{\nu_{\alpha,\beta}}{m_\alpha + m_\beta}(T_\alpha - T_\beta) = -Q^{\rm eq}_{\beta,\alpha}$$

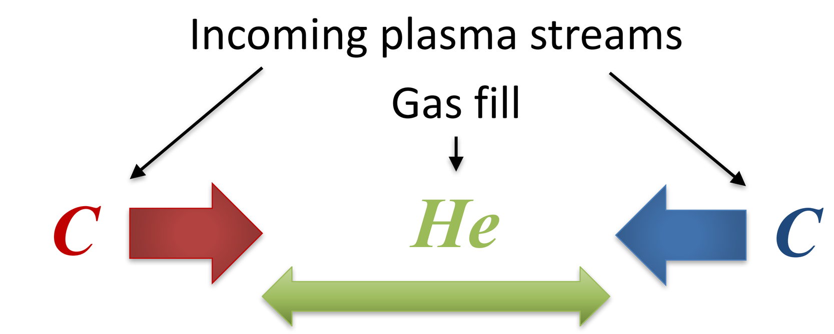
Frictional drag

$$\mathbf{R}_{\alpha,\beta} = m_\alpha n_\alpha \nu_{\alpha,\beta} (\mathbf{u}_\beta - \mathbf{u}_\alpha) = -\mathbf{R}_{\beta,\alpha}$$

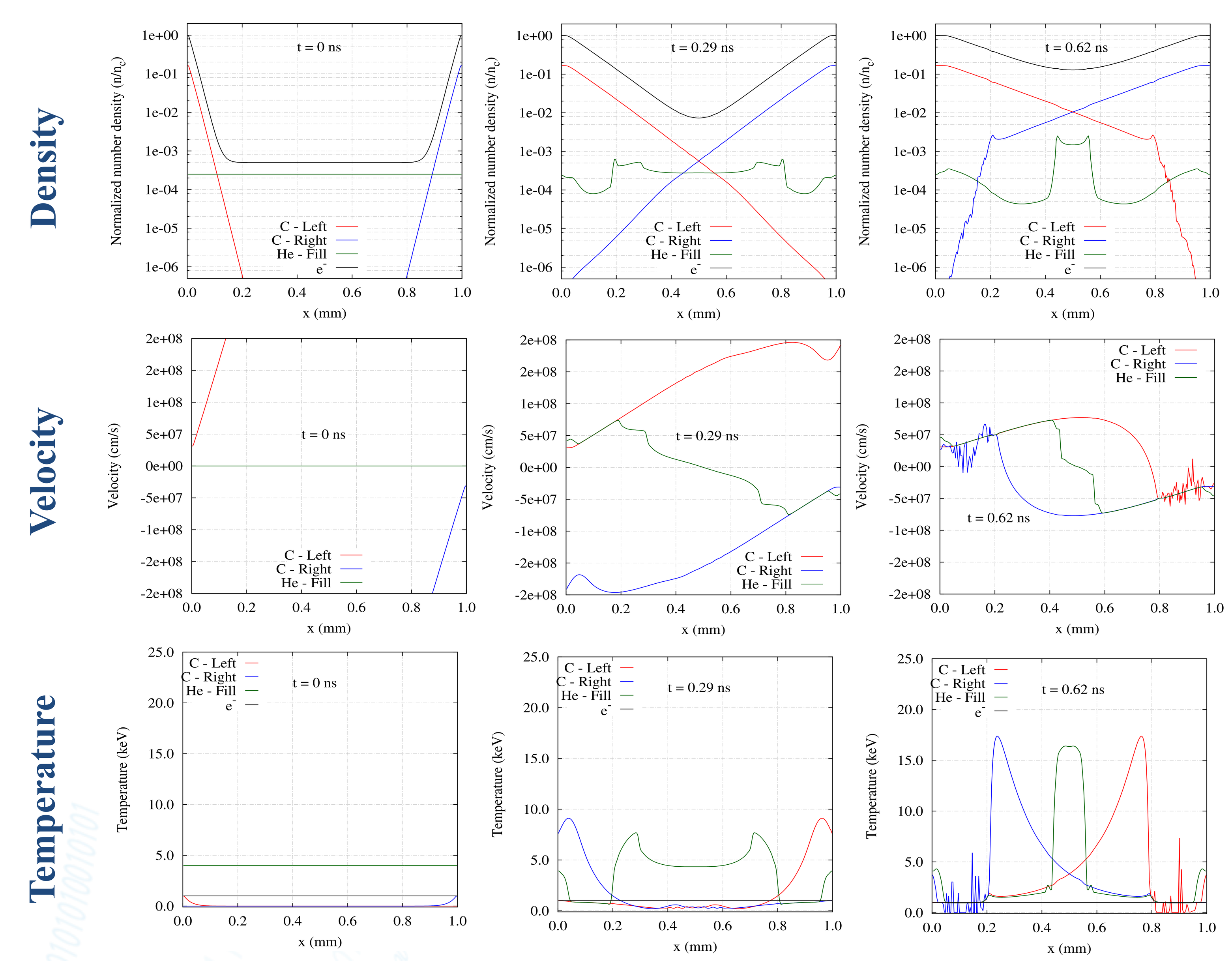
1D Results – Quasi-neutral Plasmas, Inertia-less and Isothermal Electrons

Finite-volume code for n fluids

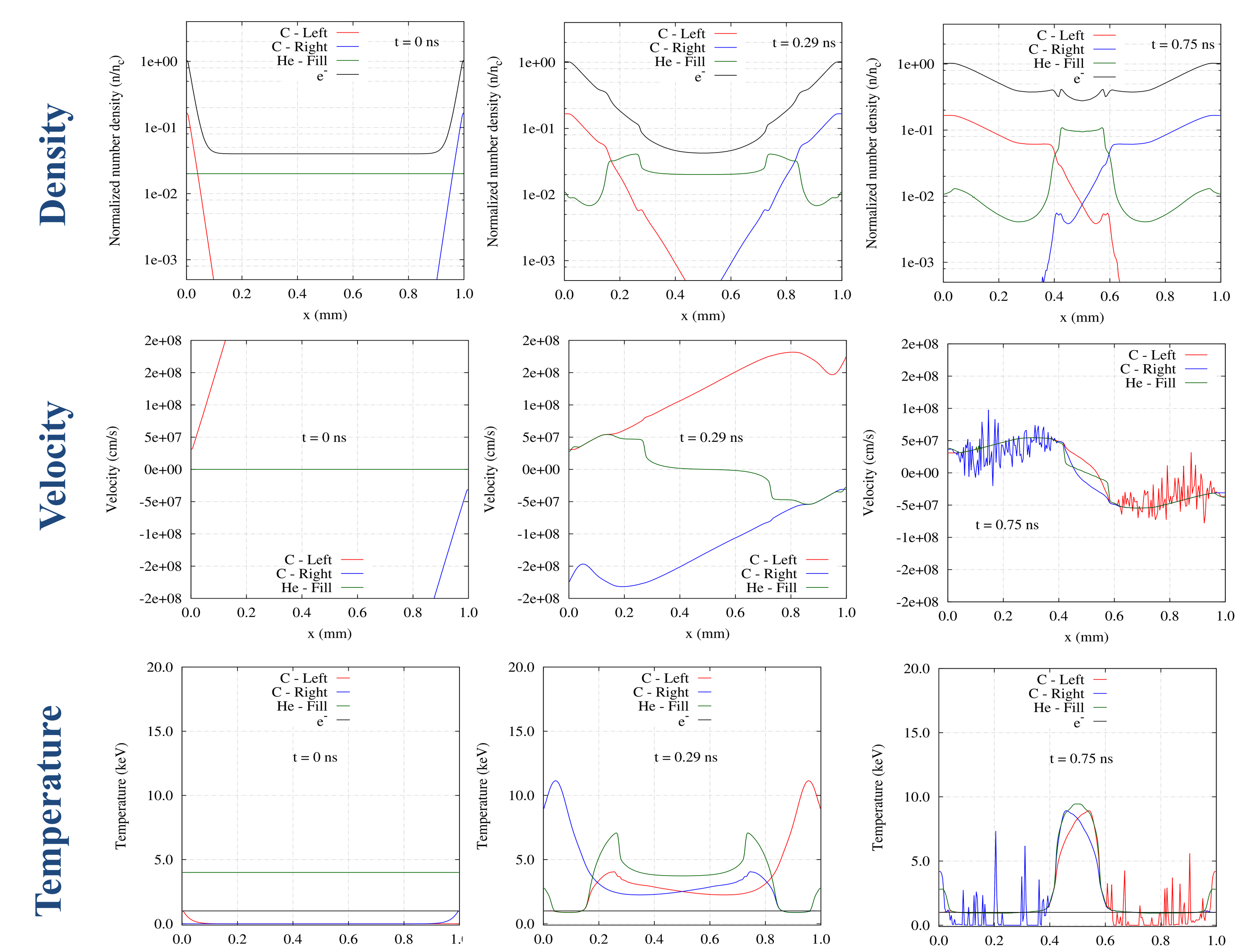
- Applied to simulate colliding plasmas
- 5th order WENO scheme for spatial discretization, 4th order explicit Runge-Kutta method for time integration



Low-density gas fill

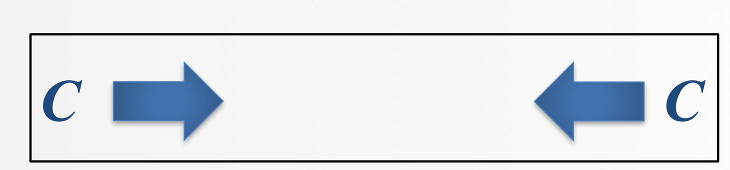


High-density gas fill



Why Not Single Fluid?

Single-fluid simulation *of colliding carbon plasma streams*

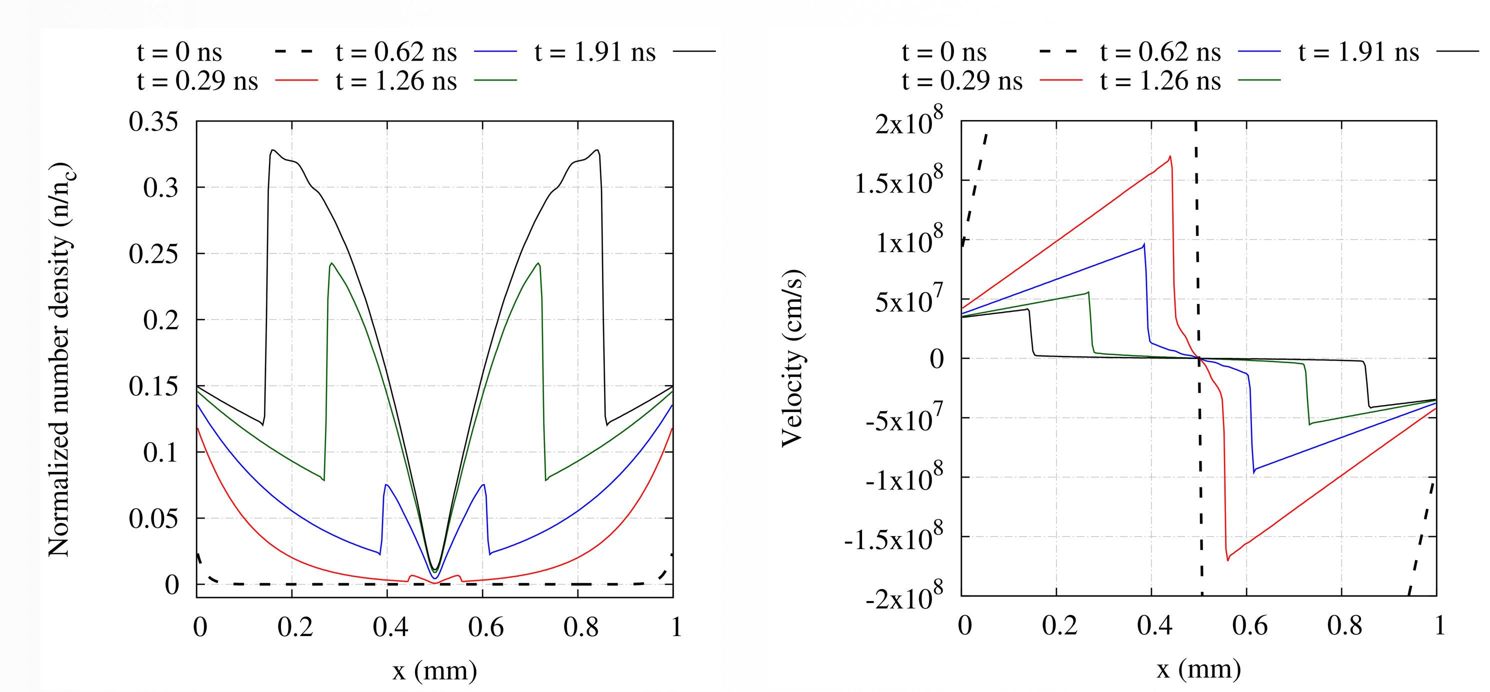


Initial and boundary conditions:

- Expansion fan inflows at x = 0, 1
- Vacuum inside the domain

Unphysical solution

- **Stagnation and density pile-up, shocks**
- Push-back of incoming plasma stream



Current and Future Work

- Develop high-order finite-volume code for the 3D multifluid equations (with AMR)
- Include ion and electron heat conduction and inverse Bremsstrahlung heat source
- Simulate recent experiments and validate 3D interpenetration measurements
- Develop reduced models to incorporate kinetic effects

References and previous work:

- S. Le Pape et al., APS DPP Annual Meeting (2016).
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- H.-S. Park et al., High Energy Density Phys. 8 (2012), 38
- C. Chenais-Popovics et al., Phys. Plas. 4, 190 (1997)

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