Modeling Neutral & Charged Fluids in VSim

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Introduction

- VSim has had neutral fluid capability for years, but these fluids are static and exist mainly for reactions

- We have recently developed **new** fluid models:
  - Fluid evolves in time according to
    - Euler equations for neutral fluid
    - MHD model (hybrid - Stanier 2018) for electron fluid
  - Includes stair-step boundaries/shapes
  - CPU/GPU capable

Neutral fluid

- Fluid evolved with Euler equations
- Fluid consists of 3 fields: density (*n*), flux (*nv*), and energy density (*E*)

$$\begin{aligned}\frac{\partial n}{\partial t} &= -\vec{\nabla}\cdot(n\vec{v}) \\ \frac{\partial n\vec{v}}{\partial t} &= -\vec{\nabla}\cdot(n\vec{v}\otimes\vec{v}+p\mathbf{I}) \\ \frac{\partial E}{\partial t} &= -\vec{\nabla}\cdot([E+p]\vec{v})\end{aligned}$$

witl $p = \left(E - \frac{1}{2}nmv^2\right)(\gamma - 1)$

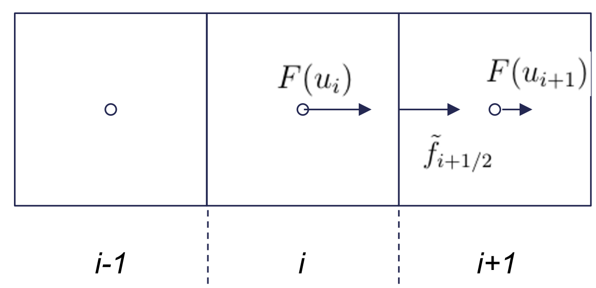
Neutral fluid (cont.)

- Conservative form lends itself to finite volume approach
- Calculate flux on cell faces, evolve local field based on these flux values according to:

$$\frac{du_i}{dt} = -\frac{1}{V_i}\left(A_{i+1/2}\tilde{f}_{i+1/2} - A_{i-1/2}\tilde{f}_{i-1/2}\right)$$

with

$$\tilde{f}_{i+1/2} = \frac{1}{2}\left(F(u_{i+1}) + F(u_i)\right) - \frac{\Delta x_i}{2\Delta t}\left(u_{i+1} - u_i\right)$$



VSim Euler Fluid Demo

Switching to VSim..

VSim Euler Grid Bndry Demo

Switch to VSim

Hybrid fluid model

- Sometimes the electron time scales and behavior are not important to the physics and the ion kinetics dominate
- In these cases, we need PIC ions, but would like to have fluid electrons
  - Increases time step
  - Decreases spatial resolution requirements
  - Assumes Maxwellian electrons

Hybrid fluid model (cont)

- Ions are kinetic: $$\frac{\partial f}{\partial t} + \vec{\nabla} \cdot (f_s \vec{v}) + (q_s/m_s)(\vec{E}^* + \vec{v} \times \vec{B}) \cdot \vec{\nabla}_v f_s = 0$$

- Electrons are fluid: $$\frac{\partial \vec{B}}{\partial t} + \vec{\nabla} \times \vec{E} = 0$$

$$(\gamma - 1)^{-1} \left[\frac{\partial p_e}{\partial t} + \vec{\nabla} \cdot (\vec{v}_e p_e) \right] + p_e \vec{\nabla} \cdot \vec{v_e} = H_e - \vec{\nabla} \cdot \vec{q_e}$$

$$\vec{E} = \vec{E}^* + \eta \vec{j} = -\vec{v}_i \times \vec{B} + \frac{\vec{j} \times \vec{B}}{ne} - \frac{\nabla p_e}{ne} - \frac{\vec{\nabla} \cdot \overleftrightarrow{\Pi}_e}{ne} + \eta \vec{j}.$$

Model from Stanier (2018) *Journal of Computational Physics*

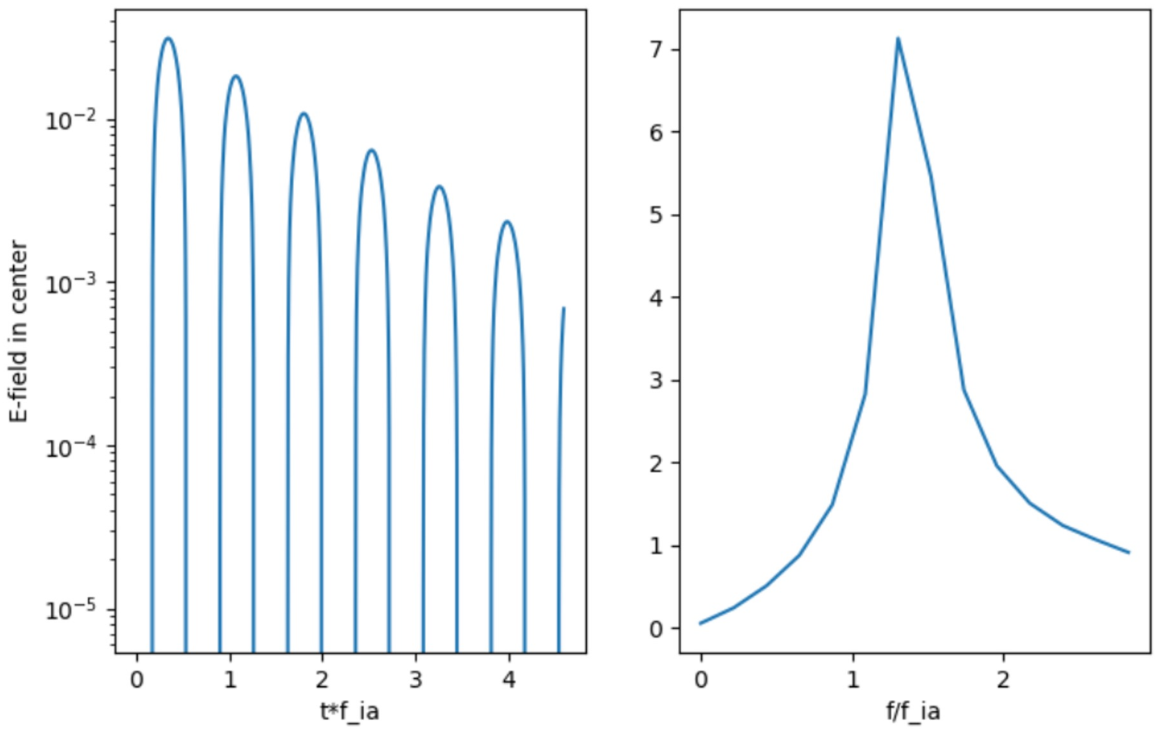
Benchmarking the model

- Two benchmarks:
  - Ion acoustic Landau damping
  - GEM challenge problem
- In both cases, the hybrid model should give as good an answer as PIC but with increased speed

Landau damping

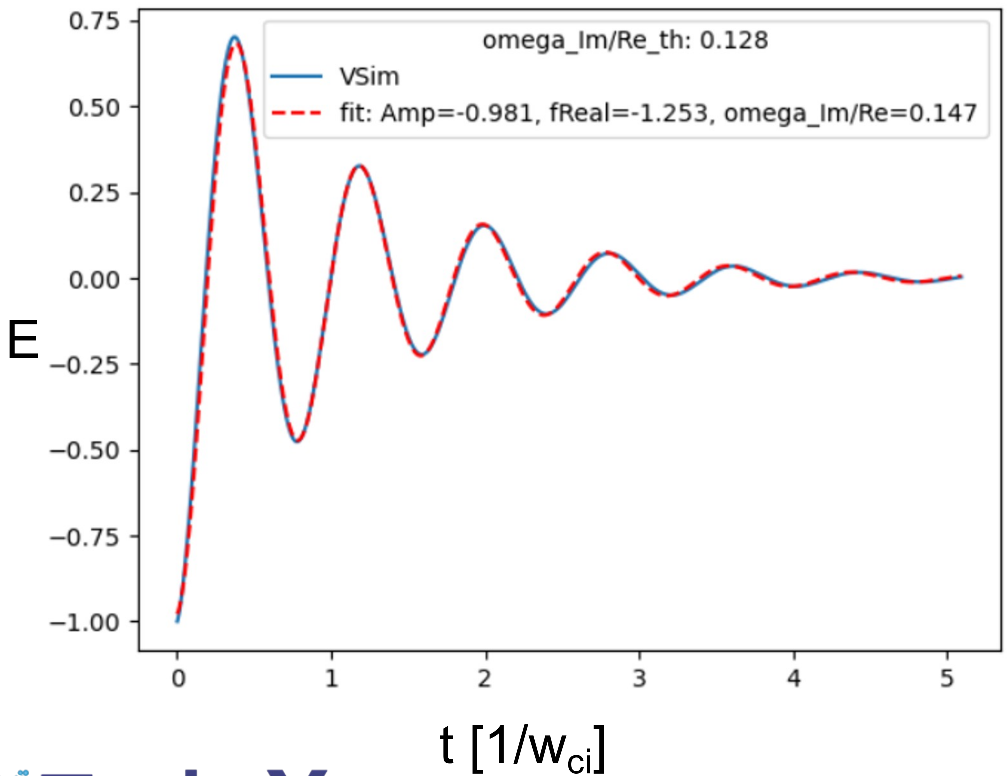
- Thermal plasma with density perturbation at ion acoustic wavelength results in electrostatic ion acoustic wave
- Wave and electron energy transferred to ions due to ion kinetic effects, damps oscillation of the ion acoustic wave
- Damping rate and oscillation frequency are known from theory

Landau damping results



Can look in VSim as well

Landau damping results



- Electric field decays, can fit to determine rate and frequency

- This is for Te/Ti = 5, damping rate is within 15% of theory

GEM Challenge

Setup:

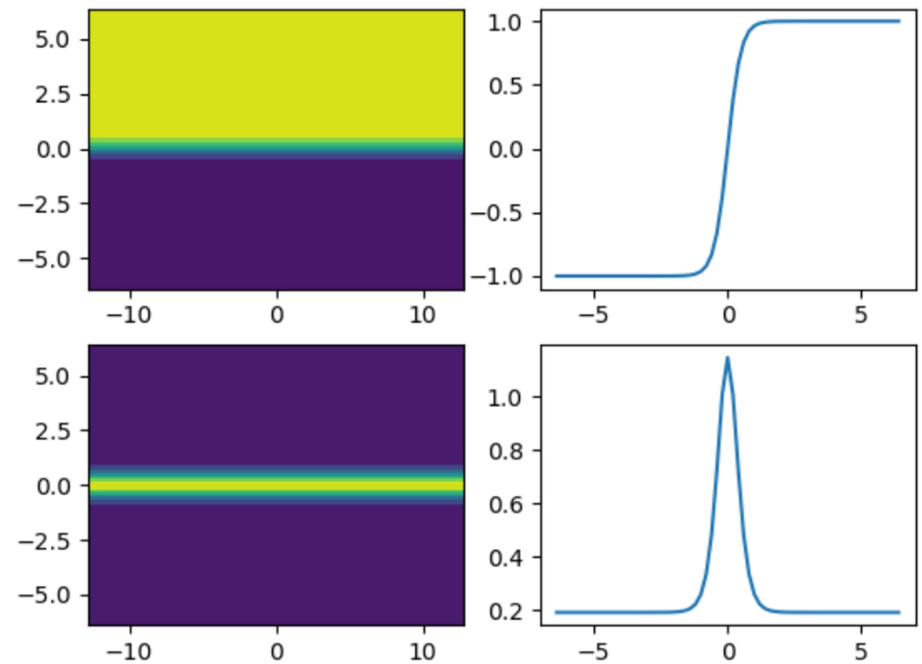
current sheet into page, narrow band of plasma pressure

Stable configuration with ideal plasma

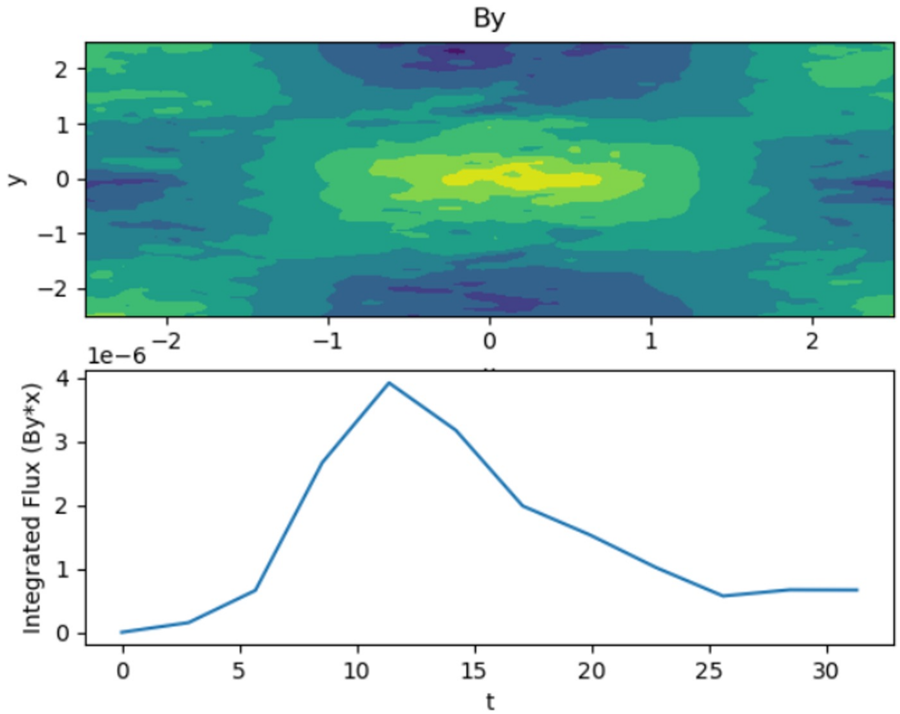
With resistivity, unstable

Bx

pe



GEM Challenge Results

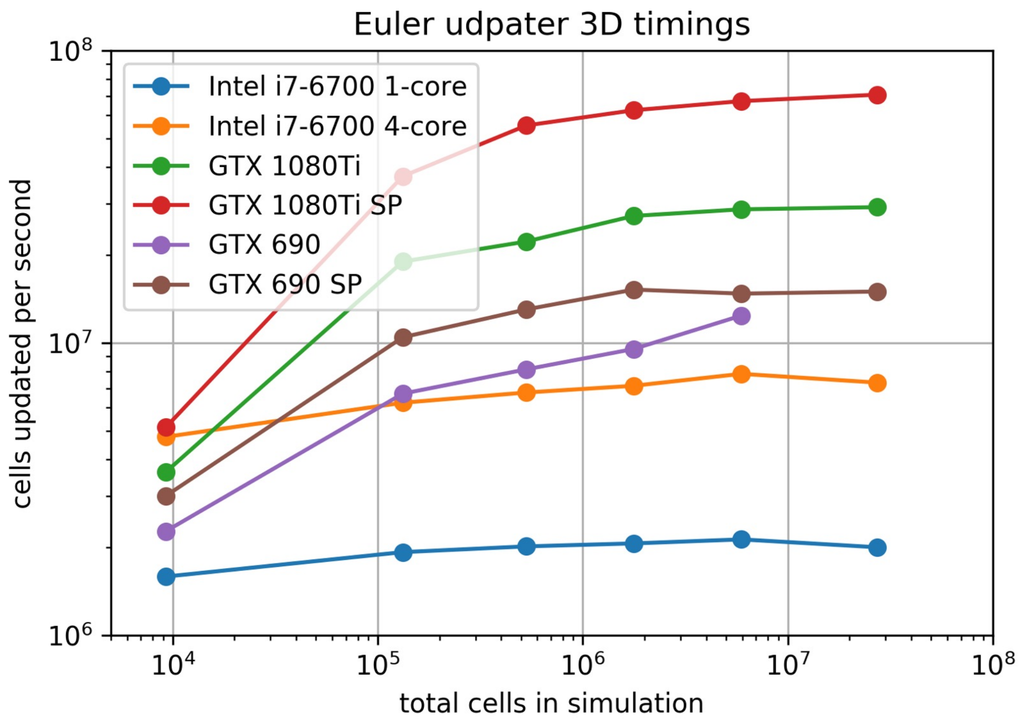


- Magnetic reconnection begins with generation of By as islands form
- Integrated vertical magnetic flux agrees with accepted results

Summary

- VSim12 will bring the ability to evolve fluids, both neutral and charged
- Fluids can be evolved in periodic, slab, or more complicated geometries
- What you saw today is all text-based setup, but will be in GUI for VSim12
- Any questions?

Fluid performance



GEM - Fluid vs Hybrid