

# **Tutorial for 1D hybrid (kinetic ions/massless fluid electrons) simulation code**

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**Materials found at:**

<https://gitlab.com/kyungguk/hybrid-code-tutorial>

- Introduction
- Hybrid Scheme & Demo Code Description
- Examples

## Hierarchy

1) Individual particles: Klimontovich equation

2) Kinetic:  $f = f(\mathbf{v}, \mathbf{x}, t)$

- Eulerian: Full Vlasov solvers

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} + \frac{q}{m} \left( \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right) \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

- Lagrangian: Particle-in-cell codes (where PSD is represented by simulation "marker" particles)
- Darwin, gyro-kinetic, drift kinetic, etc.

3) Hybrid

- One species kinetic, the other fluid; low-frequency approx. of EM fields
- Typically kinetic ions and inertial-less, quasi-neutral fluid electrons

4) Fluid

- MHD

## Hybrid Codes

- Hybrid codes arise from the need to model phenomena that do not resolve processes that occur on electron scales.
- Relevant scales: Ion gyro-radius, ion inertial spatial scales, and inverse ion gyro-frequency time scale.
- A full-dynamics PIC code must resolve electron dynamics at scales far smaller than that for ions, even though it is not relevant to the physical problems to be addressed.
- The hybrid approach differs from PIC in that
  - The displacement current is neglected in Ampère-Maxwell's law, eliminating the propagation of light waves;
  - The electrons are modeled as a massless charge-neutralizing fluid; and
  - The electric field is calculated from the generalized Ohm's law.

## Governing Equations

- Ion dynamics

$$m_i \frac{d\mathbf{v}_p}{dt} = q_i \left( \mathbf{E} + \frac{\mathbf{v}_p}{c} \times \mathbf{B} \right)$$

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p$$

- Electron dynamics  $\rightarrow \mathbf{E}(n_e, \mathbf{V}_e, P_e, \mathbf{B})$ : No explicit time dependence

$$n_e m_e \frac{d\mathbf{V}_e}{dt} = 0 = -en_e \left( \mathbf{E} + \frac{\mathbf{V}_e}{c} \times \mathbf{B} \right) - \nabla P_e$$

- Equation of state:  $d(P_e/n_e^\gamma)/dt = 0$

- Quasi-neutrality:  $q_e n_e = -q_i n_i$

- Ampere's law

$$\nabla \times \mathbf{B} = \frac{4\pi}{c} J + \cancel{\frac{\partial \mathbf{E}}{\partial t}}$$

- Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t} = -c(\nabla \times \mathbf{E})$$

## Typical Update Cycle and the Challenge

- Ion acceleration: Assume at time step  $N$ ,  $\mathbf{x}_p^N$ ,  $\mathbf{E}^N$ , and  $\mathbf{B}^N$  are known.

$$\mathbf{v}_p^{N+1/2} = \mathbf{v}_p^{N-1/2} + \frac{q_i \Delta t}{m_i} \left( \mathbf{E}^N + \frac{\mathbf{v}_p^N}{c} \times \mathbf{B}^N \right)$$

$$\mathbf{x}_p^{N+1} = \mathbf{x}_p^N + \mathbf{v}_p^{N+1/2} \Delta t$$

- Collect current at  $N + 1/2$  and density at  $N + 1$ .
- Update  $\mathbf{B}$  by a half-time step.

$$\mathbf{B}^{N+1/2} = \mathbf{B}^N - \frac{c \Delta t}{2} (\nabla \times \mathbf{E}^N)$$

- Calculate  $\mathbf{E}$  using the quantities at  $N+1/2$ .

$$\begin{aligned} \mathbf{E}^{N+1/2} &= -\frac{\mathbf{V}_i^{N+1/2}}{c} \times \mathbf{B}^{N+1/2} - \frac{\nabla P_e^{N+1/2}}{q_i n_i^{N+1/2}} - \frac{\mathbf{B}^{N+1/2} \times (\nabla \times \mathbf{B}^{N+1/2})}{4\pi q_i n_i^{N+1/2}} \\ &= \mathbf{E}(\mathbf{B}^{N+1/2}, n_i^{N+1/2}, \mathbf{V}_i^{N+1/2}) \end{aligned}$$

- Update  $\mathbf{B}$  by a half-time step.

$$\mathbf{B}^{N+1} = \mathbf{B}^{N+1/2} - \frac{c \Delta t}{2} (\nabla \times \mathbf{E}^{N+1/2})$$

- To complete the cycle, we need  $\mathbf{E}$  at  $N+1$ , but  $\mathbf{V}_i^{N+1}$  is not known.
- The evolution of hybrid codes has been developing a good algorithm that best calculates  $\mathbf{E}$  at the time step when the velocity is not available.

## **Algorithm 1: Predictor-corrector Method**

- Execute one or more of provisional updates to fine-tune  $\mathbf{E}$  at the desired time step.
  - Pros: Implementation is straightforward.
  - Cons: This involves multiple provisional particle pushes which are the most time-consuming part in PIC-type code.
- Basic idea:
  1. Make a prediction of the fields at  $N+1$
  2. Advance particles in the predicted field to get the ion source terms
  3. Use current and density to compute predicted fields at  $N+3/2$
  4. Determine corrected field at  $N+1$

## Algorithm 2: Current Advanced Method

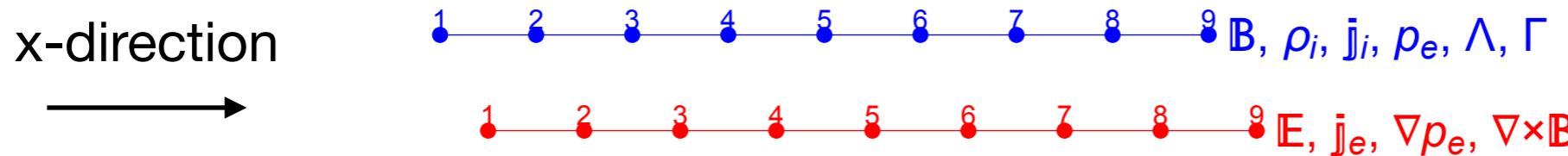
- Since the problem is not knowing  $\mathbf{V}_i^{N+1}$ , one can extrapolate  $\mathbf{V}_i^{N+1}$  using previously saved values.
- The most popular approach along that line is to calculate the current at  $N+1$  by doing an extra half-time step push.

$$\mathbf{V}'_i^{N+1} = \mathbf{V}_i^{N+1/2} + \frac{\Delta t q_i}{2m_i} \left( \mathbf{E}^* + \frac{\mathbf{V}_i^{N+1/2}}{c} \times \mathbf{B}^{N+1} \right)$$
$$\mathbf{E}^* = \mathbf{E}(\mathbf{B}^{N+1}, n_i^{N+1}, \mathbf{V}_i^{N+1/2})$$

- Because the current is defined at grid points, this extra step is trivial. And yet, it results in good energy conservation.

## Demo Code

- 1.5D: One-dimensional dependence and all three components of the field vectors.
- It assumes a homogeneous, collisionless, quasi-neutral plasma in a uniform background magnetic field.
- Both Predictor-corrector (Kunz et al., 2014) and CAM-CL (Matthew, 1994) algorithms are implemented.
- PIC technique and implementation are based on the full-dynamics code written by Liu (2007).
- Particles are advanced using the usual leap-frog algorithm with Boris push.
- **B** and **E** are saved at staggered grid points as follows:

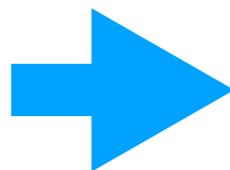


- Other quantities are defined so as to the 2nd-order centered difference makes sense as much as possible.
- All vector components are placed at the same grid point (not entirely Yee lattice).
- Three-point Hamming filter is applied to source terms to reduce grid-scale fluctuations:

$$\Phi_j^{filtered} = \frac{1}{4} \left( \Phi_{j-1}^{source} + 2\Phi_j^{source} + \Phi_{j+1}^{source} \right)$$

## Change of Variables

$$\left\{ \begin{array}{l} \frac{q_0}{m_0 c} \mathbf{E} = \vec{\Xi} \\ \frac{q_0}{m_0 c} \mathbf{B} = \vec{\Omega} \\ \frac{4\pi q_0}{m_0} \rho = \Pi \\ \frac{4\pi q_0}{m_0 c} \mathbf{J} = \vec{\mathcal{J}} \\ \frac{4\pi q_0^2}{m_0^2 c^2} P_e = \mathcal{P}_e \\ \omega_s = \sqrt{\frac{4\pi q_s^2 n_s(0)}{m_s}} \\ \Omega_s = \frac{q_s B_0}{m_s c} \end{array} \right.$$



$$\left\{ \begin{array}{l} \Pi_e = -\Pi_i = -\sum_{s \neq e} \Pi_s & \text{Charge neutrality} \\ \frac{\partial \vec{\Omega}}{\partial t} = -c \nabla \times \vec{\Xi} & \text{Faraday's law} \\ \vec{\mathcal{J}} = c \nabla \times \vec{\Omega} & \text{Ampere's law} \\ \vec{\Xi} = \frac{1}{\Pi_i} \left[ (\vec{\mathcal{J}} - \vec{\mathcal{J}}_i) \times \vec{\Omega} - c \nabla \mathcal{P}_e \right] & \text{Generalized Ohm's law} \\ \frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p & \text{Velocity} \\ \frac{d\mathbf{v}_p}{dt} = \frac{\Omega_s}{\Omega_0} \left( c \vec{\Xi} + \mathbf{v}_p \times \vec{\Omega} \right) & \text{Lorentz force} \\ \frac{\partial \vec{\mathcal{J}}_i}{\partial t} = \sum_{s \neq e} \Pi_s \frac{\Omega_s}{\Omega_0} \left( \vec{\Xi} + \frac{\mathbf{V}_s}{c} \times \vec{\Omega} \right) \\ = \Lambda_i \vec{\Xi} + \vec{\Gamma}_i \times \vec{\Omega} & \text{Current Advance} \end{array} \right.$$

Background B

Bulk velocity

- Electron pressure:

$$\mathcal{P}_e(t) = \Omega_0^2 \frac{\beta_e}{2} \left( \frac{\Pi_e(t)}{\Pi_e(0)} \right)^\gamma = \Omega_0^2 \frac{\beta_e}{2} \left( -\frac{\Omega_e \Pi_i(t)}{\Omega_0 \omega_e^2} \right)^\gamma, \text{ where } \omega_e^2 = \frac{\Omega_e}{\Omega_0} \Pi_e(0)$$

## Change of Variables

- With new variables, a population of ions is described by their cyclotron frequency ( $\Omega_s$ ), plasma frequency ( $\omega_s$ ) (and temperatures, etc. depending on velocity distribution functions), instead of mass, charge, and the number density.
- The electric field ( $\Xi$ ) and the magnetic field ( $\Omega$ ) have units of frequency, and are understood to be a sum of the static and perturbed part (i.e.,  $\Omega = \Omega_0 + \delta\Omega$ ).
- Whereas, charge, current, and energy densities (or pressure) has units of frequency squared.
- The electric and magnetic field energy densities are  $\Xi^2/2$  and  $\Omega^2/2$ , which then have units of frequency squared.
- $\Omega_0$  denotes magnitude of the uniform background magnetic field. Time is in units of  $\Omega_0^{-1}$ .
- The ratio  $\Omega_s/\Omega_0$  describes the kind of ions. As an example, if  $\Omega_p/\Omega_0 = 2\pi$ , protons gyrate once per  $\Omega_0^{-1}$ . For  $\text{He}^+$ , this ratio is then  $2\pi/4$ ; and for  $\text{He}^{2+}$ , it is  $2\pi/2$ .

## **Particle Update & Overall PIC Technique**

- See Dr. Lee San-Yun's tutorial.

## Magnetic Field Update

x-direction  
→

$j=1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9$   $\mathbf{B}, \rho_i, \mathbf{j}_i, p_e, \Lambda, \Gamma$

$j=1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9$   $\mathbf{E}, \mathbf{j}_e, \nabla p_e, \nabla \times \mathbf{B}$

- Magnetic field

$$\frac{\partial \vec{\Omega}}{\partial t} = -c \nabla \times \vec{\Xi} \quad \longrightarrow \quad \begin{cases} \Omega_{x;j}^{t+\Delta t} - \Omega_{x;j}^t = 0; \\ \Omega_{y;j}^{t+\Delta t} - \Omega_{y;j}^t = \frac{c\Delta t}{\Delta x} \left( +\Xi_{z;j-0}^{t+\Delta t/2} - \Xi_{z;j-1}^{t+\Delta t/2} \right); \\ \Omega_{z;j}^{t+\Delta t} - \Omega_{z;j}^t = \frac{c\Delta t}{\Delta x} \left( -\Xi_{y;j-0}^{t+\Delta t/2} + \Xi_{y;j-1}^{t+\Delta t/2} \right). \end{cases}$$

// BField.cc

```
void H1D::BField::_update(BField &B, EField const &E, Real cdt0Dx) noexcept
{
    for (long i = 0; i < E.size(); ++i) {
        B[i].x += 0;
        B[i].y += (+E[i-0].z - E[i-1].z) * cdt0Dx;
        B[i].z += (-E[i-0].y + E[i-1].y) * cdt0Dx;
    }
}
```

$$\frac{c\Delta t}{\Delta x}$$

# Electric Field Calculation

x-direction  
→

$j=1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9$   $\mathbf{B}, \rho_i, \mathbf{j}_i, p_e, \Lambda, \Gamma$

$j=1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9$   $\mathbf{E}, \mathbf{j}_e, \nabla p_e, \nabla \times \mathbf{B}$

- Electron pressure
  - $\beta_e = n_e(0)T_e(0)/(B_0^2/8\pi)$
  - $\omega_e = \sqrt{(4\pi e^2 n_e(0)/m_e)}$ ; initial electron plasma frequency
  - $\Omega_e = -eB_0/(m_e c)$ ; initial electron cyclotron frequency

$$\mathcal{P}_e(t) = \Omega_0^2 \frac{\beta_e}{2} \left( \frac{\Pi_e(t)}{\Pi_e(0)} \right)^\gamma = \Omega_0^2 \frac{\beta_e}{2} \left( -\frac{\Omega_e \Pi_i(t)}{\Omega_0 \omega_e^2} \right)^\gamma$$

// EField.cc

```
void H1D::EField::_update_Pe(decltype(Pe) &Pe, Charge const &rho) noexcept
{
```

```
    namespace eFluid = Input::eFluid;
```

```
//
```

```
using Input::00;
```

```
Real const 002be02 = (00*00)*eFluid::beta*0.5;
```

```
Real const m0e000oe2 = -eFluid::0c/(00*(eFluid::op*eFluid::op));
```

```
Real const gamma = Real{eFluid::closure/10}/(eFluid::closure%10);
```

```
for (long i = -Pad; i < Pe.size() + Pad; ++i) {
```

```
    Pe[i] = std::pow(m0e000oe2*Real{rho[i]}, gamma) * 002be02;
```

```
}
```

```
}
```

$$-\frac{\Omega_e}{\Omega_0 \omega_e^2}$$

$$\frac{\Omega_0^2 \beta_e}{2}$$

$$\Pi_i$$

## Electric Field Calculation (cont'd)

x-direction  
→

$j=1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9$   $\mathbf{B}, \rho_i, \mathbf{j}_i, p_e, \Lambda, \Gamma$

$j=1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9$   $\mathbf{E}, \mathbf{j}_e, \nabla p_e, \nabla \times \mathbf{B}$

- Electron current:  $\mathbf{J}_e = \mathbf{J} - \mathbf{J}_i = c \nabla \times \boldsymbol{\Omega} - \mathbf{J}_i$

$$\left\{ \begin{array}{l} \mathcal{J}_{e,x;j} = -\frac{\mathcal{J}_{i,x;j+1} + \mathcal{J}_{i,x;j+0}}{2} + 0; \\ \mathcal{J}_{e,y;j} = -\frac{\mathcal{J}_{i,y;j+1} + \mathcal{J}_{i,y;j+0}}{2} + \frac{c}{\Delta x} \left( -\Omega_{z;j+1} + \Omega_{z;j+0} \right); \\ \mathcal{J}_{e,z;j} = -\frac{\mathcal{J}_{i,z;j+1} + \mathcal{J}_{i,z;j+0}}{2} + \frac{c}{\Delta x} \left( +\Omega_{y;j+1} - \Omega_{y;j+0} \right). \end{array} \right.$$

// EField.cc

```
void H1D::EField::_update_Je(decltype(Je) &Je, Current const &Ji, BField const &B) noexcept
{
    Real const c0Dx = Input::c/Input::Dx;
    for (long i = 0; i < B.size(); ++i) {
        // J total
        //
        Je[i].x = 0;
        Je[i].y = (-B[i+1].z + B[i+0].z)*c0Dx;
        Je[i].z = (+B[i+1].y - B[i+0].y)*c0Dx;

        // Je = J - Ji
        //
        Je[i] -= (Ji[i+1] + Ji[i+0])*0.5;
    }
}
```

## Electric Field Calculation (cont'd)

x-direction  
→

$j=1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9$   $\mathbf{B}, \rho_i, \mathbf{j}_i, p_e, \Lambda, \Gamma$

$j=1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9$   $\mathbf{E}, \mathbf{j}_e, \nabla p_e, \nabla \times \mathbf{B}$

- Electric field

$$\vec{\mathbf{E}} = \frac{2}{\Pi_{i;j+1} + \Pi_{i;j+0}} \left[ \vec{\mathcal{J}}_e \times \frac{\vec{\Omega}_{j+1} + \vec{\Omega}_{j+0}}{2} - c \nabla \mathcal{P}_e \right] \leftarrow \begin{cases} (c \nabla \mathcal{P}_e)_{x;j} = \frac{c}{\Delta x} (\mathcal{P}_{e;j+1} - \mathcal{P}_{e;j+0}); \\ (c \nabla \mathcal{P}_e)_{y;j} = 0; \\ (c \nabla \mathcal{P}_e)_{z;j} = 0. \end{cases}$$

// EField.cc

```
void H1D::EField::_update_E(EField &E, BField const &B, Charge const &rho) noexcept
{
    Real const c0Dx = Input::c/Input::Dx;
    for (long i = 0; i < E.size(); ++i) {
        Vector &Ei = E[i];

        // 1.  $\mathbf{J}_e \times \mathbf{B}$  term
        //
        Ei = cross(Je[i], (B[i+1] + B[i+0])*0.5);

        // 2. pressure gradient term
        //
        Ei.x -= Real{Pe[i+1] - Pe[i+0]}*c0Dx;
        Ei.y -= 0;
        Ei.z -= 0;

        // 3. divide by charge density
        //
        Ei /= Real{rho[i+1] + rho[i+0]}*0.5;
    }
}
```

## Velocity Moments

- Solving field equations only requires quantities weighted by a velocity distribution function and summed over velocity space.

0th:  $n_s = \langle 1 \rangle_s = \int (1) f_s(t, \mathbf{x}, \mathbf{v}) d^3\mathbf{v} \longrightarrow \text{Charge density} = q_s \langle 1 \rangle_s$

1st:  $n_s \mathbf{V}_s = \langle \mathbf{v} \rangle_s = \int (\mathbf{v}) f_s(t, \mathbf{x}, \mathbf{v}) d^3\mathbf{v} \longrightarrow \text{Current density} = q_s \langle \mathbf{v} \rangle_s$

2nd:  $\langle \mathbf{v}\mathbf{v} \rangle_s = \int (\mathbf{v}\mathbf{v}) f_s(t, \mathbf{x}, \mathbf{v}) d^3\mathbf{v}$   
→ Kinetic energy density =  $m_s \sum_{j=x,y,z} \left\langle \frac{v_j^2}{2} \right\rangle_s$

→ Pressure Tensor  $= m_s \left( \langle \mathbf{v}\mathbf{v} \rangle_s - n_s \mathbf{V}_s \mathbf{V}_s \right)$

- How can velocity moments be obtained? More generally, what does the operation  $\langle \dots \rangle$  mean in a PIC code?

## Velocity Moments (cont'd)

- Imagine equally-spaced simulation grid points.
- Initially, the number density  $n_s(0)$  is spatially uniform and the particle velocity distribution is represented by  $N_c = 10$  marker (simulation) particles.

**t = 0**

$j - 1$	$j$ Cell	$j + 1$
10	10	10

- Over time, some particles will leave the  $j$  cell; Likewise, some also enter the  $j$  cell.

**t > 0**

$j - 1$	$j$ Cell	$j + 1$
20	5	10

$$n_s(t) = 2 \times n_s(0)$$

$$n_s(t) = 1 \times n_s(0)$$

$$n_s(t) = 0.5 \times n_s(0)$$

- In the figure above, the number of particles in the  $j$ th cell decreased by a factor of 2; that means  $n_s(t)$  there is also half of the initial value.
- Formally,

$$\frac{n_{s;j}(t)}{n_s(0)} = \sum_{p=1}^{N_{s,p}} \frac{S(x_{s,p}(t) - X_j)}{N_{c,s}}$$

Shape function

$$n_s = \langle 1 \rangle_s = \int (1) f_s d^3v$$

## Velocity Moments (cont'd)

$$\frac{\int (1) f_s(t, \mathbf{x}, \mathbf{v}) d^3v}{n_s(0)} = \frac{\sum_{p=1}^{N_{s,p}} (1) S(x_{s,p}(t) - X_j)}{N_{c,s}}$$

Generalization



$$\langle \dots \rangle_s = \int (\dots) f_s(t, \mathbf{x}, \mathbf{v}) d^3v = n_s(0) \frac{\sum_{p=1}^{N_{s,p}} (\dots) S(x_{s,p}(t) - X_j)}{N_{c,s}}$$

$$\omega_s^2 = \frac{4\pi q_s^2 n_s(0)}{m_s} = \frac{\Omega_s}{\Omega_0} \Pi_s(0)$$

$$\Pi_{i;j}(t) = \sum_{s \neq e} \frac{\Omega_0}{\Omega_s} \omega_s^2 \langle 1 \rangle'_s$$

$$\vec{\mathcal{J}}_{i;j}(t) = \sum_{s \neq e} \frac{\Omega_0}{\Omega_s} \frac{\omega_s^2}{c} \langle \mathbf{v} \rangle'_s$$

$$\mathcal{E}_{i;j}(t) = \sum_{s \neq e} \frac{\Omega_0^2}{\Omega_s^2} \frac{\omega_s^2}{c^2} \langle v^2/2 \rangle'_s$$

where

$$\langle \dots \rangle'_s = \frac{\langle \dots \rangle_s}{n_s(0)} = \frac{\sum_{p=1}^{N_{s,p}} (\dots) S(x_{s,p}(t) - X_j)}{N_{c,s}}$$

## Velocity Moments (cont'd)

```
// Species.cc

void H1D::Species::_collect_all(GridQ<Scalar> &n, GridQ<Vector> &nV, GridQ<Tensor> &nvv) const
{
    n.fill(Scalar{0});
    nV.fill(Vector{0});
    nvv.fill(Tensor{0});
    Tensor tmp{0};
    ::Shape sx;
    for (Particle const &ptl : bucket) {
        sx(ptl.pos_x); // position is normalized by grid size
        n.deposit(sx, 1); (a)
        nV.deposit(sx, ptl.vel); (b)
        tmp.hi() = tmp.lo() = ptl.vel;
        tmp.lo() *= ptl.vel; // diagonal part; {vx*vx, vy*vy, vz*vz}
        tmp.hi() *= {ptl.vel.y, ptl.vel.z, ptl.vel.x}; // off-diag part; {vx*vy, vy*vz, vz*vx}
        nvv.deposit(sx, tmp); (c)
    }
    // ...
    n /= Scalar{Nc};
    nV /= Vector{Nc};
    nvv /= Tensor{Nc};
}


$$\frac{\sum_{p=1}^{N_{s,p}} (\dots) S(x_{s,p}(t) - X_j)}{N_{c,s}}$$


```

$$\left\{ \begin{array}{l} (a) \rightarrow \sum_{p=1}^{N_{s,p}} (1) S(x_{s,p}(t) - X_j) \\ (b) \rightarrow \sum_{p=1}^{N_{s,p}} (\mathbf{v}_p) S(x_{s,p}(t) - X_j) \\ (c) \rightarrow \sum_{p=1}^{N_{s,p}} (\{v_x^2, v_y^2, v_z^2, v_x v_y, v_y v_z, v_z v_x\}) S(x_{s,p}(t) - X_j) \end{array} \right.$$

## Velocity Moments (cont'd)

$$\Pi_i = \sum_{s \neq e} \frac{\Omega_0}{\Omega_s} \omega_s^2 \langle 1 \rangle'_s$$

// Charge.cc

```
H1D::Charge &H1D::Charge::operator+=(Species const &sp) noexcept
{
    ::accumulate(this->dead_begin(), sp.moment<0>().dead_begin(), sp.moment<0>().dead_end(), sp.charge_density_conversion_factor());
    return *this;
}
```

$$\Pi_i \quad \langle 1 \rangle'_s \quad \frac{\Omega_0}{\Omega_s} \omega_s^2$$

$$\vec{\mathcal{J}}_i = \sum_{s \neq e} \frac{\Omega_0}{\Omega_s} \frac{\omega_s^2}{c} \langle \mathbf{v}_p \rangle'_s$$

// Current.cc

```
H1D::Current &H1D::Current::operator+=(Species const &sp) noexcept
{
    ::accumulate(this->dead_begin(), sp.moment<1>().dead_begin(), sp.moment<1>().dead_end(), sp.current_density_conversion_factor());
    return *this;
}
```

$$\vec{\mathcal{J}}_i \quad \langle \mathbf{v}_p \rangle'_s \quad \frac{\Omega_0}{\Omega_s} \frac{\omega_s^2}{c}$$

# Current Advance Algorithm

$$\left\{ \begin{array}{l} \frac{\partial \vec{\mathcal{J}}_i}{\partial t} = \Lambda_i \vec{\Xi} + \vec{\Gamma}_i \times \vec{\Omega}, \\ \text{where } \Lambda_i = \sum_{s \neq e} \omega_s^2 \langle 1 \rangle'_s = \sum_{s \neq e} \frac{\Omega_s}{\Omega_0} \left( \frac{\Omega_0}{\Omega_s} \omega_s^2 \langle 1 \rangle'_s \right), \\ \text{and } \vec{\Gamma}_i = \sum_{s \neq e} \frac{\omega_s^2}{c} \langle \mathbf{v}_p \rangle'_s = \sum_{s \neq e} \frac{\Omega_s}{\Omega_0} \left( \frac{\Omega_0}{\Omega_s} \frac{\omega_s^2}{c} \langle \mathbf{v}_p \rangle'_s \right). \end{array} \right.$$

// Charge.cc

```
H1D::Lambda &H1D::Lambda::operator+=(Species const &sp) noexcept
{
    ::accumulate(this->dead_begin(), sp.moment<0>().dead_begin(), sp.moment<0>().dead_end(),
                sp.charge_density_conversion_factor()*sp.0c/Input::00);
    return *this;
}
```

$\Lambda_i$	$\langle 1 \rangle'_s$	$\frac{\Omega_0}{\Omega_s} \omega_s^2$	$\frac{\Omega_s}{\Omega_0}$
-------------	------------------------	--	-----------------------------

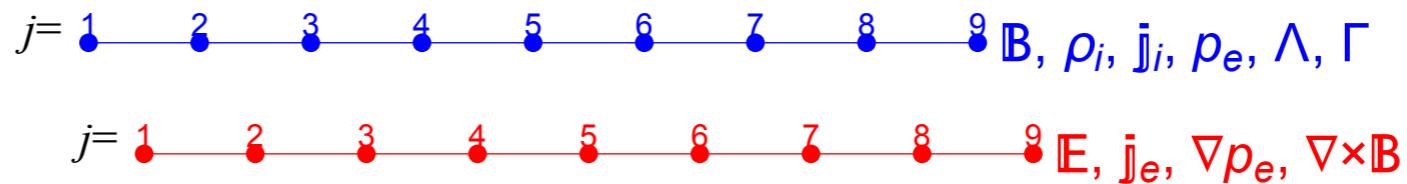
// Current.cc

```
H1D::Gamma &H1D::Gamma::operator+=(Species const &sp) noexcept
{
    ::accumulate(this->dead_begin(), sp.moment<1>().dead_begin(), sp.moment<1>().dead_end(),
                sp.current_density_conversion_factor()*sp.0c/Input::00);
    return *this;
}
```

$\vec{\Gamma}_i$	$\langle \mathbf{v}_p \rangle'_s$	$\frac{\Omega_0}{\Omega_s} \frac{\omega_s^2}{c}$	$\frac{\Omega_s}{\Omega_0}$
------------------	-----------------------------------	--	-----------------------------

## Current Advance Algorithm (cont'd)

x-direction  
→



$$\vec{\mathcal{J}}_{i;j}^{t+\Delta t} - \vec{\mathcal{J}}_{i;j}^t = \Delta t \left( \Lambda_{i;j} \frac{\vec{\Xi}_{j-0} + \vec{\Xi}_{j-1}}{2} + \vec{\Gamma}_{i;j} \times \vec{\Omega}_j \right)$$

// Current.cc

```
void H1D::Current::_advance(Current &J, Lambda const &L, Gamma const &G, BField const &B,
EField const &E, Real const dt) noexcept
{
    for (long i = 0; i < J.size(); ++i) {
        Vector const &Ei = (E[i-0] + E[i-1])*0.5;
        J[i] += (Ei*Real{L[i]} + cross(G[i], B[i])) *= dt;
    }
}
```

# Update Cycle: Kunz's PC

## 1. Predict $\mathbf{B}$ and $\mathbf{E}$ at $N+1/2$

$$\mathbf{B}'^{N+1} = \mathbf{B}^N - c\Delta t(\nabla \times \mathbf{E}^N)$$

$$\mathbf{E}'^{N+1} = \mathbf{E}(\mathbf{B}'^{N+1}, \rho_i^N, \mathbf{J}_i^N)$$

$$\mathbf{B}'^{N+1/2} = (\mathbf{B}'^{N+1} + \mathbf{B}^N)/2$$

$$\mathbf{E}'^{N+1/2} = (\mathbf{E}'^{N+1} + \mathbf{E}^N)/2$$

```
// Domain_PC.cc
//
// 1. Faraday's law; predict 1
//
bfield_1 = bfield_0;
bfield_1.update(efield_0, dt), delegate->pass(domain, bfield_1);
//
// 2. Ohm's law; predict 1
//
efield_1.update(bfield_1, charge, current), delegate->pass(domain, efield_1);
//
// 3. Average fields
//
(bfield_1 += bfield_0) *= Vector{.5};
(efield_1 += efield_0) *= Vector{.5};
```

## 2. Provisional particle push

$$\mathbf{x}_p'^{N+1/2} = \mathbf{x}_p^N + \mathbf{v}_p^N \Delta t / 2$$

$$\mathbf{v}_p'^{N+1} = \mathbf{v}_p^N + \frac{q_i}{m_i c} \Delta t (c \mathbf{E}'^{N+1/2} + \mathbf{v}_p^{N+1/2} \times \mathbf{B}'^{N+1/2})$$

$$\mathbf{x}_p'^{N+1} = \mathbf{x}_p'^{N+1/2} + \mathbf{v}_p'^{N+1} \Delta t / 2$$

```
// Domain_PC.cc
//
// 4 & 5. Particle push and deposit charge and
//         current densities; predict
//
charge.reset();
current.reset();
for (Species const &sp : species) {
    predictor = sp;
    predictor.update_pos(dt/2.0, 0.5);
    predictor.update_vel(bfield_1, efield_1, dt);
    predictor.update_pos(dt/2.0, 0.5),
        delegate->pass(domain, predictor);
```

## 3. Collect provisional charge and current

densities:  $\rho_i'^{N+1}$ ,  $\mathbf{J}_i'^{N+1}$

```
predictor.collect_part();
charge += predictor;
current += predictor;
}
delegate->gather(domain, current),
    delegate->pass(domain, current);
delegate->gather(domain, charge),
    delegate->pass(domain, charge);
```

## Update Cycle: Kunz's PC (cont'd)

### 4. Refine $\mathbf{B}$ and $\mathbf{E}$ at $N+1/2$

$$\mathbf{B}'^{N+1} = \mathbf{B}^N - c\Delta t(\nabla \times \mathbf{E}'^{N+1/2})$$

$$\mathbf{E}'^{N+1} = \mathbf{E}(\mathbf{B}'^{N+1}, \rho_i'^N, \mathbf{J}_i'^N)$$

$$\mathbf{B}'^{N+1/2} = (\mathbf{B}'^{N+1} + \mathbf{B}^N)/2$$

$$\mathbf{E}'^{N+1/2} = (\mathbf{E}'^{N+1} + \mathbf{E}^N)/2$$

### 5. Particle push

$$\mathbf{x}_p^{N+1/2} = \mathbf{x}_p^N + \mathbf{v}_p^N \Delta t / 2$$

$$\mathbf{v}_p^{N+1} = \mathbf{v}_p^N + \frac{q_i}{m_i c} \Delta t (c \mathbf{E}'^{N+1/2} + \mathbf{v}_p^{N+1/2} \times \mathbf{B}'^{N+1/2})$$

$$\mathbf{x}_p^{N+1} = \mathbf{x}_p^{N+1/2} + \mathbf{v}_p^{N+1} \Delta t / 2$$

### 6. Collect corrected charge and current densities: $\rho_i^{N+1}$ , $\mathbf{J}_i^{N+1}$

$$\rho_i^{N+1}, \mathbf{J}_i^{N+1}$$

```
// Domain_PC.cc
//
// 6. Faraday's law; predict 2
//
bfield_1 = bfield_0;
bfield_1.update(efield_1, dt), delegate->pass(domain, bfield_1);
//
// 7. Ohm's law; predict 2
//
efield_1.update(bfield_1, charge, current), delegate->pass(domain, efield_1);
//
// 8. Average fields
//
(bfield_1 += bfield_0) *= Vector{.5};
(efield_1 += efield_0) *= Vector{.5};
```

```
// Domain_PC.cc
//
// 9 & 10. Particle push and deposit charge and
//           current densities; correct
//
charge.reset();
current.reset();
for (Species &sp : species) {
    sp.update_pos(dt/2.0, 0.5);
    sp.update_vel(bfield_1, efield_1, dt);
    sp.update_pos(dt/2.0, 0.5),
        delegate->pass(domain, sp);
```

```
    sp.collect_part();
    charge += sp;
    current += sp;
}
delegate->gather(domain, current),
    delegate->pass(domain, current);
delegate->gather(domain, charge),
    delegate->pass(domain, charge);
```

## Update Cycle: Kunz's PC (cont'd)

### 7. Calculate corrected **B** and **E** at N+1

$$\begin{aligned}\mathbf{B}^{N+1} &= \mathbf{B}^N - c\Delta t(\nabla \times \mathbf{E}'^{N+1/2}) \\ \mathbf{E}^{N+1} &= \mathbf{E}(\mathbf{B}^{N+1}, \rho_i^N, \mathbf{J}_i^N)\end{aligned}$$

```
// Domain_PC.cc
//
// 11. Faraday's law; correct
// bfield_0.update(efield_1, dt), delegate->pass(domain, bfield_0);
// 12. Ohm's law; correct
// efield_0.update(bfield_0, charge, current), delegate->pass(domain, efield_0);
```

# Update Cycle: Matthews' CAM-CL

## 1. Advance particle velocity from N-1/2 to N+1/2 and collect moments

$$\mathbf{v}_p^{N+1/2} = \mathbf{v}_p^{N-1/2} + \frac{q_i}{m_i c} \Delta t (c \mathbf{E}^N + \mathbf{v}_p^N \times \mathbf{B}^N)$$

$$\rho_i^N = \rho(\mathbf{x}_p^N)$$

$$\mathbf{J}_i^- = \mathbf{J}(\mathbf{x}_p^N, \mathbf{v}_p^{N+1/2})$$

## 2. Advance particle position from N to N+1 and collect moments

$$\mathbf{x}_p^{N+1} = \mathbf{x}_p^N + \mathbf{v}_p^{N+1/2} \Delta t$$

$$\rho_i^{N+1} = \rho(\mathbf{x}_p^{N+1})$$

$$\mathbf{J}_i^+ = \mathbf{J}(\mathbf{x}_p^{N+1}, \mathbf{v}_p^{N+1/2})$$

$$\Lambda_i^{N+1} = \Lambda(\mathbf{x}_p^{N+1})$$

$$\Gamma_i^+ = \Gamma(\mathbf{x}_p^{N+1}, \mathbf{v}_p^{N+1/2})$$

## 3. Calculate charge and current at N+1/2

$$\rho_i^{N+1/2} = (\rho_i^N + \rho_i^{N+1})/2$$

$$\mathbf{J}_i^{N+1/2} = (\mathbf{J}_i^- + \mathbf{J}_i^+)/2$$

```
// Domain_CAMCL.cc
// 1 & 2. update velocities and positions by full step and
//          collect charge and current densities
//
current_0.reset();
current_1.reset();
charge_0.reset();
charge_1.reset();
lambda.reset();
gamma.reset();
for (Species &sp : species) {
    sp.update_vel(bfield, efield, dt); // v^N-1/2 -> v^N+1/2
    sp.collect_part();
    current_0 += sp; // J^-
    charge_0 += sp; // rho^N

    sp.update_pos(dt, 1),
        delegate->pass(domain, sp); // x^N -> x^N+1
    sp.collect_part();
    current_1 += sp; // J^+
    charge_1 += sp; // rho^N+1
    lambda += sp; // L^N+1
    gamma += sp; // G^+
}
//
// 3. gather, smooth and average charge and current densities
//
delegate->gather(domain, current_0),
    delegate->pass(domain, current_0);
delegate->gather(domain, charge_0),
    delegate->pass(domain, charge_0);
delegate->gather(domain, current_1),
    delegate->pass(domain, current_1);
delegate->gather(domain, charge_1),
    delegate->pass(domain, charge_1);
delegate->gather(domain, lambda);
delegate->gather(domain, gamma);

(charge_0 += charge_1) *= Scalar{.5}; // rho^N+1/2
(current_0 += current_1) *= Vector{.5}; // J^N+1/2
```

## Update Cycle: Matthews' CAM-CL (cont'd)

### 4. Calculate $\mathbf{B}$ at N+1 using subcycling algorithm

$$\mathbf{B}^{N+1} = \mathbf{B}^N - c \int_{t^N}^{t^{N+1}} \nabla \times \mathbf{E}(\mathbf{B}(t), \rho_i^{N+1/2}, \mathbf{J}_i^{N+1/2}) dt$$

```
// Domain_CAMCL.cc
// 4. subcycle magnetic field by full step
// subcycle(domain, charge_0, current_0, dt);
```

### 5. Advance current by half step

$$\mathbf{E}^* = \mathbf{E}(\mathbf{B}^{N+1}, \rho_i^{N+1}, \mathbf{J}_i^{N+1/2})$$

$$\mathbf{J}_i^{N+1} = \mathbf{J}^+ + \frac{\Delta t}{2} (\Lambda_i^{N+1} \mathbf{E}^* + \Gamma_i^+ \times \mathbf{B}^{N+1})$$

```
//
// 5. calculate electric field* and
//      advance current density
//
efield.update(bfield, charge_1, current_0),
            delegate->pass(domain, efield);
current_1.advance(lambda, gamma, bfield, efield, dt/2.0),
            delegate->pass(domain, current_1);
```

### 6. Calculate $\mathbf{E}$ at N+1

$$\mathbf{E}^{N+1} = \mathbf{E}(\mathbf{B}^{N+1}, \rho_i^{N+1}, \mathbf{J}_i^{N+1})$$

```
//
// 6. calculate electric field
//
efield.update(bfield, charge_1, current_1),
            delegate->pass(domain, efield);
```

## Update Cycle: Matthews' CAM-CL (cont'd)

- Magnetic field subcycling algorithm ( $m$  is the number of sub-cycles)

Define  $\mathbf{E}_j = \mathbf{E}(\mathbf{B}_j, \rho_i^{N+1/2}, \mathbf{J}_i^{N+1/2})$ , where  $\mathbf{B}_j = \mathbf{B}^{N+j/m}$  and  $\delta t = \Delta t/m$ .

```
 $\mathbf{B}_1 = \mathbf{B}_0 - c\delta t \nabla \times \mathbf{E}_0,$     // prologue
 $\mathbf{B}_{j+1} = \mathbf{B}_{j-1} - 2c\delta t \nabla \times \mathbf{E}_j,$  where  $j = 1, \dots, m-1,$     // loop
 $\mathbf{B}_m^* = \mathbf{B}_{m-1} - c\delta t \nabla \times \mathbf{E}_m,$  and finally    // epilogue
 $\mathbf{B}^{N+1} = (\mathbf{B}_m + \mathbf{B}_m^*)/2.$     // average
// Domain_CAMCL.cc

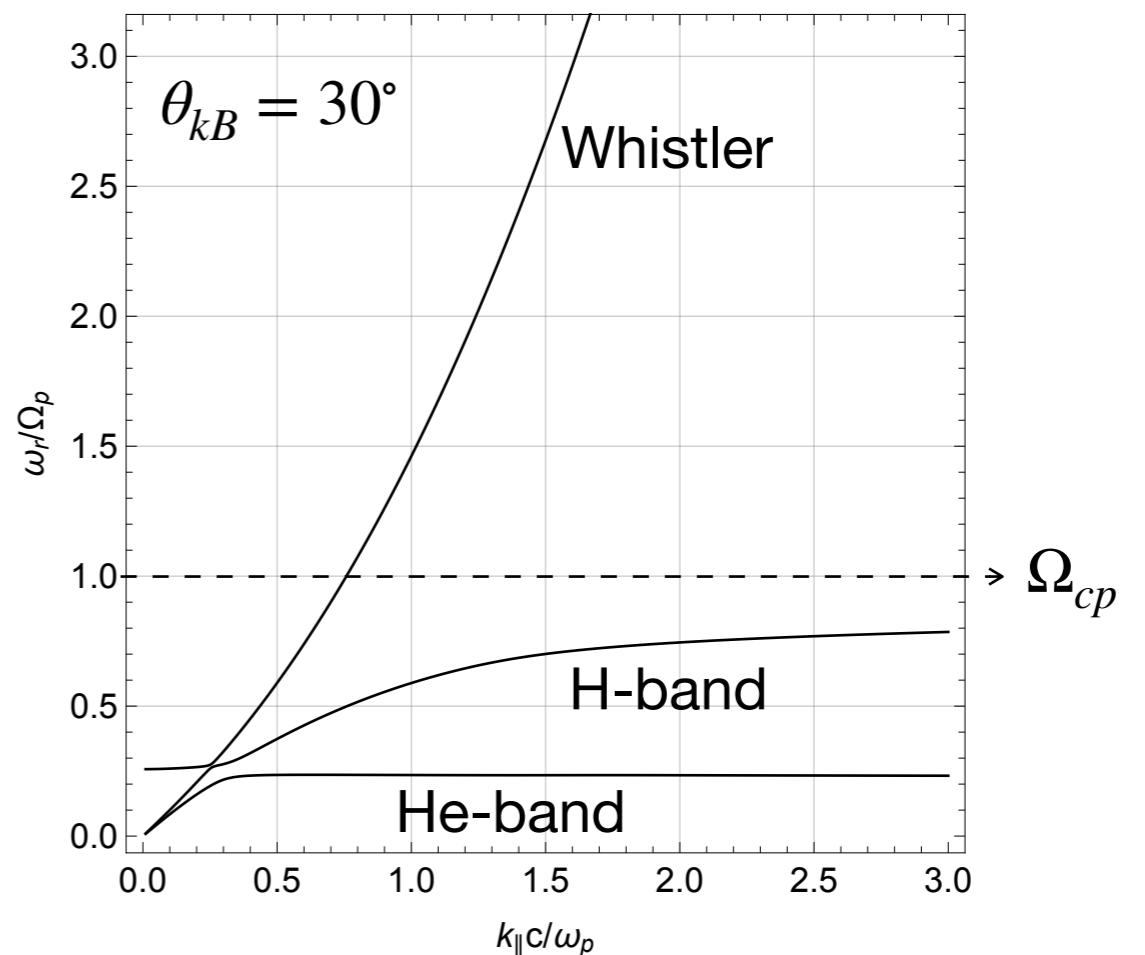
void H1D::Domain_CAMCL::subcycle(Domain const &domain, Charge const &charge,
Current const &current, Real const _Dt)
{
    Real const dt = _Dt/m, dt_x_2 = dt*2.0;
    //
    // prologue
    //
    bfield_1 = bfield_0;
    efield.update(bfield_0, charge, current), delegate->pass(domain, efield);
    bfield_1.update(efield, dt), delegate->pass(domain, bfield_1);
    //
    // loop
    //
    for (long i = 1; i < m; ++i) {
        efield.update(bfield_1, charge, current), delegate->pass(domain, efield);
        bfield_0.update(efield, dt_x_2), delegate->pass(domain, bfield_0);
        bfield_0.swap(bfield_1);
    }
    //
    // epilogue
    //
    efield.update(bfield_1, charge, current), delegate->pass(domain, efield);
    bfield_0.update(efield, dt), delegate->pass(domain, bfield_0);
    //
    // average
    //
    (bfield_0 += bfield_1) *= Vector{.5};
}
```

## **Example 1: Low-frequency electromagnetic fluctuations in a relatively cool H+-He+ plasma**

*Input parameters under “examples/1\_cold\_dispersion\_theta-{0,30,60}”*

## Low-frequency dispersion relation

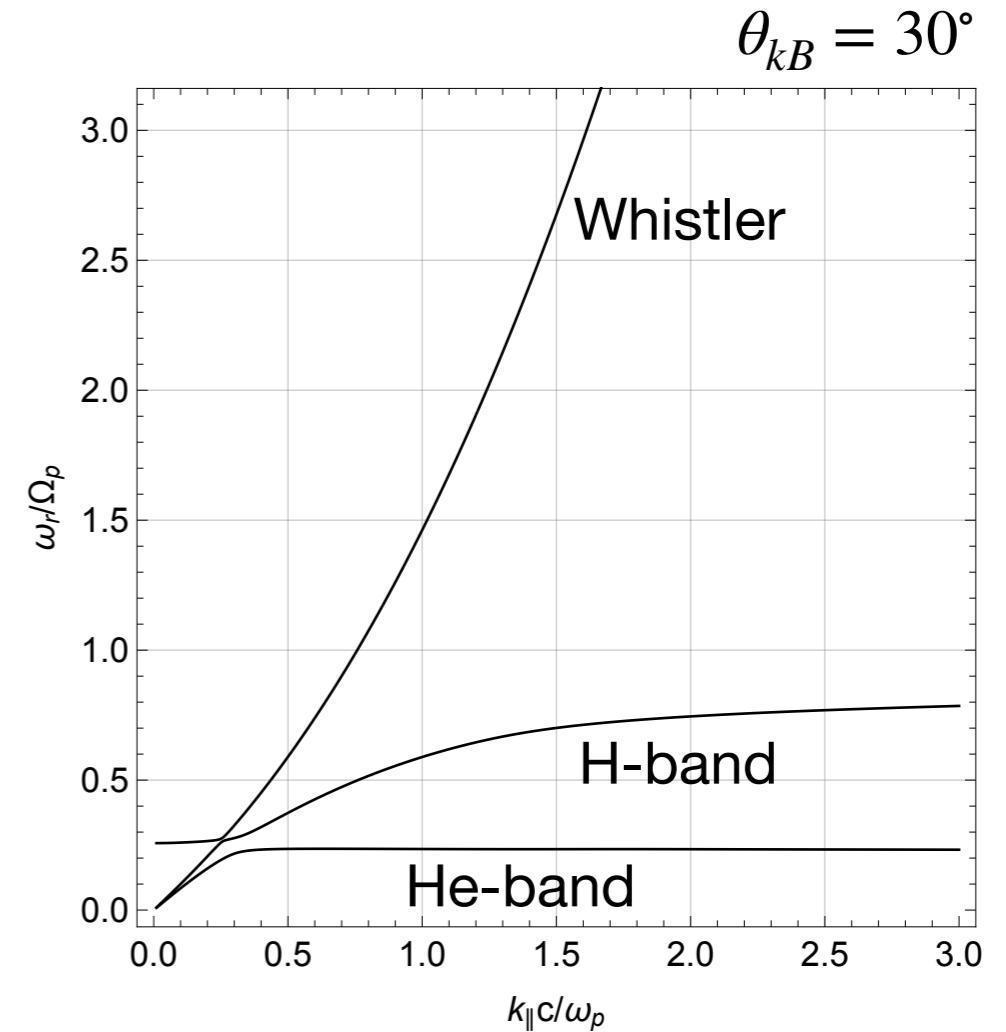
- Input parameters under “examples/1\_cold\_dispersion\_theta-{0,30,60}”
- $\omega_{pe}/|\Omega_{ce}| = 5$  and  $\beta_e = 0.01$
- 99% protons with  $\tilde{\beta}_p \equiv 8\pi n_e T_p / B_0^2 = 0.01 \rightarrow \beta_p = \frac{n_p}{n_e} \tilde{\beta}_p = 0.0099$
- 1% singly-ionized helium with  $\tilde{\beta}_{He^+} = 0.01 \rightarrow \beta_{He^+} = \frac{n_{He^+}}{n_e} \tilde{\beta}_{He^+} = 0.0001$
- Wave normal angles  $\theta_{kB} = 0, 30, and }60^\circ$
- Normalization:  
 velocity by  $v_{A0} = B_0 / \sqrt{4\pi n_e m_p}$   
 frequency by  $\Omega_{cp} = eB_0 / m_p c$   
 time by  $\Omega_{cp}^{-1}$   
 length by  $\lambda_{p0} = v_{A0} / \Omega_{cp}$



# Low-frequency dispersion relation

```
// Inputs.h
/// light speed
///
constexpr Real c = 214.243;    =  $\frac{\omega_{pe}}{|\Omega_{ce}|} \sqrt{\frac{m_p}{m_e}} v_A = 5\sqrt{1836}v_A$ 
/// angle in degrees between the x-axis and the uniform magnetic field direction.
///
constexpr Real theta = 30;     $\theta_{kB} = 0, 30, \text{ or } 60^\circ$ 
/// simulation grid size
///
constexpr Real Dx = 0.2;     $k_{\max} = \pi/\Delta x \approx 15.7\lambda_p^{-1}$ 
/// number of grid points
///
constexpr unsigned Nx = 1440;     $k_{\min} = 2\pi/(N_x \Delta x) \approx 0.022\lambda_p^{-1}$ 

namespace eFluid {
    /// electron cyclotron frequency
    ///
    constexpr Real 0c = -1836;    =  $-\frac{m_p}{m_e}\Omega_{cp} \approx -1836\Omega_{cp}$ 
    /// electron plasma frequency
    ///
    constexpr Real op = 9180;    =  $\frac{\omega_{pe}}{\Omega_{ce}}\Omega_{ce} = 5 \times 1836\Omega_{cp}$ 
    /// electron beta
    ///
    constexpr Real beta = 0.01;
}
```



# Low-frequency dispersion relation

```
// Inputs.h

namespace eFluid {
    /// electron cyclotron frequency
    ///
    constexpr Real Oc = -1836;

    /// electron plasma frequency
    ///
    constexpr Real op = 9180;      =  $\frac{\omega_{pe}}{\Omega_{ce}} \Omega_{ce} = 5 \times 1836 \Omega_{cp}$ 

    /// electron beta
    ///
    constexpr Real beta = 0.01;
}
```

```
namespace iKinetic {
    /// number of ion species
    ///
    constexpr unsigned Ns = 2;      H+ and He+
    /// number of simulation particles per cell for individual populations
    ///
    constexpr std::array<unsigned, Ns> Ncs = {500, 500};

    /// ion cyclotron frequencies for individual populations
    ///
    constexpr std::array<Real, Ns> Ocs = {1, .25};

    /// ion plasma frequencies for individual populations
    ///
    constexpr std::array<Real, Ns> Ops = {213.169, 10.7122};    $\omega_{pp} = \omega_{p0}\sqrt{0.99}$     $\omega_{pHe^+} = \omega_{p0}\sqrt{0.01}/\sqrt{4}$ 

    /// parallel (w.r.t the background magnetic field direction)
    /// ion betas for individual populations
    ///
    constexpr std::array<Real, Ns> betas = {0.0099, 0.0001};    $\{0.99\tilde{\beta}_p, 0.01\tilde{\beta}_{He^+}\}$ 

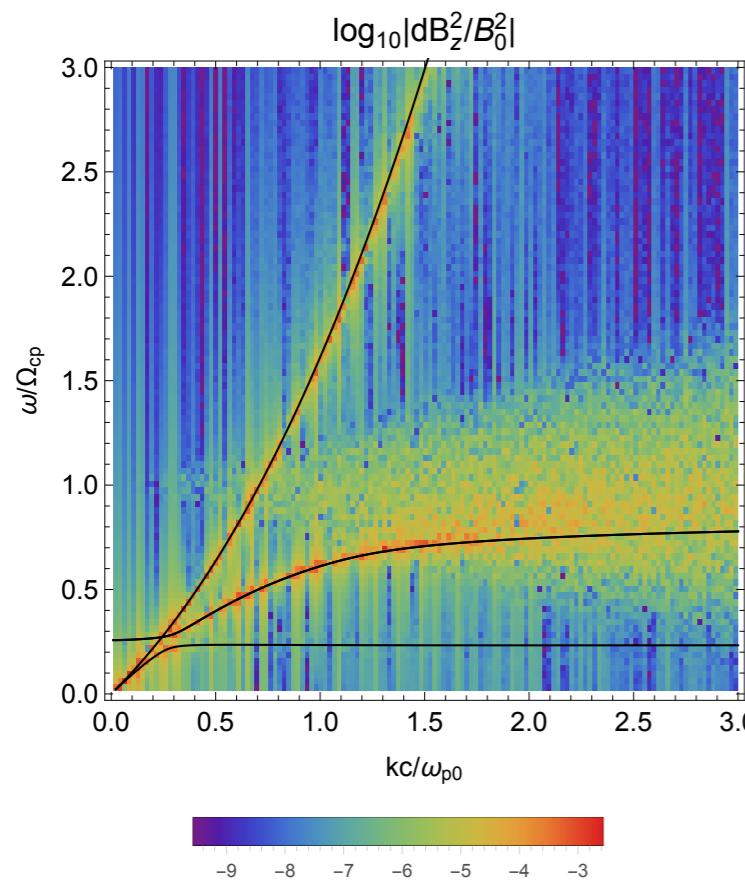
    /// ion temperature anisotropies (T_perp/T_para) for individual populations
    ///
    constexpr std::array<Real, Ns> T20T1s = {1, 1};            $T_{\perp i}/T_{\parallel i}$ 
}
```

$$\omega_{p0} \equiv \sqrt{\frac{4\pi e^2 n_e}{m_p}} = \frac{c}{v_{A0}} \Omega_{cp}$$

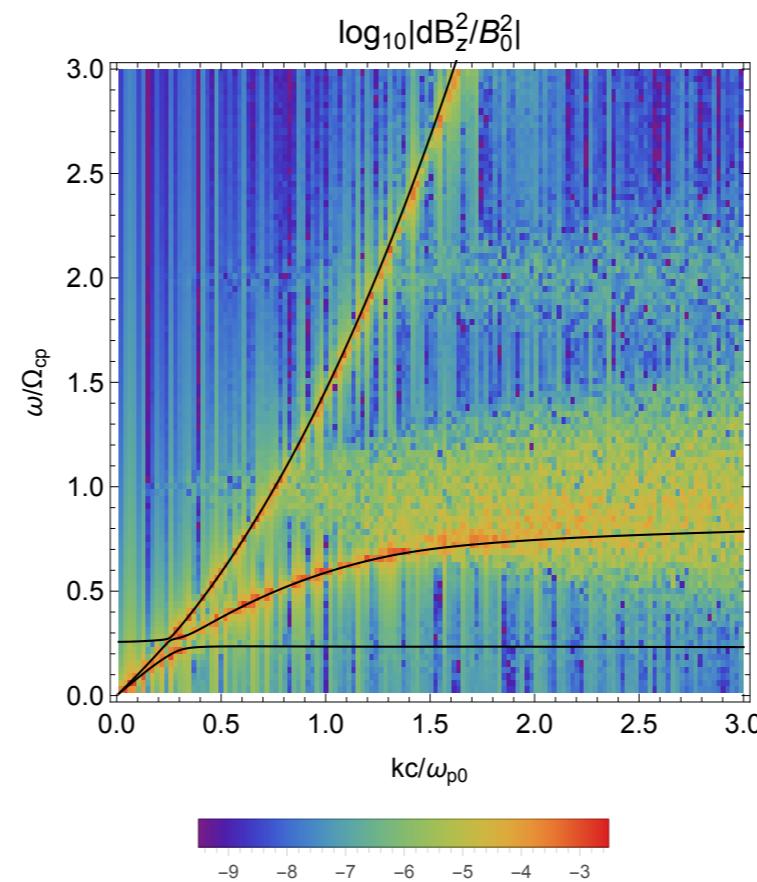
$$\tilde{\beta}_i \equiv 8\pi n_e T_i / B_0^2 = 0.01$$

# Low-frequency dispersion relation

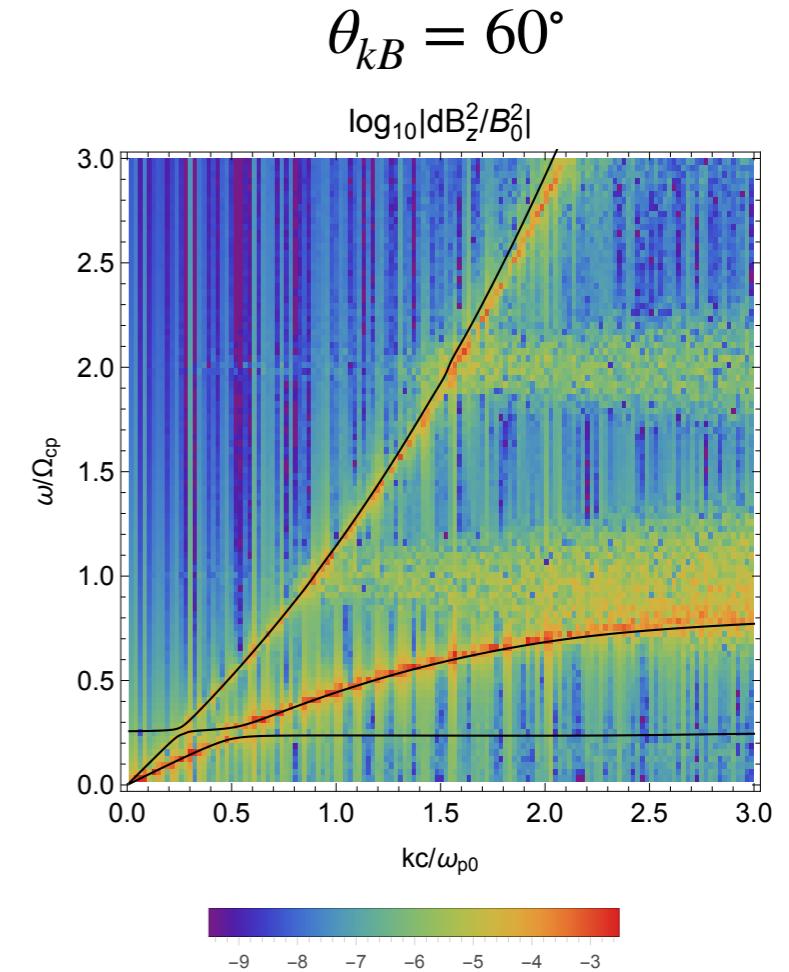
$$\theta_{kB} = 0^\circ$$



$$\theta_{kB} = 30^\circ$$



$$\theta_{kB} = 60^\circ$$



## **Example 2: Temperature anisotropy-driven H+-band & He+-band EMIC waves relevant to Earth's Magnetosphere**

*Input parameters under “examples/2\_Fu\_et\_al\_2016\_EMIC\_baseline\_run”*

# Fu et al. (2016) EMIC Study

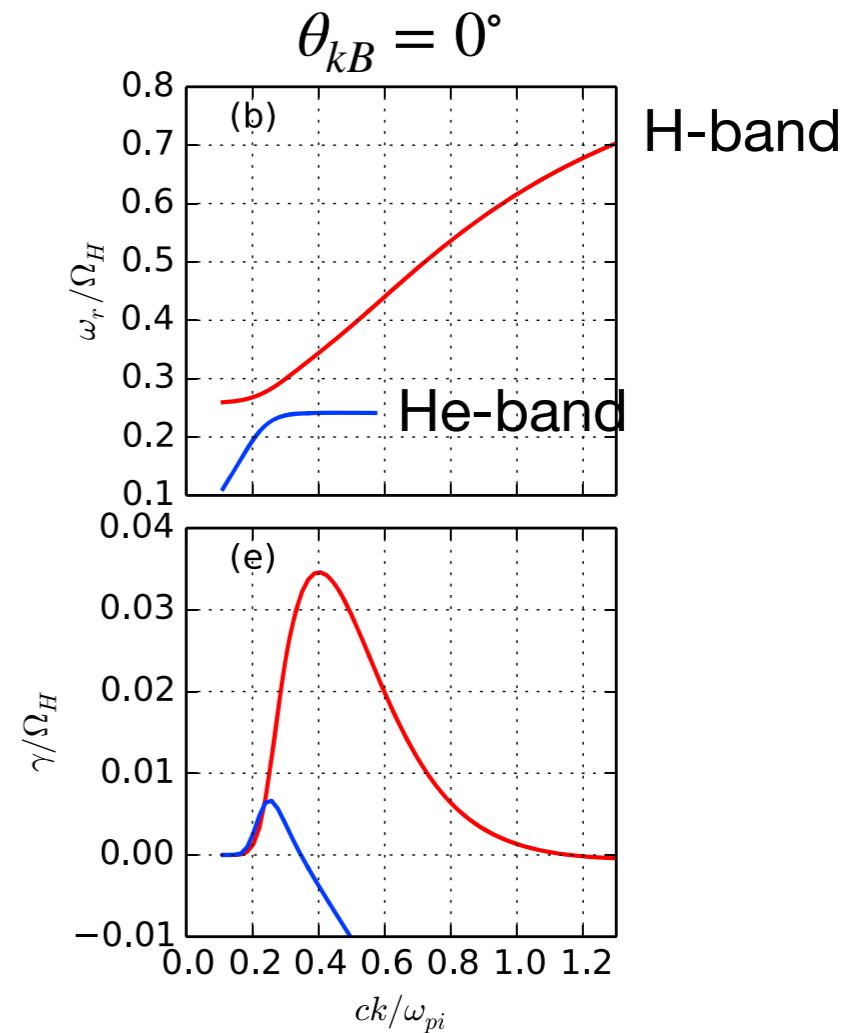
## Predicting electromagnetic ion cyclotron wave amplitude from unstable ring current plasma conditions

Xiangrong Fu<sup>1</sup>, Misa M. Cowee<sup>2</sup>, Vania K. Jordanova<sup>2</sup>, S. Peter Gary<sup>3</sup>,  
Geoffrey D. Reeves<sup>1,2</sup>, and Dan Winske<sup>2</sup>

<sup>1</sup>New Mexico Consortium, Los Alamos, New Mexico, USA, <sup>2</sup>Los Alamos National Laboratory, Los Alamos, New Mexico, USA, <sup>3</sup>Space Science Institute, Boulder, Colorado, USA

**Table 1.** Initial Plasma Parameters for EMIC Waves

Parameter	Values
$\omega_{pe}/\omega_{ce}$	5
$\tilde{\beta}_h = n_e T_h / (B_0^2 / 8\pi)$	0.3, 1.0, 3.0, 10.0 0.05, 0.1, 0.2, 0.4
$T_{\perp h}/T_{\parallel h}$	2, 3, 4, 5
$n_{He}/n_e$	0, 0.01, 0.03, 0.05



- Fu, X., M. M. Cowee, V. K. Jordanova, S. P. Gary, G. D. Reeves, and D. Winske (2016), Predicting electromagnetic ion cyclotron wave amplitude from unstable ring current plasma conditions, *J. Geophys. Res. Space Physics*, 121, doi:10.1002/2016JA023303.

# Fu et al. (2016) EMIC Study

**Table 1.** Initial Plasma Parameters for EMIC Waves

Parameter	Values
$\omega_{pe}/\omega_{ce}$	5
$\tilde{\beta}_h = n_e T_h / (B_0^2 / 8\pi)$	0.3, 1.0, 3.0, 10.0
$n_h/n_e$	0.05, 0.1, 0.2, 0.4
$T_{\perp h}/T_{\parallel h}$	2, 3, 4, 5
$n_{He}/n_e$	0, 0.01, 0.03, 0.05

```

namespace iKinetic {
    /// number of ion species
    ///
    constexpr unsigned Ns = 3; {5% hot H+, 94% cool H+, 1% He+}

    /// number of simulation particles per cell for individual populations
    ///
    constexpr std::array<unsigned, Ns> Ncs = {1000, 500, 500};

    /// ion cyclotron frequencies for individual populations
    ///
    constexpr std::array<Real, Ns> Ocs = {1, 1, .25};

    /// ion plasma frequencies for individual populations
    ///
    constexpr std::array<Real, Ns> Ops = {47.9062, 207.716, 10.7122};

    /// ion betas for individual populations
    ///
    constexpr std::array<Real, Ns> Betas = {0.15, 0.0094, 0.0001};

    /// ion temperature anisotropies (T_perp/T_para) for individual populations
    ///
    constexpr std::array<Real, Ns> T20T1s = {3, 1, 1};
}

```

# Fu et al. (2016) EMIC Study

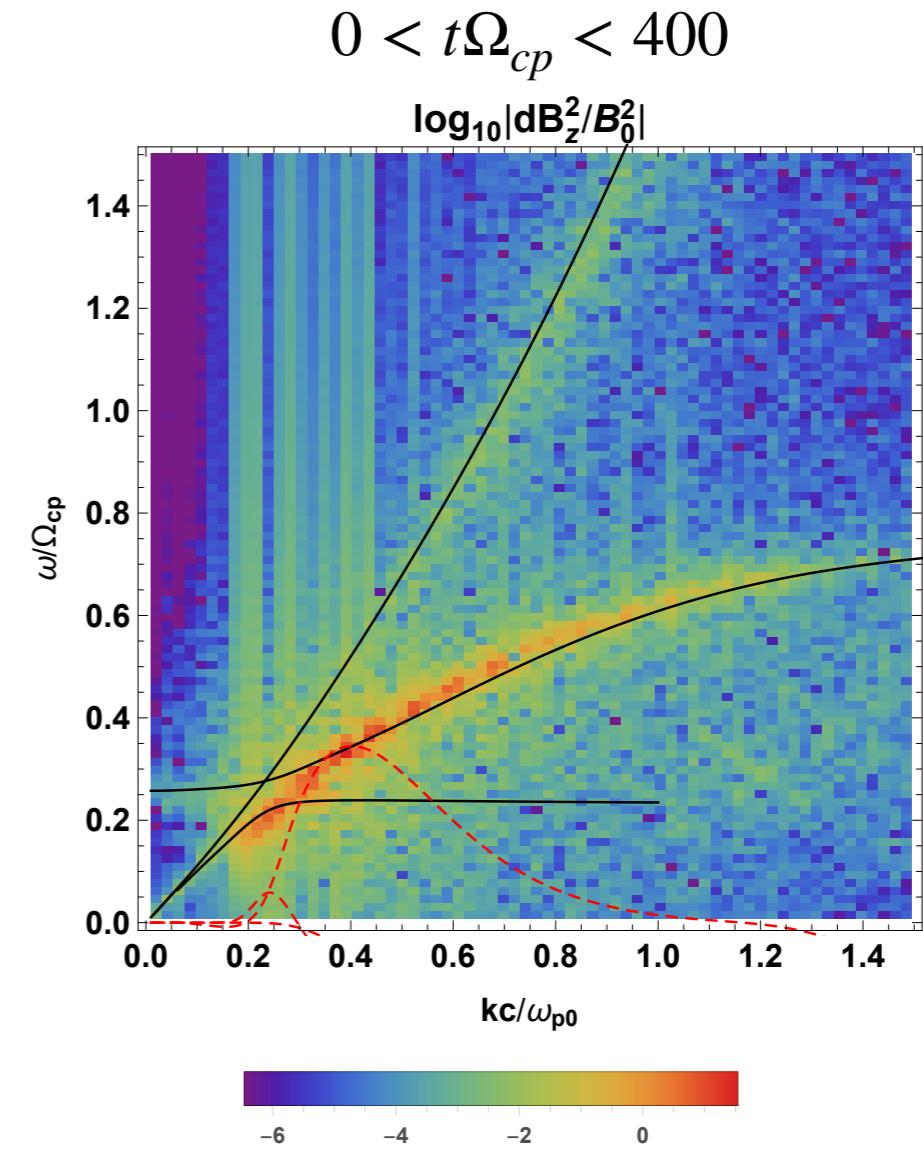
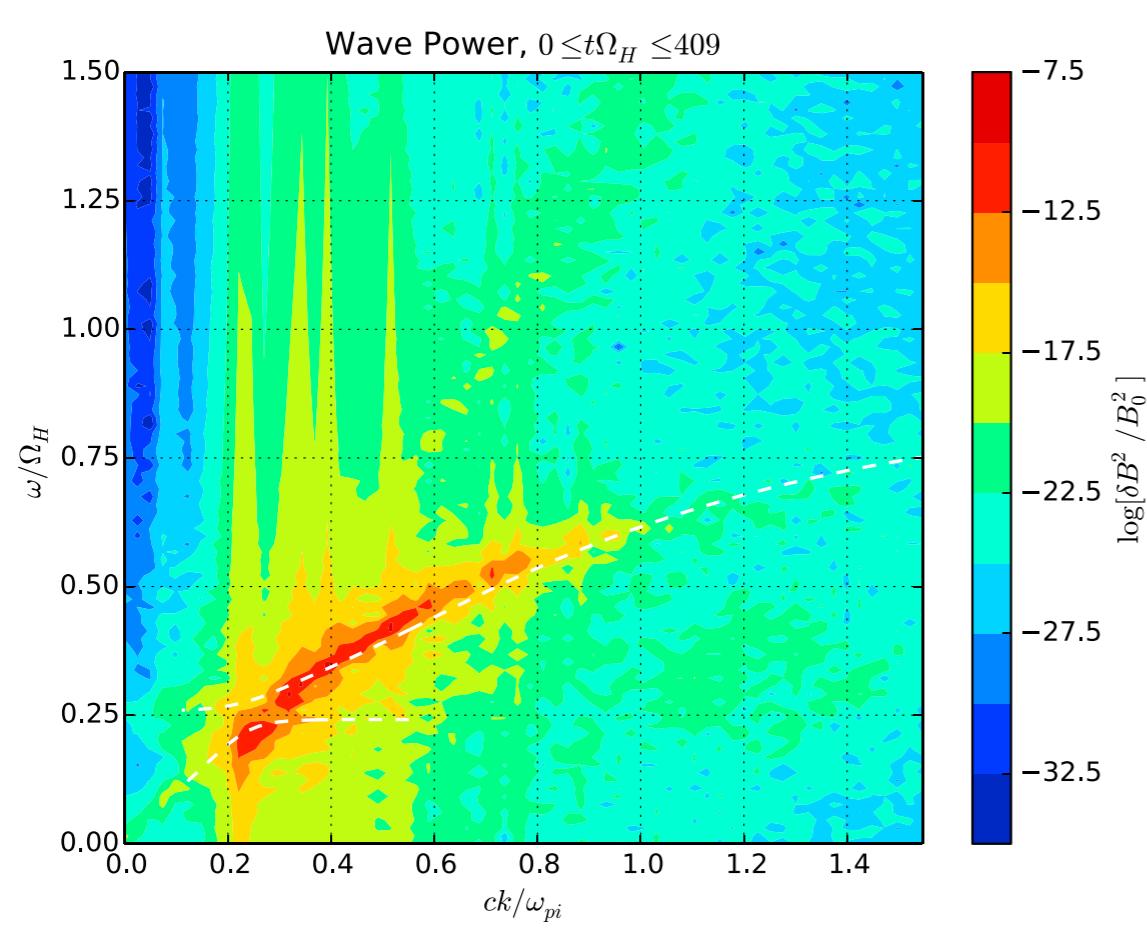


Figure 5 of Fu et al. (2016)

# Fu et al. (2016) EMIC Study

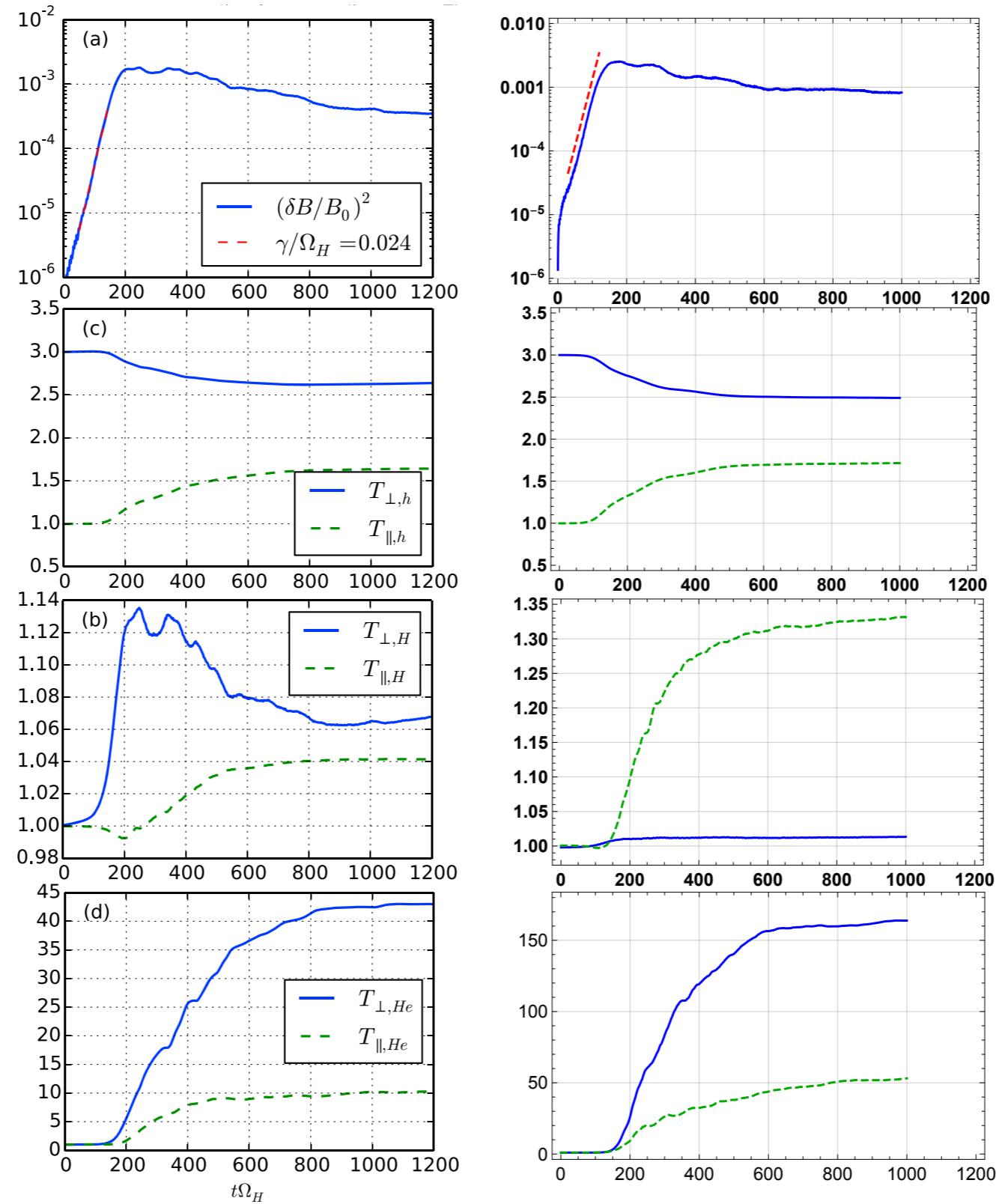


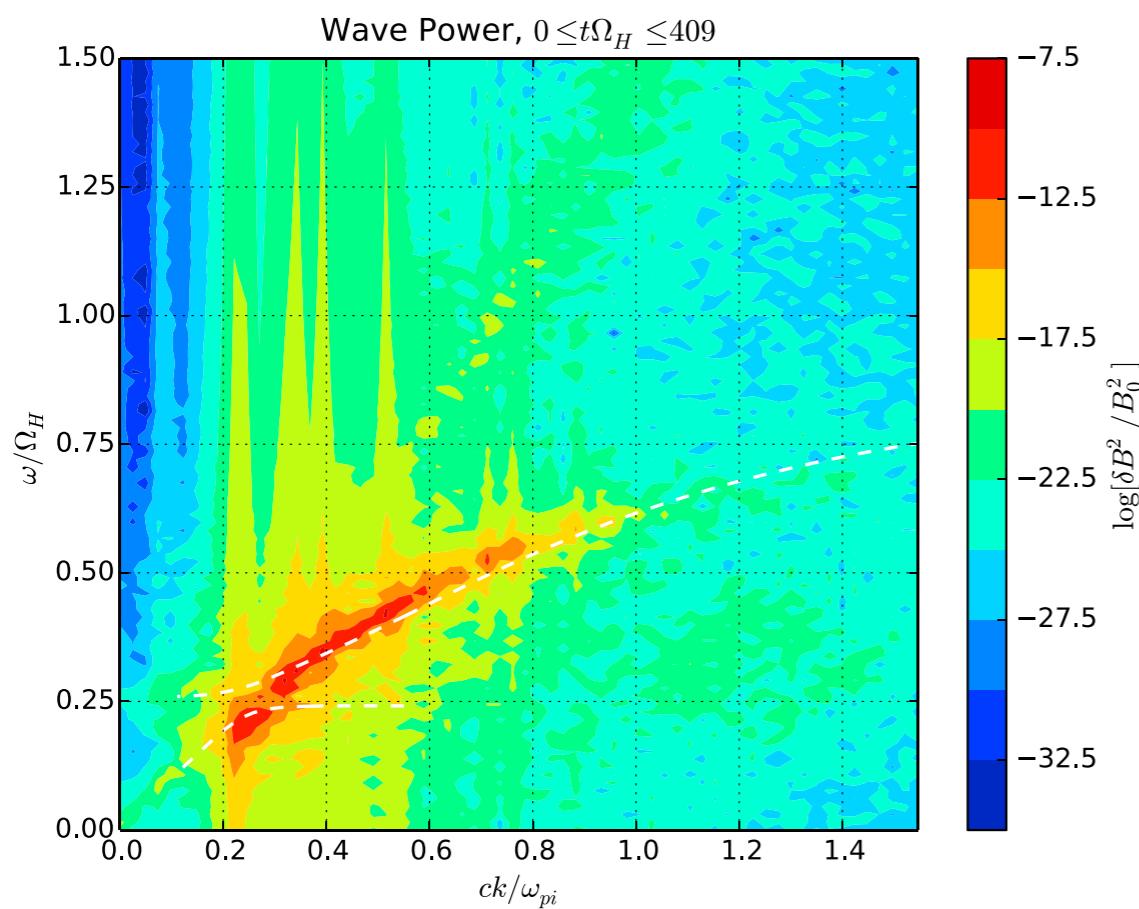
Figure 4 of Fu et al. (2016)

# Fu et al. (2016) EMIC Study

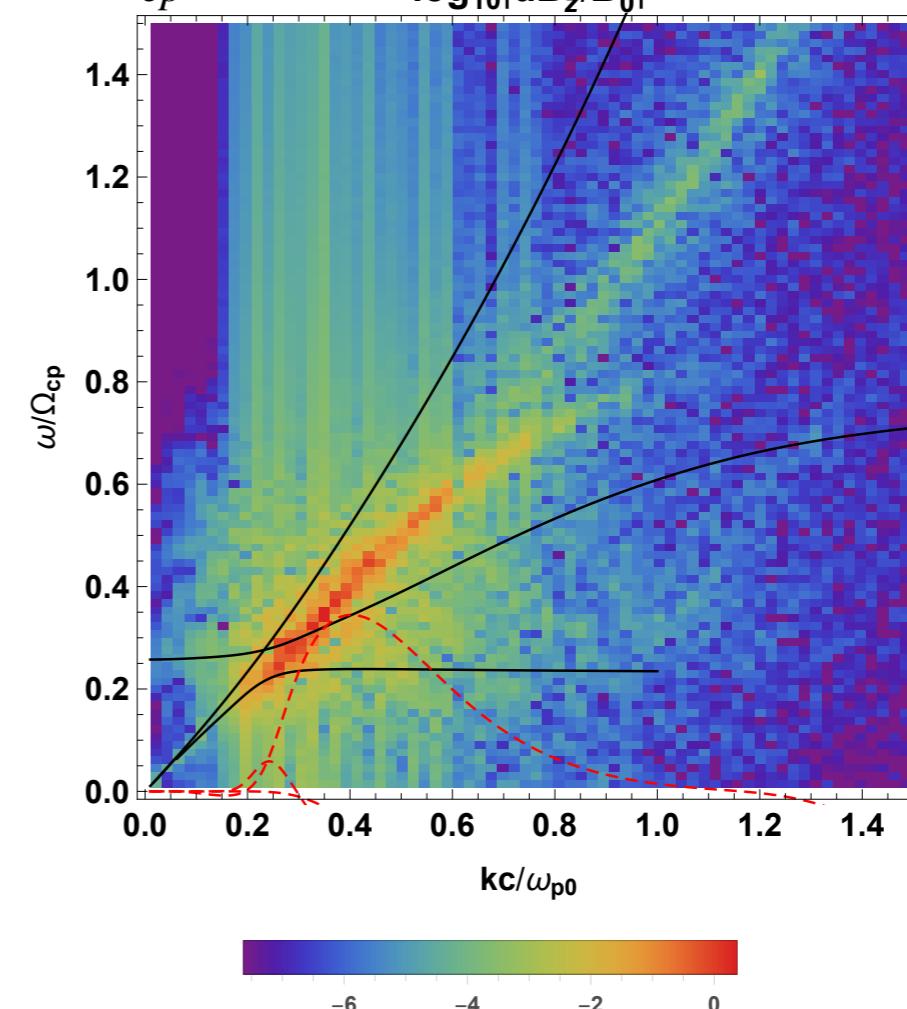
**Table 2.** Hybrid Simulation Parameters

Parameter	Description	Value
nx	number of cells along $\mathbf{B}_0$	256
dx	cell size	$1.0 c/\omega_{pi}$
nt	number of time steps	12,000 – 24,000
dt	time step size	$0.05 \omega_{ci}^{-1}$
nppc	number of super particles per cell per species	24,000

vs. 1440  
vs. 0.2  
vs.  $\leq 0.01$   
vs.  $\leq 1000$



Simulation results using the same parameters  
 $0 < t\Omega_{cp} < 409$     $\log_{10}|\delta B_z^2 / B_0^2|$



## **Example 3: Firehose Instability**

*Input parameters under “examples/3\_FHI”*

## Firehose Instability

- $\omega_{pp}/\Omega_{cp} = 400$  and  $\beta_e = 1$
- 100% protons with  $\beta_{\parallel p} = 8\pi n_p T_{\parallel p} / B_0^2 = 3$  and  $T_{\perp p} / T_{\parallel p} = 1/3$

- Wave normal angle  $\theta_{kB} = 0^\circ$

- Normalization:

velocity by  $v_A = B_0 / \sqrt{4\pi n_p m_p}$

frequency by  $\Omega_{cp} = eB_0 / m_p c$

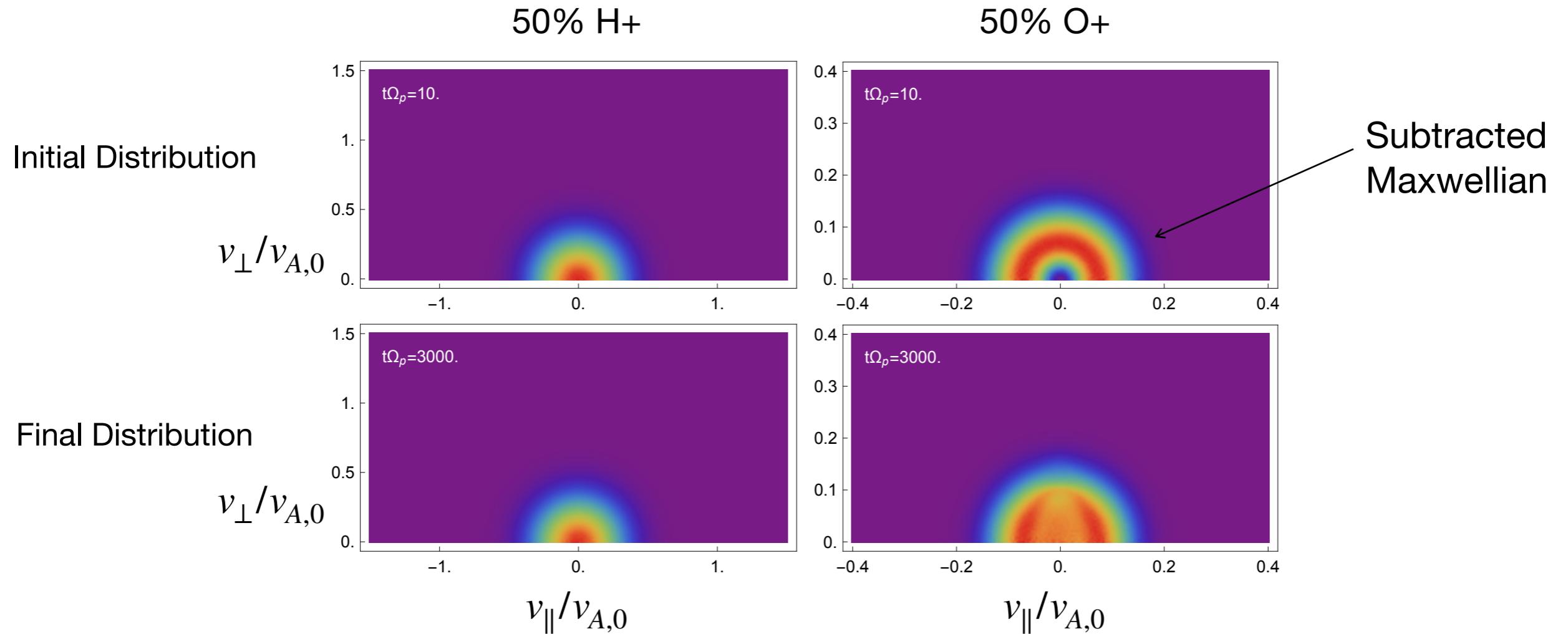
time by  $\Omega_{cp}^{-1}$

length by  $\lambda_p = v_A / \Omega_{cp}$

## **Extra Example: O+ harmonic Bernstein modes**

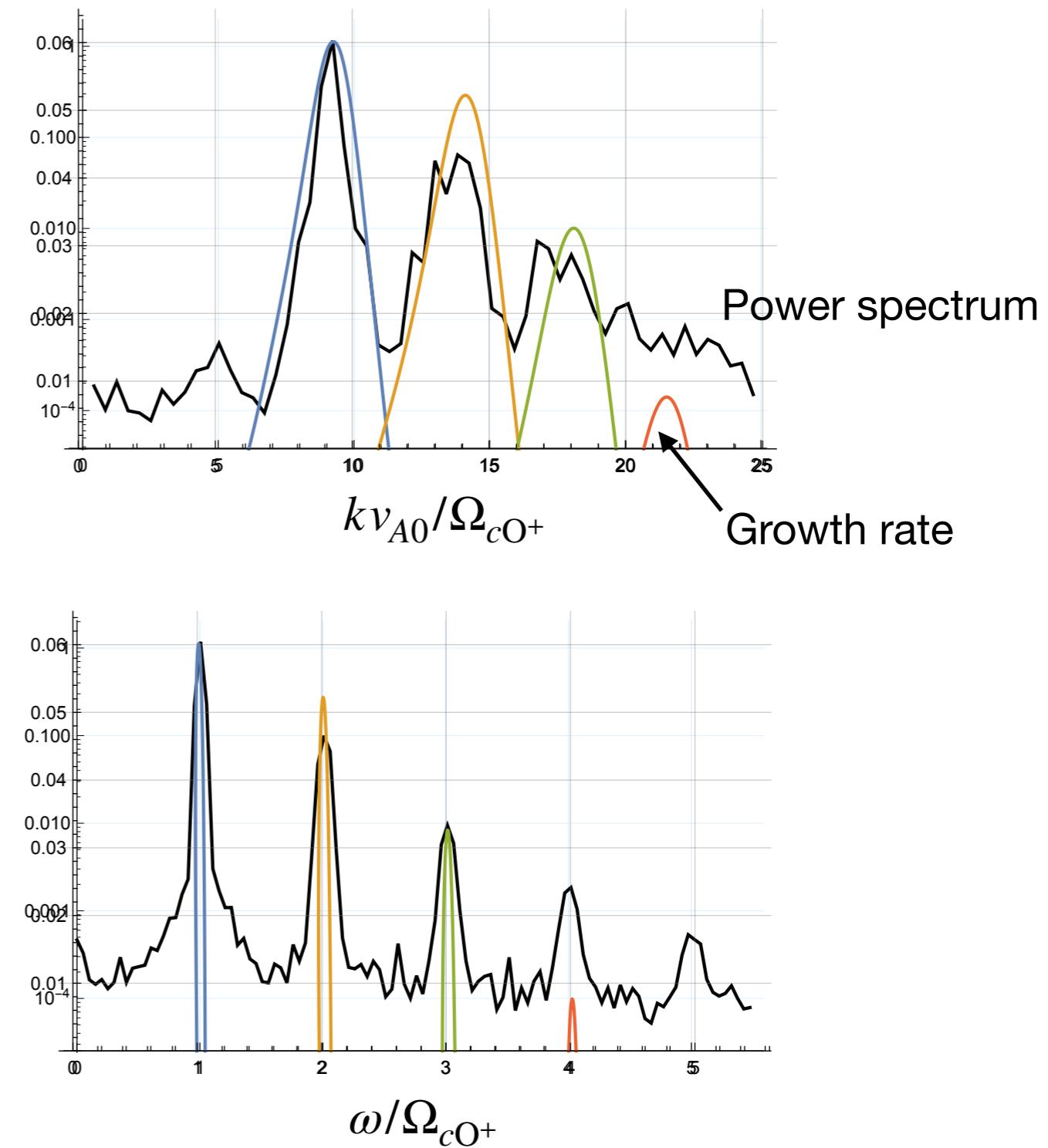
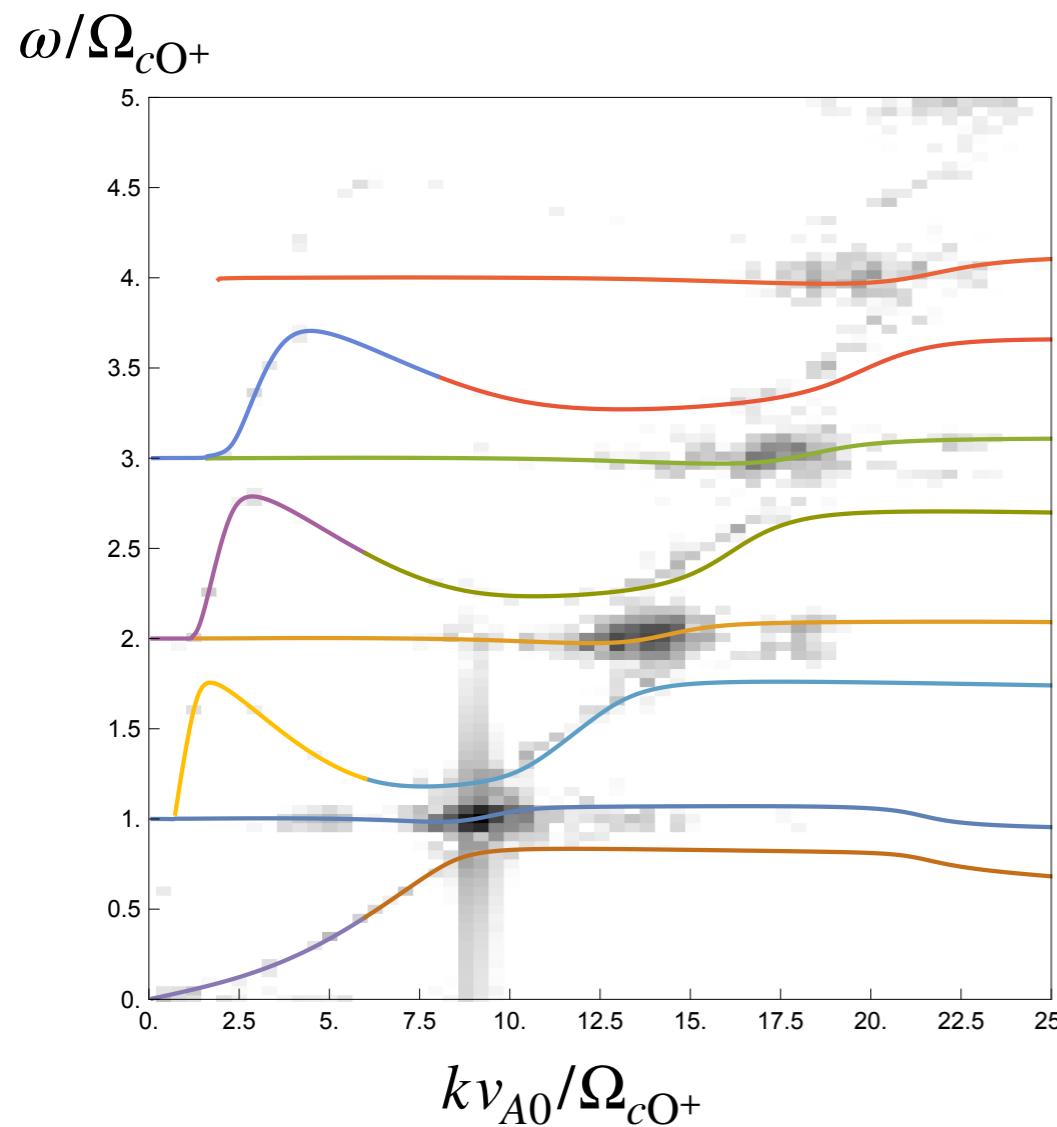
*No corresponding example*

$$\omega_{pe}/\Omega_{ce} = 1.2$$



$$v_{A,0} = B_0 / \sqrt{4\pi n_e m_{O^+}}$$

$$\theta_{kB} = 88.2^\circ$$

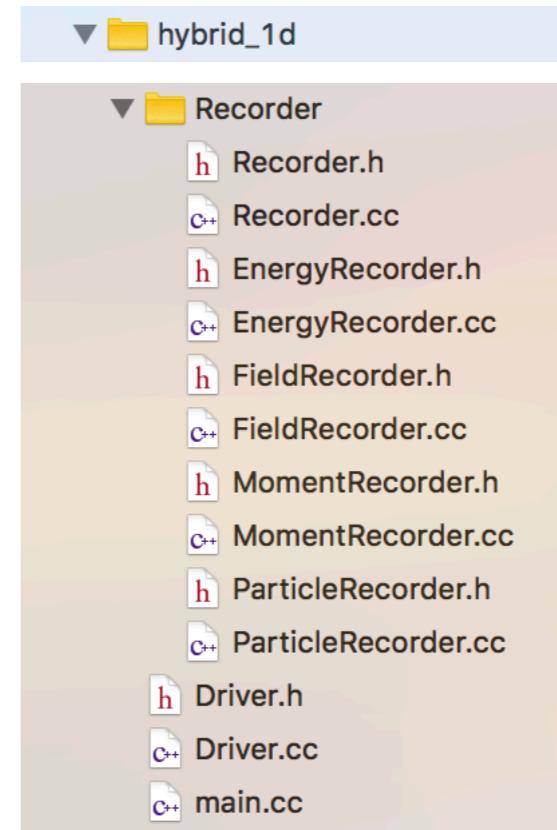
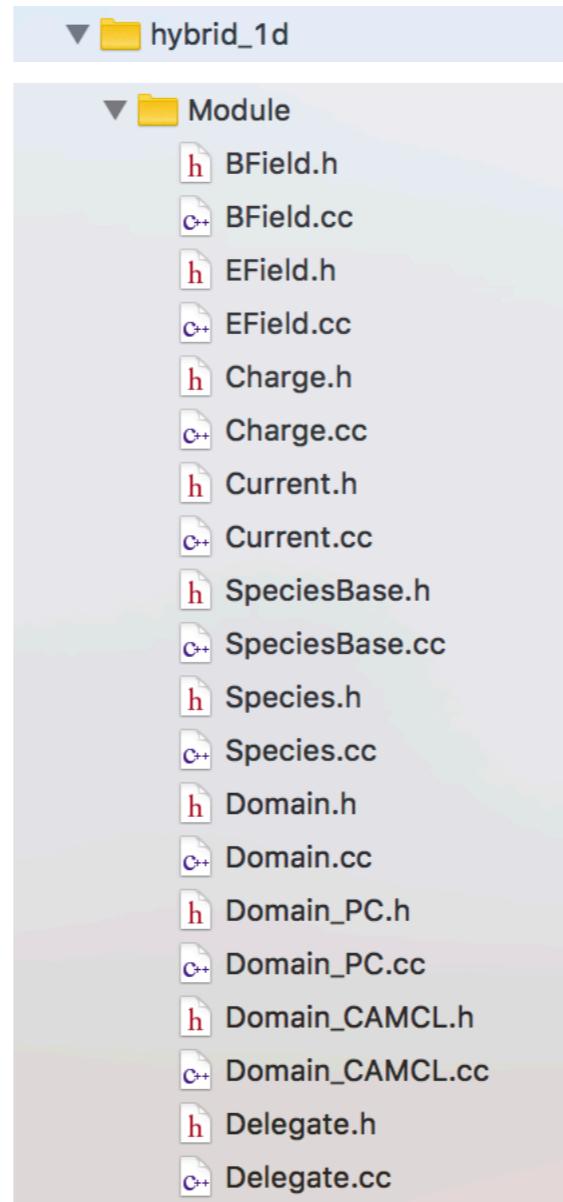
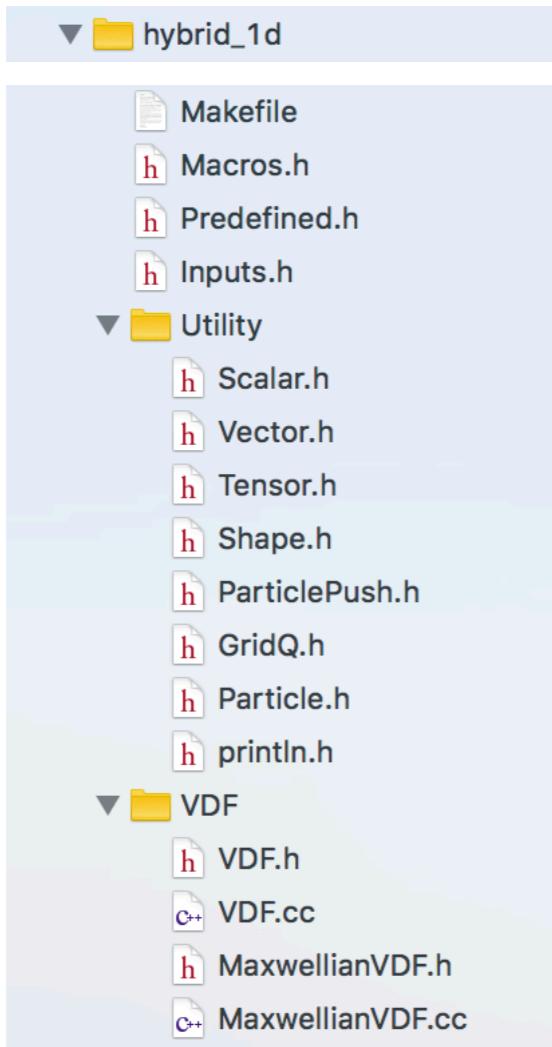


## References

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- Kunz, Matthew W.; Stone, James M.; Bai, Xue-Ning (2014), Pegasus: A new hybrid-kinetic particle-in-cell code for astrophysical plasma dynamics, *Journal of Computational Physics*, Volume 259, p. 154-174.
- Matthews, A. P. (1994). Current Advance Method and Cyclic Leapfrog for 2D Multispecies Hybrid Plasma Simulations. *Journal of Computational Physics*, 112, 102–116. <https://doi.org/10.1006/jcph.1994.1084>
- Liu, K. (2007), Particle-in-cell simulations of particle energization in the auroral region, PhD thesis, Cornell Univ., New York.
- Lipatov, Alexander S. (2002), *The Hybrid Multiscale Simulation Technology*, Springer-Verlag Berlin Heidelberg.
- Birdsall, C. K., and A. B. Langdon (1985), *Plasma Physics via Computer Simulation*, McGraw-Hill, New York.



# Source Tree



## Input Parameters: Inputs.h

```
//  
// MARK:- Housekeeping  
  
/// parallelize particle update  
///  
constexpr bool enable_concurrency = false; // Predefined.h  
  
/// electric field extrapolation method  
///  
constexpr _Algorithm algorithm = PC; →  
  
// Predefined.h  
enum _Algorithm : long {  
    PC, //!< Using predictor-corrector by Kunz et al. (2014).  
    CAMCL //!< Using CAM-CL by Matthew (1994).  
};  
  
/// particle and interpolation order  
///  
constexpr _ShapeOrder shape_order = CIC;  
  
// Predefined.h  
enum _ShapeOrder : long {  
    CIC = 1, //!< First order; cloud-in-cell scheme.  
    TSC = 2 //!< Second order; Triangular-shaped density cloud sheme.  
};  
  
/// number of subcycles for magnetic field update; applied only for CAM-CL algorithm  
///  
constexpr unsigned Nsubcycles = 4;  
  
/// number of smoothings  
///  
constexpr unsigned Nsmooths = 2;
```

## Input Parameters: Inputs.h (cont'd)

```
//  
// MARK: Global parameters  
  
/// light speed  
///  
constexpr Real c = 400;  
  
/// magnitude of uniform background magnetic field  
///  
constexpr Real B0 = 1;  
  
/// angle in degrees between the x-axis and the uniform magnetic field direction.  
///  
constexpr Real theta = 0;  
  
/// simulation grid size  
///  
constexpr Real Dx = 0.4;  
  
/// number of grid points  
///  
constexpr unsigned Nx = 960;  
  
/// time step size  
///  
constexpr Real dt = 0.04;  
  
/// number of time steps for inner loop  
/// total time step Nt = inner_Nt * outer_Nt  
/// simulation time t = dt*Nt  
///  
constexpr unsigned inner_Nt = 5;  
  
/// number of time steps for outer loop  
/// total time step Nt = inner_Nt * outer_Nt  
/// simulation time t = dt*Nt  
///  
constexpr unsigned outer_Nt = 1000;
```

Outer loop

```
// driver.cc  
void H1D::Driver::operator()() const  
{  
    long step_count{};  
    for (long i_step = 1; i_step <= Input::outer_Nt; ++i_step) {  
        // advance simulation  
        //  
        domain->advance_by(Input::inner_Nt); Inner loop  
        // update step count  
        //  
        long const steps = step_count += Input::inner_Nt;  
        // record data  
        //  
        for (auto &pair : recorders) {  
            if (pair.second) {  
                pair.second->record(*domain, steps);  
            }  
        }  
    }  
}
```

## Input Parameters: Inputs.h (cont'd)

```
//  
// MARK: Fluid Electrons  
//  
namespace eFluid {  
    /// electron cyclotron frequency  
    ///  
    constexpr Real 0c = -1836;  
  
    /// electron plasma frequency  
    ///  
    constexpr Real op = 17139.4;  
  
    /// electron beta  
    ///  
    constexpr Real beta = 0.0;  
  
    /// specific heat ratio, gamma  
    ///  
    constexpr _Closure closure = isothermal;  
}  
  
// Predefined.h  
  
enum _Closure : long {  
    isothermal = 11, //!< gamma = 1/1  
    adiabatic = 53 //!< gamma = 5/3  
};
```

## Input Parameters: Inputs.h (cont'd)

```
//  
// MARK: Kinetic Ions  
//  
namespace iKinetic {  
    /// number of ion species  
    ///  
    constexpr unsigned Ns = 2;  
  
    /// number of simulation particles per cell for individual populations  
    ///  
    constexpr std::array<unsigned, Ns> Ncs = {100, 100};  
  
    /// ion cyclotron frequencies for individual populations  
    ///  
    constexpr std::array<Real, Ns> Ocs = {1, 1};  
  
    /// ion plasma frequencies for individual populations  
    ///  
    constexpr std::array<Real, Ns> Ops = {282.843, 282.843};  
  
    /// ion betas for individual populations  
    ///  
    constexpr std::array<Real, Ns> betas = {.5, .5};  
  
    /// ion temperature anisotropies (T_perp/T_para) for individual populations  
    ///  
    constexpr std::array<Real, Ns> T20T1s = {3, 3};  
}
```

## Input Parameters: Inputs.h (cont'd)

```
//  
// MARK: Data Recording  
  
/// a top-level directory to which outputs will be saved  
///  
constexpr char working_directory[] = ".";  
  
/// frequency of field and particle energy density recordings; in units of inner_Nt  
/// `0' means `not interested'  
///  
constexpr unsigned energy_recording_frequency = 1;  
  
/// frequency of electric and magnetic field recordings  
///  
constexpr unsigned field_recording_frequency = 3;  
  
/// frequency of kinetic ion moment recordings  
///  
constexpr unsigned moment_recording_frequency = 5;  
  
/// frequency of simulation particle recordings  
///  
constexpr unsigned particle_recording_frequency = 10000;
```