A new multi-fluid model for space plasma simulations

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Abstract

We propose a new numerical code based on a new multi-species theoretical model to study the mass, momentum and energy exchanges (MMEE) that happen across the magnetospheric boundaries. We use two distinct populations for ions, one cold and one hot (plus one neutralising electron population), to take into account the differences between the properties of the plasmas coming from the magnetosphere and from the solar wind. This approach represents a step forward in the context of the study of coupled large-scale plasma systems being a new and efficient compromise between fluid and kinetic codes in tracing the different plasma contributions during MMEE. Due to the very important role that magnetic reconnection plays in connecting the shocked Solar Wind to the Earth's magnetosphere, we show and discuss the results we obtained about the simulations of the tearing mode instability occurring across an Earth's magnetopause that we modelled thanks to our most recents MMS observations [Rezeau 2018]. Rezeau, Belmont, Manuzzo, Aunai, Dargent, 2018, Journal of Geophysical Research: Space Physics, 123, doi: 10.1002/2017JA024526.

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NO PHOTOS

A new multi-fluid model for space plasma simulations

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Laboratoire de Physique des Plasmas

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Abstract

We propose a new numerical code based on a new multi-species theoretical model to study the mass, momentum and energy exchanges (MMEE) that happen across the magnetospheric boundaries. We use two distinct populations for ions, one cold and one hot (plus one neutralising electron population), to take into account the differences between the properties of the plasmas coming from the magnetosphere and from the solar wind. This approach represents a step forward in the context of the study of coupled large-scale plasma systems being a new and efficient compromise between fluid and kinetic codes in tracing the different plasma contributions during MMEE. Due to the very important role that magnetic reconnection plays in connecting the shocked Solar Wind to the Earth's magnetosphere, we show and discuss the very preliminary results we obtained about the simulations of the tearing mode instability occurring across an Earth's magnetopause that we modelled thanks to our most recents MMS observations about the 16/10/15, 13:05:30+60s crossing [Rezeau 2018].

Theoretical and computational methods employed: the three fluid code

The plasma region we intend to simulate is of the order of about a thousand of ion inertial length d_i (where d_i ~ 100 km in the MP) and we must follow the plasma dynamics down to, at least, a fraction of d_i. In order to simulate such a large scale structure and, at the same time, in order to resolve the length scales at which the plasma mixing occurs (around 1 d_i), we make use of a performant, parallelised numerical multi-fluid code recently builded up onto the skeleton of a MHD code that has already successfully used by our group to study the solar wind/magnetosphere interaction [Faganello & Califano, 2017].

The code evolves in time a set of fluid quantities (density, velocities, etc...) by means of a set of equations (very similar to MHD equations) for three charged fluids representing two ions and one electron population. The set of equations is self-consistently coupled to the Maxwell equations via the charge and current densities. Two directions, y and z, are periodic while the x direction, corresponding to the inhomogeneity direction (i.e. transition layer) has transparent boundary conditions (or numerical open boundary conditions). The code has been massively parallelised along directions y and z with MPI in collaboration with the HPC center CINECA (Italy); it advances in time with a standard Runge-Kutta algorithm; it uses sixth order explicit finite difference stencils along the periodic y and z-direction and a sixth-order compact finite difference scheme with spectral like resolution for spatial derivative along the inhomogeneous x-direction. The numerical stability is guaranteed by means of a spectral filter along the periodic y and z directions and a spectral-like filtering scheme along the inhomogeneous x-direction [Canuto et al., 1988 and Lele, 1992].

The analytical equations for a 3fluid equilibrium

The model assumes a minimum set of *known quantities* to recover firstly a *i-e* equilibrium, and subsequently a *cold ions* - *hot ions* - *electrons* equilibrium:

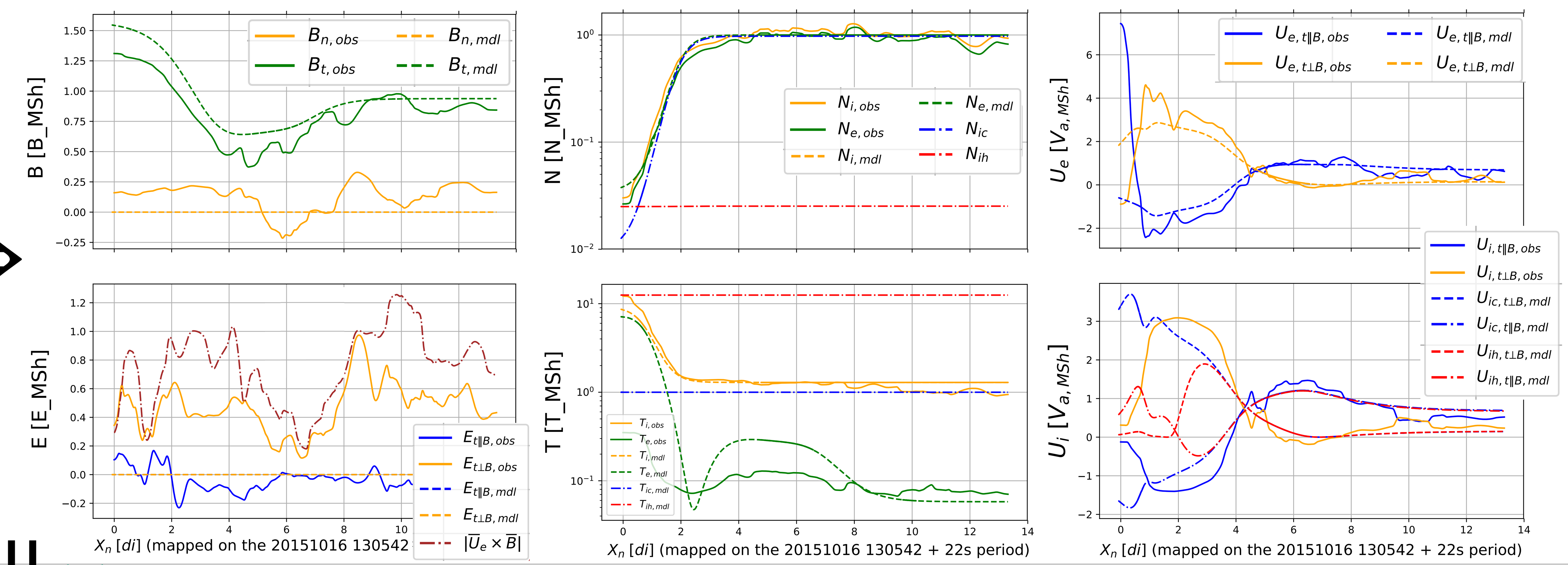
$$i-e:\begin{cases} n_e = n_i \\ \mathbf{U}_e = \mathbf{U}_i - \frac{1}{n_i}\frac{(\overline{\nabla}\times\mathbf{B})}{e\mu_0} \\ P_e = P_{tot} - (P_B + n_i T_i) \\ \mathbf{E} = -\frac{1}{en_e}\overline{\nabla}P_e - (\mathbf{U}_e\times\mathbf{B}) \end{cases}$$

$$ic-ih-e:\begin{cases} n_{ic} + n_{ih} = n_i \\ P_{ic} + P_{ih} = P_{tot} - (P_B + P_e) \\ n_{ic}\mathbf{U}_{ic} + n_{ih}\mathbf{U}_{ih} = n_e\mathbf{U}_e + \frac{1}{e\mu_0}\overline{\nabla}\times\mathbf{B} \\ \overline{\nabla}P_{ic} - [q_{ic}n_{ic}\mathbf{E} + q_{ic}n_{ic}\mathbf{U}_{ic}\times\mathbf{B}] = 0 \\ \overline{\nabla}P_{ih} - [q_{ih}n_{ih}\mathbf{E} + q_{ih}n_{ih}\mathbf{U}_{ih}\times\mathbf{B}] = 0 \end{cases}$$

$\Rightarrow$

Analytical model vs MMS Data

The *known quantities* are mimed by analytical functions fitting MMS data (16/10/15, 13:05:30+60s) translated to space; the remaining unknowns, which are derived by the 3fluid equations, partially recover the observations (the differences are due to very close non-stationary phenomena affecting the examined data [Burch et al., 2016]).

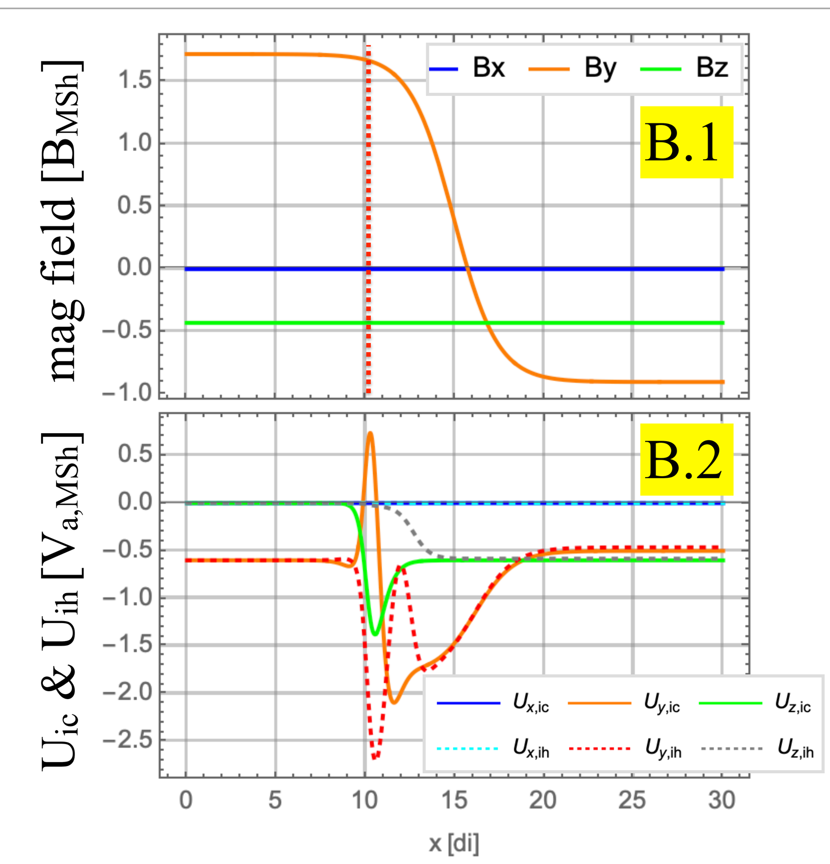


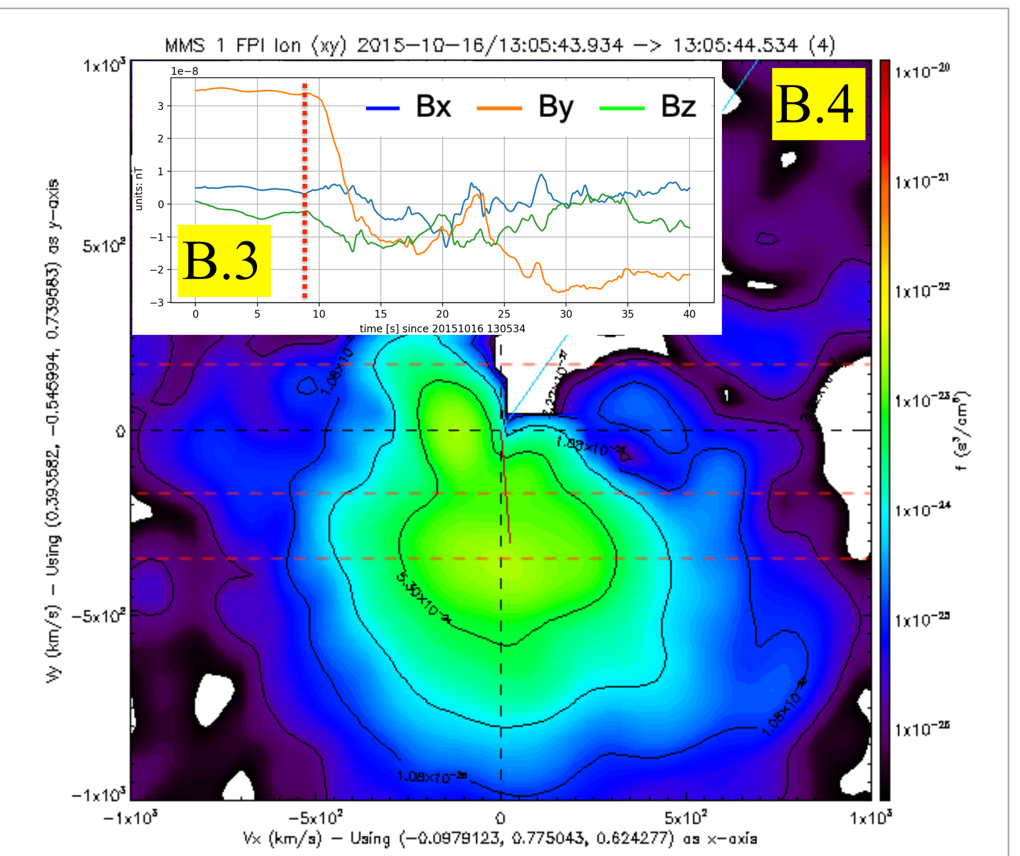
$\Downarrow$

Preliminary results

A deeper look at data due to a theoretical suggestion

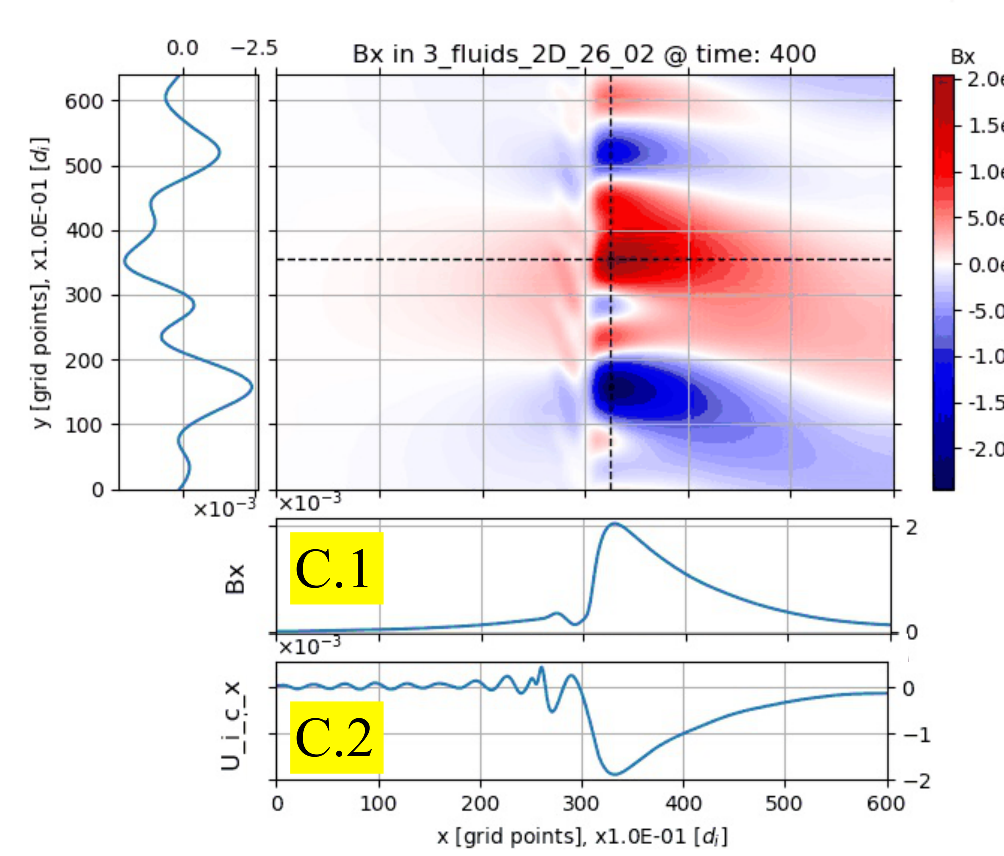
For particular parameters adopted in shaping the 3fluid equilibrium model, the theoretical curves of the cold and the hot ions bulk flows show counter-ward directed peaks (U_y, B.2) at the magnetospheric side of the magnetopause (red vertical dashed line, B.1-B.3). At the time corresponding to this location, the ions distribution function provided by MMS shows two beams, one hot and one cold, having nearly the same amplitude of the theoretical one (the red horizontal dashed lines of B.4 corresponds to +1, -1 and -2 $V_{a,MSh}$).

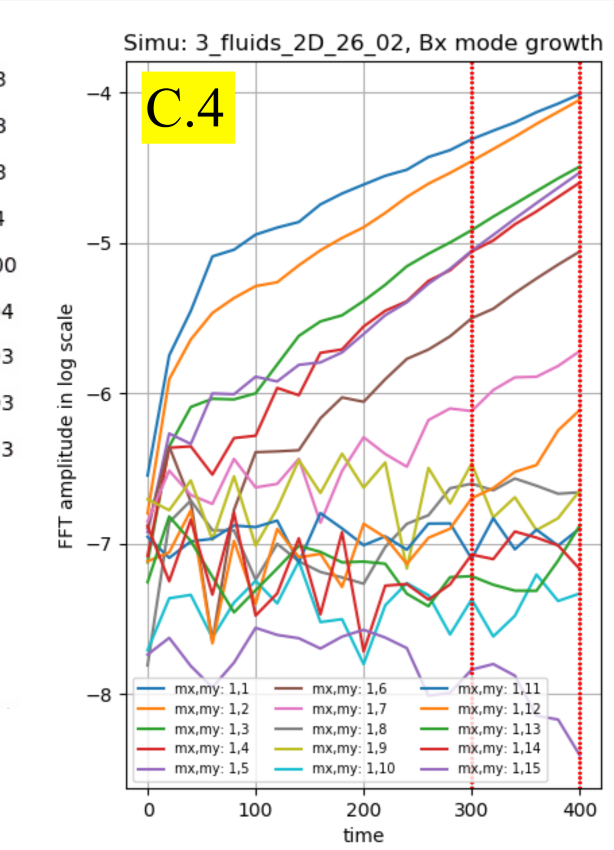


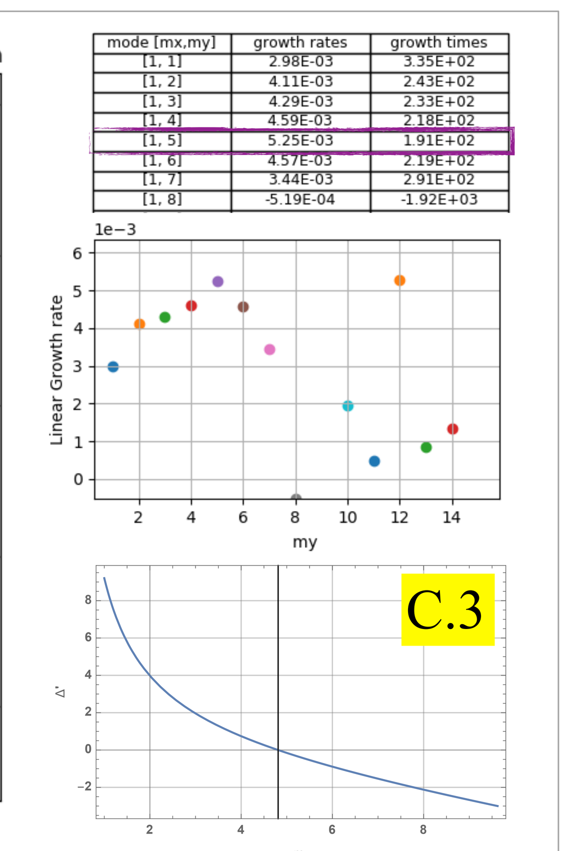


The tearing instability

By means of a magnetic perturbation, we trigger a tearing mode instability that shows magnetic field/ions velocity eigenfunctions (C.1 - C.2), FGM wave numbers (cfr. C.3 with C.4) and FGM growth rates (C.4) that agree with the theory [Furth et al., 1963].







The 3fluid numerical scheme

1. Transport of the density of ions and electrons entropies ($nS \equiv Pn^{1-\gamma}$), $\alpha = \{ic, ih, e\}$:

$$\frac{\partial(n_\alpha S_\alpha)}{\partial t} + \overline{\nabla}\cdot[\mathbf{U}_\alpha(n_\alpha S_\alpha)] = 0 \qquad (1)$$

2. Ions densities, $\alpha = \{ic, ih\}$:

$$\frac{\partial n_\alpha}{\partial t} + \overline{\nabla}\cdot(n_\alpha\mathbf{U}_\alpha) = 0 \qquad (2)$$

3. Electron density from updated ions densities[1], $\alpha = \{ic, ih\}$:

$$n_e^* = \sum_\alpha n_\alpha^* \qquad (3)$$

4. Ions momenta, $\alpha = \{ic, ih\}$:

$$\frac{\partial(n_\alpha\mathbf{U}_\alpha)}{\partial t} + \frac{1}{m_\alpha}\overline{\nabla}P_\alpha + \overline{\nabla}\cdot(n_\alpha\mathbf{U}_\alpha\mathbf{U}_\alpha) - \frac{q_\alpha n_\alpha}{m_\alpha}(\mathbf{E} + \mathbf{U}_\alpha\times\mathbf{B}) = 0 \qquad (4)$$

5. Ions and electrons pressures, $\alpha = \{ic, ih, e\}$:

$$P_\alpha^* = [n_\alpha S_\alpha]^*(n_\alpha^*)^{\gamma-1} \qquad (5)$$

6. Ions velocities, $\alpha = \{ic, ih\}$:

$$\mathbf{U}_\alpha^* = (n_\alpha\mathbf{U}_\alpha)^*/n_\alpha^* \qquad (6)$$

7. Magnetic field

$$\frac{\partial\mathbf{B}}{\partial t} + \overline{\nabla}\times\mathbf{E} = 0 \qquad (7)$$

8. Electronic velocities, $\alpha = \{ic, ih\}$:

$$\mathbf{U}_e^* = \left[\sum_\alpha(n_\alpha^*\mathbf{U}_\alpha^*) + \frac{1}{q_e\mu_0}\overline{\nabla}\times\mathbf{B}^*\right]/n_e^* \qquad (8)$$

9. Electric field

$$\mathbf{E}^* = -\mathbf{U}_e^*\times\mathbf{B}^* + \frac{1}{q_e n_e^*}\overline{\nabla}P_e^* \qquad (9)$$

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