

Direct Grid-Based Vlasov Simulation of Collisionless Plasma Expansion

Chen Cui*, Yuan Hu†, and Joseph Wang‡

Department of Astronautical Engineering, University of Southern California, Los Angeles, CA, 90089

The expansion of a collisionless, unmagnetized plasma expansion into a vacuum is a fundamental problem in plasma physics topic and is relevant to many application problems in electric propulsion and spacecraft-plasma interactions. For most electric propulsion and spacecraft interaction applications, the plasma is collisionless and thus a kinetic based modeling approach is typically required in a simulation study. Previous kinetic simulation studies of collisionless plasma expansion are mostly based on the particle-in-cell (PIC) method. However, a PIC based plasma expansion simulation may not be able to resolve the expansion front accurately due to statistical noise from insufficient number of macro-particles in the low density region. This paper presents an alternative approach using a grid-based Vlasov solver.

An electrostatic Vlasov solver directly solves the velocity distribution function for specie α , $f_\alpha(\mathbf{x}, \mathbf{v}, t)$, from the Vlasov equation:

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f_\alpha + \mathbf{a} \cdot \nabla_{\mathbf{v}} f_\alpha = 0 \quad (1)$$

where $\mathbf{v}$ is particles velocity and $\mathbf{a}$ is particles' acceleration,

$$\mathbf{a} = \frac{\mathbf{F}_\alpha}{m_\alpha} = \frac{q_\alpha \cdot \mathbf{E}}{m_\alpha} = \frac{-q_\alpha \nabla \Phi}{m_\alpha} \quad (2)$$

and Φ is the electric potential determined from the Poisson's equation,

$$\nabla \cdot (\epsilon_0 \nabla \Phi) = -e(Z_i n_i - n_e) \quad (3)$$

The Vlasov-Poisson equations are a set of non-linear a partial differential equations (PDE) due to the coupling between the Poisson's equation and the Vlasov equation. Because of the difficulties involved in solving these equations self-consistently, very few application problems can be solved through analytical solutions to the Vlasov-Poisson equations. On the other hand, numerical solutions of the Vlasov-Poisson equations are typically computationally expensive.

The Vlasov solver uses the Positive and Flux Conservative (PFC) Method proposed by Filbet et al. to accurately handle the strong nonlinearity in the system. The solver is tested for one dimensional plasma expansion and the results are compared with PIC simulations. Comparing to PIC, we find that the grid-based Vlasov method significantly reduces the statistical noise and is able to accurately predict the local electron and ion properties in the low-density regions. A grid-based Vlasov solver may be applied efficiently for simulations of collisionless plasma expansion.

*Research Assistant, cuichen@usc.edu

†Research Assistant, yuanhu@usc.edu

‡Professor, josephjw@usc.edu