2D Particle-in-cell Simulations for ESW Research in Space Plasma

Section Ⅱ Methods

2.1 Initializations of the Simulations

Two-dimensional (2D) electrostatic particle-in-cell simulations were performed to investigate the nonlinear evolution of electron bi-stream instability in weakly ($\Omega_e = 0.5\omega_{pe}$, where Ω_e and ω_{pe} were the electron frequency and electron plasma frequency, respectively) and strongly ($\Omega_e = 2\omega_{pe}$) magnetized plasma.

The charged particles motion in *x*-*y* plane and the background magnetic field $\boldsymbol{B}_0$ was along the *x* direction. Periodical boundary condition was considered that the electric field value of one side was equal to that of the opposite side and one particle leave one side while another particle enters from the opposite side. In initial, the temperature and the density of the both component electrons were equal and the velocity obeyed Maxwellian distribution. The background electrons had no average velocity, while the beam electrons had considerable velocity which was five times than the electron thermo-velocity. However, the ions were in the same initial state with the background electrons. The mass ratio of ion to electron was 1,836. The space and the time scale were normalized with Debye shield length (λ_D) and plasma frequency (ω_{pe}). The electric field was nondimensionalized with $m_e\omega_{pe}v_{te}/e$. 128×256 cells were used in the simulations, the size of which was $\lambda_D \times \lambda_D$. The step length of time was $0.02\omega_{pe}^{-1}$ and the number of each component particles was 3,276,800.

2.2 Processes of the Simulation

Maxwell equations and Newton mechanics equations had been discretized as follows.

1. Equations of motion

$$\boldsymbol{x}_i^{n+1} - \boldsymbol{x}_i^{n} = \boldsymbol{x}_i^{n+1/2} DT \tag{2.2.1}$$

$$\frac{\boldsymbol{v}_i^{n+1/2} - \boldsymbol{v}_i^{n-1/2}}{DT} = \frac{\boldsymbol{F}(x_i^n)}{N_s M_s m_e} \tag{2.2.2}$$

2. Force interpolation

$$\boldsymbol{F}_i^n = \boldsymbol{F}(x_i^n) = N_s M_s q[\sum_{r=0}^{M_s-1} \sum_{p=0}^{N_s-1} W(\boldsymbol{x}_i^n - \boldsymbol{x}_{p,r}) \boldsymbol{E}_{p,r}^n + \boldsymbol{v}_i^{n-\frac{1}{2}} \times \boldsymbol{B}_0] \tag{2.2.3}$$

3. Field equations

$$\frac{\phi_{p-1,r-1}^n + \phi_{p-1,r}^n + \phi_{p+1,r}^n + \phi_{p+1,r+1}^n - 4\phi_{p,r}^n}{H^2} = -\frac{\rho_{p,r}^n}{\varepsilon_0} \tag{2.2.4}$$

$$\boldsymbol{E}_{p,r}^n = \frac{\phi_{p-1,r}^n - \phi_{p+1,r}^n}{2H} \boldsymbol{e}_x + \frac{\phi_{p,r-1}^n - \phi_{p,r+1}^n}{2H} \boldsymbol{e}_y \tag{2.2.5}$$

4. Charge assignment

$$\rho_{p,r}^n = \frac{q N_s M_s}{H} \sum_{i=1}^{N_p} W(\boldsymbol{x}_i^n - \boldsymbol{x}_{p,r}) + \rho_0 \tag{2.2.6}$$

Given the state of the system $\{\boldsymbol{x}_i^n; \boldsymbol{v}_i^{n-1/2}; i = 1, N_p\}$, successively solving Eqs. (2.2.1) to (2.2.6) for $\{\rho_{p,r}^n\}, \{\phi_{p,r}^n\}, \{\boldsymbol{E}_{p,r}^n\}, \{\boldsymbol{F}_i^n\}, \{\boldsymbol{v}_i^{n+1/2}\}, \{\boldsymbol{x}_i^{n+1}\}$, respectively, gives the state of the system $\{\boldsymbol{x}_i^{n+1}; \boldsymbol{v}_i^{n+1/2}; i = 1, N_p\}$ at time DT later. The Eqs. (2.2.4) could be solved by Fast Fourier Transform Algorithm (FFT).