Two-and-a-Half Dimensional Open Boundary Particle Simulation of Current-Driven Electrostatic Ion-Cyclotron Instabilities

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We have developed a two-and-a-half dimensional electrostatic open boundary particle simulation model and have investigated current-driven electrostatic ion cyclotron instabilities and related potential structures.

A schematic view of the simulation model is presented in Fig. 1. Uniform external magnetic field is pointing into the positive x direction. A periodic boundary condition is applied in the y direction, whereas the left and right boundaries are open. The system is divided in segments in the y direction where each segment is assumed to be connected to an external constant current generator, respectively. For each segment, we have applied the method developed by Takamaru *et al.*[1] for a one dimensional simulation. The number of particles injected from the open boundaries in the x direction is specified in such a way that the electric current is kept constant at the boundaries of each segment at each time step. The velocity distribution of injected particles is specified so as to be consistent with the initial particle velocity distribution.

The net number of particles passing through the boundary of the i-th segment in the x direction in each time step (N_{net}^{i}) may be calculated from the specified velocity distribution. The numbers of injected particles of i-th segment ($N_{in}^{i,left}$, $N_{in}^{i,right}$) are

$$N_{in}^{i,left} = N_{net}^{i} - N_{out}^{i,left}, \tag{1}$$

$$N_{in}^{i,right} = N_{out}^{i,right} - N_{net}^{i}, \tag{2}$$

where $N_{out}^{i,left}$ and $N_{out}^{i,right}$ are the observed number of outgoing particles from the left and the right boundary of i-th segment, respectively. This procedure is applied for electrons. For ions, however, the reflection boundary condition is applied because we assume a shifted Maxwellian electron and a non-shifted Maxwellian ion.

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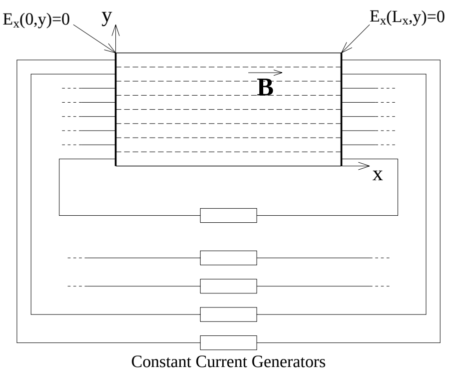

Fig. 1. Two-and-a-half open boundary particle simulation model.

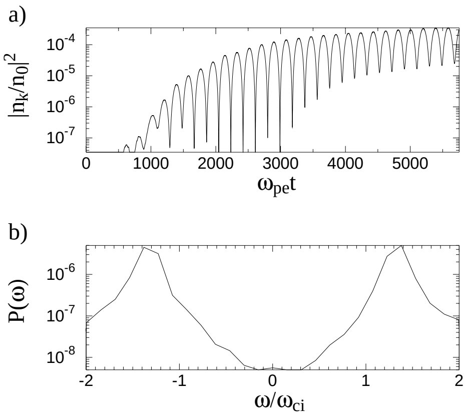

Fig. 2. Time history of ion density fluctuation (a) and frequency spectrum (b) with $k_\perp \rho_i = 0.550$ and $k_\| \rho_i = 0.103$.

The ion motion is followed in three dimensional velocity space and two dimensional real space, whereas we adopt the drift kinetic approximation for electrons.

We show the simulation results with following simulation parameters: The system sizes are $L_x = 1024\lambda_{De}$ and $L_y = 64\lambda_{De}$ and grid number is 1024×64, where λ_{De} is the Debye length. The system is assumed to be divided into 8 segments in the y direction, and thus the width of each segment is $8\lambda_{De}$. The number of ions and electrons are 67108864, respectively, and thus, 1024 particles per unit grid cell are used. The ion to electron mass ratio is 400 and the temperature ratio is 1/2. The electron cyclotron frequency $\omega_{ce} = 5\omega_{pe}$ and the ion cyclotron frequency is $\omega_{ci} = 0.0125\omega_{pe}$, where ω_{pe} is the electron plasma frequency. The electron velocity distribution is a shifted Maxwellian with drifting into the x direction, and the drift velocity is given by $v_{de} = 0.8v_{te}$. Here, $v_{te}(= (T_e/m_e)^{1/2})$ is the electron thermal velocity, T_e and m_e are the electron temperature (Energy unit) and the electron mass. The time step width $\omega_{pe}\Delta t$ is 0.2.

Figure 2 shows time evolution of the magnitude of the ion density fluctuation (a) and the frequency spectrum (b) for the mode with $k_\perp \rho_i = 0.550$ and $k_\| \rho_i = 0.103$, where we use $\cos k_x x \exp i k_y y$ transform to obtain spatial spectrum. This is the typical unstable mode for the electrostatic ion cyclotron wave for our choice of simulation parameters. The peaks of the frequency are around $\omega \simeq \pm 1.4\omega_{ci}$, indicating that the mode correspond to the ion cyclotron wave, which has a phase velocity $\omega/k_\| \simeq 0.5v_{te}$ and $\omega/k_\perp \simeq 0.09v_{te}$, and thus propagates ± 80 degrees with respect to the magnetic field with speed $\omega/|k| \simeq 0.09v_{te}$.

Figure 3 shows gray scale plot of potential profile at $\omega_{pe}t = 4000$. We can see an obliquely intersected stripe pattern which corresponds to the electrostatic ion cyclotron waves. In Fig. 4, we show the potential profile along the magnetic field lines at $y/\lambda_{De} = 32$

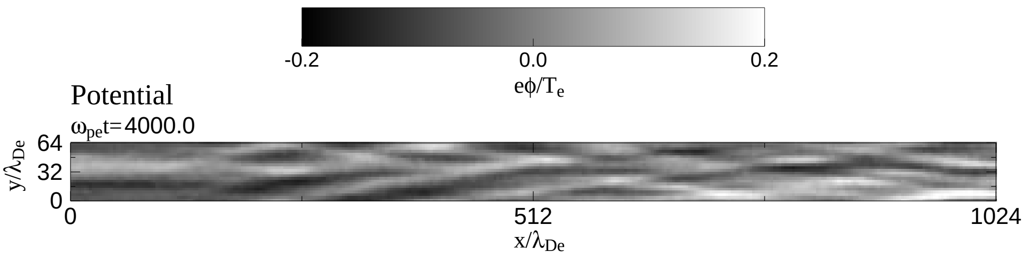

Fig. 3. Gray scale plot of the potential profile at $\omega_{pe}t = 4000$.

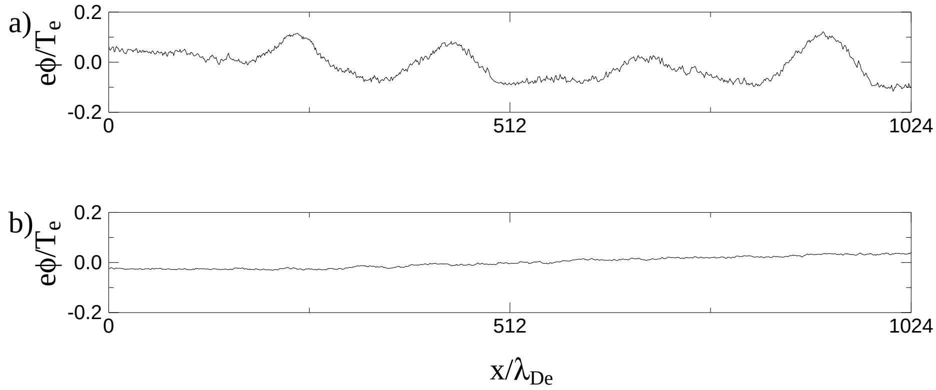

Fig. 4. Potential profile along the magnetic field lines at $y/\lambda_{De} = 32$ (a) and the potential profile which is averaged over y direction (b) at $\omega_{pe}t = 4000$.

(a) and the potential profile which is averaged over y direction (b) at $\omega_{pe}t = 4000$. The amplitude of the wave is larger in the downstream region than in the upstream region. This indicates that the amplitude of the wave grows as it propagates due to the instability. The averaged potential difference between the upstream and the downstream boundaries is about $e\Delta\phi/T_e \simeq 0.05$. The anomalous resistivity can be calculated from the relation $\eta = eE/n_0e^2v_{de} = e(\Delta\phi/L)/n_0e^2v_{de}$. Using the results with $e\Delta\phi/T_e \simeq 0.05$, $L = 1024\lambda_{De}$, $v_{de} = 0.8v_{te}$, one can get $\eta/\eta_0 \simeq 6 \times 10^{-5}$, where $\eta_0 = 4\pi/\omega_{pe}$.

Figure 5 shows the time evolutions of the electric current (a), number of outgoing electrons through the left boundary (b), and the right boundary (c) of the fourth segment ($24 < y/\lambda_{De} < 32$). As the ion cyclotron wave grows, the oscillation amplitude of the number of outgoing electrons through the right boundary increases. In spite of this large amplitude oscillation the electric current thorough the system is kept constant in time.

This is because fresh electrons are consistently injected from the left and right boundaries so as to keep constant current condition.

We have also performed a simulation for bell-shaped current flow by means of this open boundary particle simulation model and have succeeded to demonstrate that the V-shaped dc potential structure is created by the current-driven electrostatic ion-cyclotron instability[2].

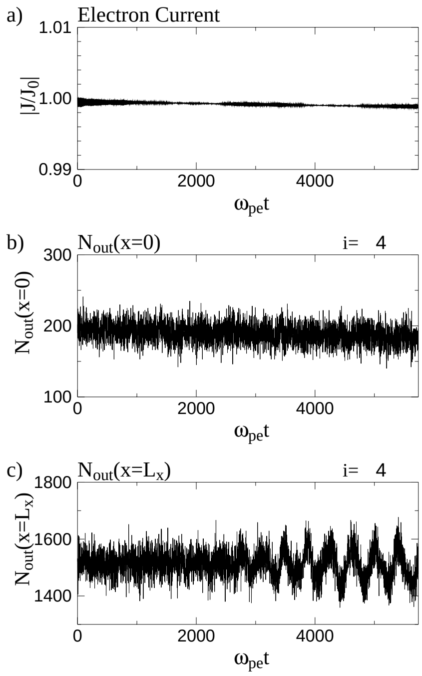

Fig. 5. Time history of electron current in the system (a), number of the outgoing electrons through the left boundary (b) and right boundary (c) of the 4-th segment.

References

[1] H. Takamaru *et al.*, J. Phys. Soc. Jpn., **66** 3826 (1997).

[2] S. Ishiguro *et al.*, Phys. Rev. Lett., **78** 4761 (1997).

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