Particle Simulation of Plasma Blob Dynamics: Preliminary Results*)

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A three dimensional electrostatic plasma particle code has been developed to investigate blob dynamics. Some results of preliminary simulations are in agreement with previous studies based on a two-dimensional reduced fluid model. When periodic boundary condition is applied in the ambient magnetic field direction, it was observed that a blob evolves to a mushroom-shaped structure. Furthermore, the relation between the observed blob propagation speed and the initial blob size is consistent with the expectation by the fluid theory.

Keywords: plasma blob, particle simulation, boundary layer plasma, convective plasma transport

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1. Introduction

Recently, the evidence of non-diffusive, i.e., convective plasma transport from the edge of core plasma to the main chamber wall in magnetic confinement fusion devices was observed. Such a transport is thought to be provided by long-lived coherent structures "blobs" in scrape-off layer (SOL) [1]. Blobs move across magnetic field lines and are believed to transport a plasma into the far SOL. Many theoretical and numerical studies of the blob dynamics have been performed on the basis of two dimensional reduced fluid models [1]. However, in the two dimensional limit, some ideal closures for parallel currents are assumed. In such closures, kinetic effects, such as sheath formation between a SOL plasma and a divertor plate, are treated under some assumptions and parameterization.

In this study, we have developed a three dimensional electrostatic plasma particle code with particle absorbing boundaries [2] in order to study blob dynamics. Results of preliminary simulations indicate that blobs propagate to the first wall across the magnetic field lines. When periodic boundary condition is applied in the ambient magnetic field direction, it is observed that a blob evolves to a mushroom-shaped object. This fact is in agreement with previous results of the fluid model simulations [3]. Observed relation between the propagation speed of the blob and the initial effective width of the blob in the poloidal direction is consistent with the expectation by the previous fluid theory. In Sec. 2, we describe the simulation configuration and parameters. In Sec. 3, we show the results of preliminary simulations. Section 4 summarizes the paper.

2. Methodology

We use a three-dimensional electrostatic particle code with full particle dynamics to study the blob dynamics. Configuration of the simulation is as follows. The ambient magnetic field is pointing into the z direction (equivalent to the toroidal direction). The strength of magnetic field increases in the positive x direction (equivalent to the counter radial direction) as $2L_xB_0/(3L_x - x)$ where L_x, L_y, and L_z are the system size in the x, y, and z directions and B_0 is the magnetic field strength at $x = L_x$. The particle absorbing boundary corresponding to the first wall is placed at $x = 0$. In the y direction (equivalent to the poloidal direction), periodic boundary condition is applied. The boundary condition in the z direction will be described in following subsections.

The simulation parameters are as follows. The grid spacing is $\Delta_g = \lambda_{De}$ where λ_{De} is the Debye length. The ion-to-electron mass ratio is $m_i/m_e = 100$. The ion-to-electron thermal velocity ratio is $v_{Ti}/v_{Te} = 0.05$. Thus, the ion-to-electron temperature ratio is $T_i/T_e = 0.25$. The external magnetic field strength in background plasma is given as $|\Omega_e|/\omega_{pe} = 10$ where Ω_e is the electron cyclotron frequency and ω_{pe} is the electron plasma frequency. The time step is $\Delta t = 0.025\ \omega_{pe}^{-1}$. There are 64 electrons and an equal number of ions per cell. Using these parameters, we obtain the relation $\rho_s = \lambda_{De}$ where $\rho_s = c_s/\Omega_i$, c_s is the ion acoustic speed given as $c_s = \sqrt{T_e/m_i}$, and Ω_i is the ion cyclotron frequency. Furthermore, if $T_e = 30$ eV and the electron density is $n_e = 10^{18}\ \mathrm{m}^{-3}$, the Debye length and the magnetic field strength become $\lambda_{De} \sim 4 \times 10^{-5}$ m and $B \sim 3$ T, respectively.

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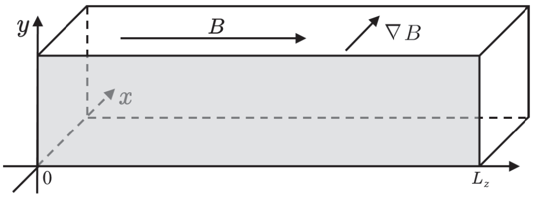

Fig. 1 Configuration of the simulation in which periodic boundary condition is applied in the z direction. Here, the shaded plane refers to absorbing boundary.

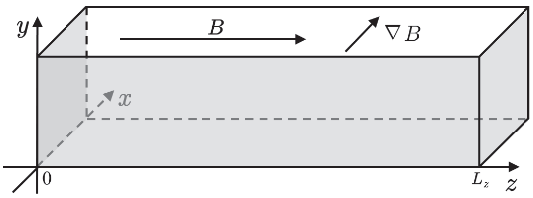

Fig. 2 Configuration of the simulation in which end plates are placed in the both ends of the z axis. Here, the shaded planes refer to absorbing boundaries.

2.1 Boundary condition A: periodic boundary

In this case, periodic boundary condition is applied in the z direction. Thus, there are not ends corresponding to divertor plates. Then the number of simulation particles in the system is not decreased by absorption at ends. The schematic figure of the simulation system is shown in Fig. 1. The shaded plane in Fig. 1 refers to absorbing boundary.

2.2 Boundary condition B: termination by end plates

In another case, particle absorbing boundaries corresponding to divertor plates are placed in the both ends of the z axis. Figure 2 presents the schematic figure of the system in this case.

3. Preliminary Results

3.1 Boundary condition A

We now present a result of preliminary simulations in which periodic boundary condition is applied in the z direction. Figure 3 displays electron density distributions in the x-y plane at $z = L_z/2$ at $\omega_{pe}t = 100, 800, 1{,}500, 2{,}200$, and 2,900 where the system size $L_x \times L_y \times L_z$ is $64\lambda_{De} \times 64\lambda_{De} \times 128\lambda_{De}$. The initial blob size is $\delta_b = 4.0\lambda_{De}$ where the initial configuration of a blob is given by the Gaussian distribution with the width δ_b. The blob is initially located as a column along the ambient magnetic field at around $(x, y) = (48\lambda_{De}, 32\lambda_{De})$. As shown in Fig. 3, the blob evolves to a mushroom-shaped structure. This fact is in agreement with previous result of the two-dimensional reduced fluid model simulations [3].

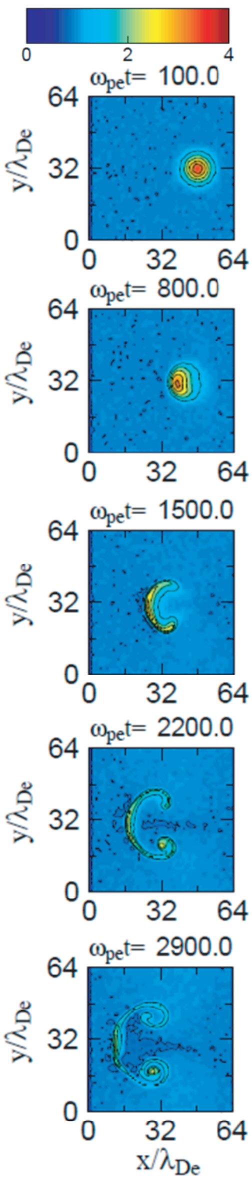

Fig. 3 Electron density distributions in the x-y plane at $z = L_z/2$ at $\omega_{pe}t = 100, 800, 1{,}500, 2{,}200$, and 2,900 in the periodic boundary condition case.

Figure 4 shows electric potential distributions in the x-y plane at $z = L_z/2$ at $\omega_{pe}t = 100, 800, 1{,}500, 2{,}200$, and 2,900. Figure 4 indicates that double vortices of the blob particles are produced by the $\boldsymbol{E} \times \boldsymbol{B}$ drift.

3.2 Boundary condition B

Next, we describe results of preliminary simulations in which end plates are placed in the both ends of z axis. In Fig. 5 we show an electron density distribution in the z-x plane at $y = L_y/2$ at $\omega_{pe}t = 100$ where the system size $L_x \times L_y \times L_z$ is $64\lambda_{De} \times 64\lambda_{De} \times 512\lambda_{De}$, the initial blob size is $\delta_b = 4.0\lambda_{De}$, and the blob is initially located as a column along the ambient magnetic field at around $(x, y) = (48\lambda_{De}, 32\lambda_{De})$. The blob has cigar like structure

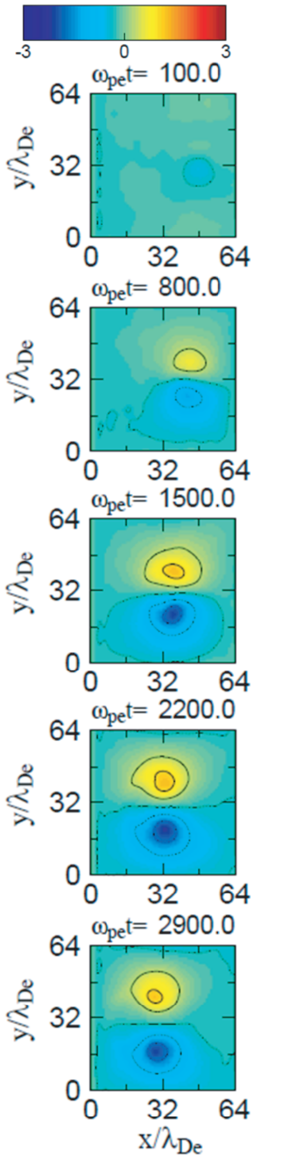

Fig. 4 Potential distributions in the x-y plane at $z = L_z/2$ at $\omega_{pe}t = 100$, 800, 1,500, 2,200, and 2,900 in the periodic boundary condition case.

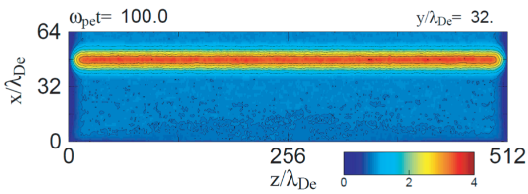

Fig. 5 Electron density distribution in the z-x plane at $y = L_y/2$ at $\omega_{pe}t = 100$ when end plates are placed in the both ends of the z axis.

because plasma particles are absorbed in the both ends of the z axis.

Figure 6 displays a potential distribution in the z-x plane at $y = L_y/2$ at $\omega_{pe}t = 100$. Figure 6 indicates that the sheath potentials are formed at around $z = 0$ and L_z.

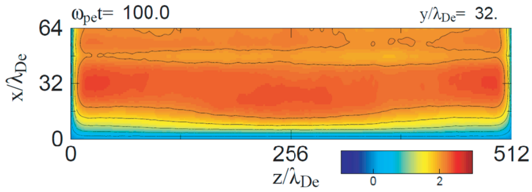

Fig. 6 Potential distribution in the z-x plane at $y = L_y/2$ at $\omega_{pe}t = 100$ when end plates are placed in the both ends of the z axis.

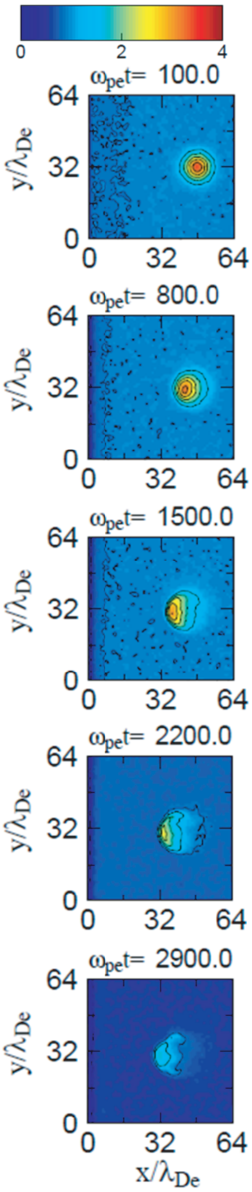

Fig. 7 Electron density distributions in the x-y plane at $z = L_z/2$ at $\omega_{pe}t = 100$, 800, 1,500, 2,200, and 2,900 when end plates are placed in the both ends of the z axis.

Figure 7 shows electron density distributions in the x-y plane at $z = L_z/2$ at $\omega_{pe}t = 100$, 800, 1,500, 2,200, and 2,900. The blob moves to the first wall across the magnetic field lines. However, the plasma density in the blob is de-

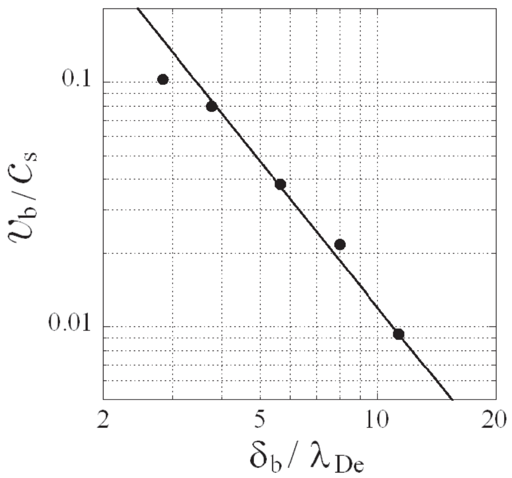

Fig. 8 Relation between the blob size and the blob propagation speed.

creased by the particle absorption. Furthermore, the effect of end plates appears a little in the propagation speed. Although the second panel ($\omega_{pe}t = 800$) in Fig. 3 shows that the x position of the density peak is $x \sim 38.9$, it is found that the peak position is $x \sim 42.6$ from the second panel in Fig. 7. Namely, the propagation speed of the blob in this case is slower than one in the periodic boundary condition case. It is thought that this difference arises from the reduction in the electric field in a blob by the end plates.

Figure 8 presents the relation between the effective width of the blob in the y direction (δ_b) and the propagation speed of the blob (v_b). Here, the observed speeds were taken at an early stage ($\omega_{pe}t = 100 \sim 1,000$) and the system size $L_x \times L_y \times L_z$ is set as $64\lambda_{De} \times 64\lambda_{De} \times 256\lambda_{De}$. In Fig. 8, the closed circle refers to results of simulations and the solid line represents

$$v_b^{th}(\delta_b) = v_b^{sim}(11.3\lambda_{De}) \left(\frac{11.3\lambda_{De}}{\delta_b} \right)^2, \quad (1)$$

where $v_b^{sim}(11.3\lambda_{De})$ is the propagation speed observed in the simulation in which the initial blob size is given as $\delta_b = 11.3\lambda_{De}$ (the value of the propagation speed of the rightmost closed circle in Fig. 8). From the theory based on the two-dimensional reduced fluid model, it was found that the blob propagation velocity is proportional to δ_b^{-2} [1, 4]. Thus, Fig. 8 indicates that the particle simulation results are consistent with the fluid theory. Further, these observed speeds ($0.01c_s \lesssim v_b \lesssim 0.1c_s$) are in agreement with some experiments [5].

4. Summary

We have developed a three dimensional electrostatic plasma particle code to study blob dynamics. We then showed results of preliminary simulations. Some results coincide with previous results from the fluid model.

The investigation into the parallel current closure with the blob particle simulations will be one of topics in future work. Also, we will optimize the code to apply it to a huge system size (large L_z) in order to avoid the fast blob amplitude decrease.

Acknowledgments

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