Particle simulation of the potential formation across the magnetic filter

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The potential formation across the magnetic filter (MF) is studied by the two-and-one-half-dimensional (two configuration and three velocity spaces) electrostatic particle simulation. The strength of the MF is selected to influence only electron dynamics; ions move freely across the MF. The MF divides the plasma into the main plasma and the diffused plasma. The density and temperature of the main plasma is controlled, while there is no artificial treatment for the diffused plasma. It is found that the (collisionless) anomalous diffusion of electrons plays an important role in determining the potential structure in which the potential of the main plasma is higher than that of the diffused plasma. It is also found that by changing the potential of the wall adjacent to the diffused plasma, the plasma potential of the diffused plasma can be controlled without affecting the main plasma. © *1996 American Institute of Physics.* [S0034-6748(96)10602-5]

I. INTRODUCTION

For optimization of the extraction of negative ions from the plasma, it is important to clarify the role of the plasma grid (PG) and the magnetic filter (MF). We have studied the negative ion extraction from the volume plasma source[1,2] and the electron diffusion across the MF[3,4] by using a two dimensional electrostatic particle simulation code. It is found that the thermally excited low frequency modes determine the electron transport across the MF.[3,4] Especially, low energy electrons can diffuse by $E\times B$ drifts faster than energetic electrons, which is similar to the results of electron transport due to convective cell modes in the uniform magnetic field.[5] This is because the high energy electrons have larger orbits which average out the small scale fluctuations; energetic electrons diffuse less than cold electrons. However those studies were limited to a uniform plasma. Also in the studies of Refs. 1 and 2, the MF is used to reflect all of the electrons.

In this paper, we treat the more realistic case in which the diffused plasma is separated from the main plasma by the MF. Because no artificial treatment was performed on the diffused plasma, the density and temperature in the diffused plasma and the potential difference across the MF are determined by the electron transport under the MF. It will be shown that anomalous transport of electrons plays a crucial role on the potential formation. Also the effect of PG, which is adjacent to the diffused plasma, on the potential of the diffused plasma is studied. The idea of low energy neutral ion beam injector is referred to in the concluding section.

II. SIMULATION MODEL

The simulation model is depicted in Fig. 1. There is a magnetic filter at the center of the system. The spatial dependence of the MF is given by

$$B=B_0 \exp\left(-\frac{(x-0.5L_x)^2}{2a_B^2}\right), \qquad (1)$$

where B_0 is the magnetic field strength at the center of the MF and a_B is the characteristic width of the MF. The strength of B_0 is represented by ω_{ce}/ω_{pe} (ω_{ce} and ω_{pe} are the cyclotron and plasma angular frequencies of electrons, respectively) in the paper. The magnetic field is in the $y-z$ plane and tilted from the z axis by the angle θ. When $\theta=0$, the magnetic field is perpendicular to the configuration space. In this case, the particle velocity in the z direction is decoupled to other equations; the system is two dimensional. When $\theta\neq 0$, the wave vectors have components parallel to the magnetic field (except for the mode propagating only in x); the system is two-and-one-half dimensional (two configuration and three velocity spaces). In this case, the particles moving along the magnetic field can interact with the wave propagating obliquely to the magnetic field. Electron motion is influenced by the MF whereas ions can move freely across the MF. Initially, charged particles are located in the region right of the magnetic filter (main plasma). The wall at $x=0$ is used as PG. The wall at $x=L_x$ represents a grounded vacuum chamber. A periodic boundary condition is used in the y direction with the period of L_y. The electrostatic potential of PG is arbitrary and given by ϕ_{PG}. Particles reaching the walls are absorbed there. Electrons and ions are injected constantly into the source region (SR) to equal the particle loss from the main plasma. To attain the stationary state, the velocity distribution of electrons in the SR is reset to form a new Maxwell distribution every several tens of time steps. Without this process, the electron velocity distri-

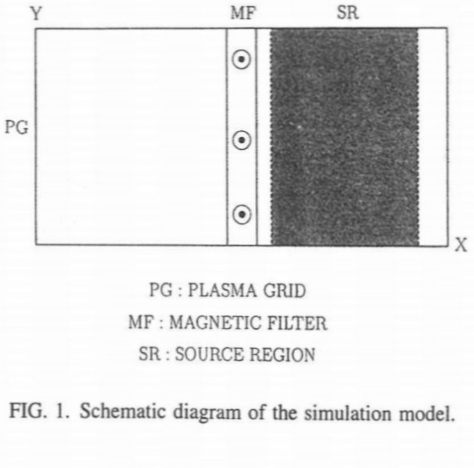


FIG. 1. Schematic diagram of the simulation model.

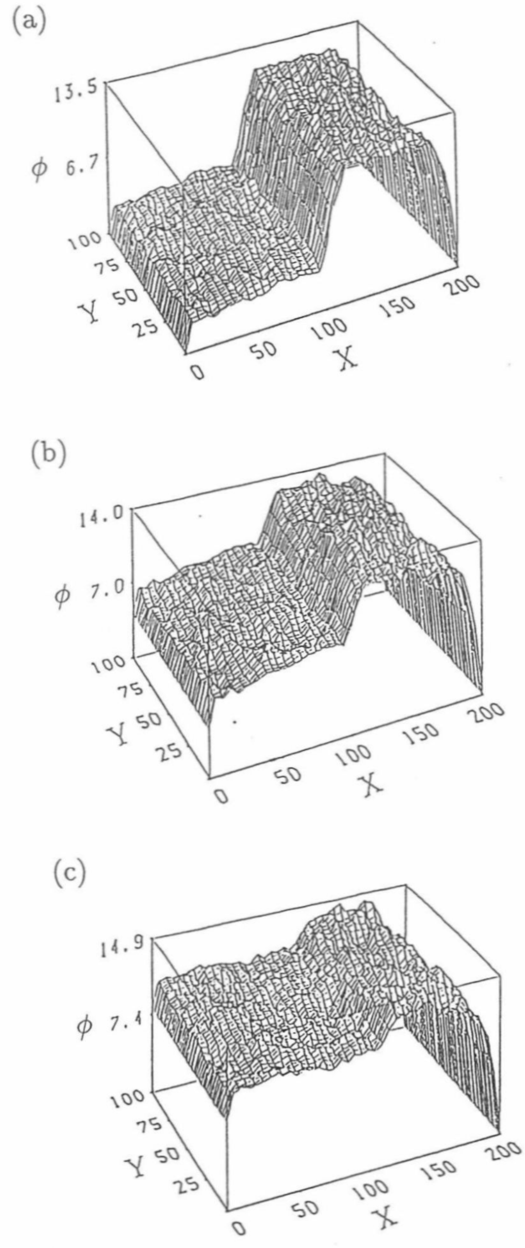


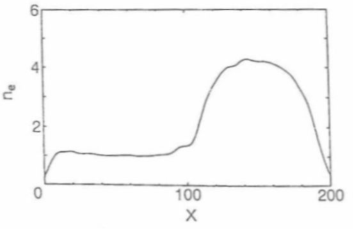
FIG. 2. Potential profiles for (a) $\phi_{PG}=0$ ($t\omega_{pe}=5400$), (b) $\phi_{PG}=4$ ($t\omega_{pe}=5600$), and (c) $\phi_{PG}=8$ ($t\omega_{pe}=6200$). ($\theta=0°$, $\omega_{ce}/\omega_{pe}=1$.)

bution would be cooled eventually because only low energy electrons are confined in the system by the sheath potential near the wall.

III. SIMULATION RESULTS

Simulation parameters are as follows. System size: $L_x=200$, $L_y=100$, $a_B=3$, mass ratio: $m_i/m_e=1836$, temperature ratio: $T_i/T_e=0.1$ (main plasma), electron Debye length: $\lambda_{De}=2$(main plasma), time step size: $\Delta t=0.2$, number of time steps: $N_t=20\,000-30\,000$, number of particles: $N_e \sim N_i \sim 40\,000$. Here the length and the time are normalized by the grid size, Δ, and ω_{pe}^{-1}, respectively. Temperatures and potentials are normalized by $m_e\Delta^2\omega_{pe}^2$ and $m_e\Delta^2\omega_{pe}^2/e$ (e is an electron charge), respectively. Therefore electron and ion temperatures are $T_e=4$ and $T_i=0.4$ (main plasma).

(a) electron density



(b) electron temperature

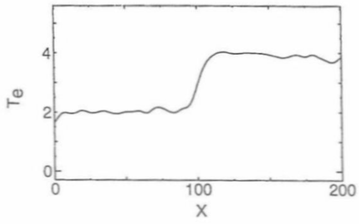


FIG. 3. Electron density and temperature profiles in x for $\theta=0°$, $\omega_{ce}/\omega_{pe}=1$, and $\phi_{PG}=0$. The parameters are the same as that of Fig. 2(a).

The results for $\theta=0°$ are shown in Figs. 2–4. Figure 2(a) presents the potential profile for $\phi_{PG}=0$ and $\omega_{ce}/\omega_{pe}=1$. We can observe that the potential in the main plasma is higher than that of the diffused plasma. The density and temperature of the diffused plasma are a quarter and a half of the main plasma, respectively (Fig. 3). The plasma potential in the separated region is determined by the electron temperature. If ϕ_{PG} is increased, the potential of the diffused plasma increases without affecting the potential of the main plasma [Figs. 2(b) and 2(c)]. In the case of $\omega_{ce}/\omega_{pe}=0.5$ we do not see any potential difference across the magnetic field because some of the electrons penetrate directly to the diffused plasma. The case of $\omega_{ce}/\omega_{pe}=2$ is shown in Fig. 4. We also observe no significant difference of the potential across the MF. This comes from the fact that the ion transport is faster than the electron transport. If the magnetic field is tilted from

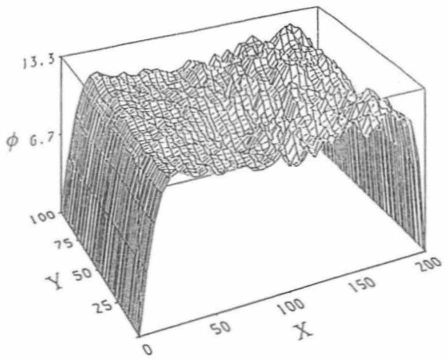


FIG. 4. Potential profile for $\theta=0°$, $\omega_{ce}/\omega_{pe}=2$, and $\phi_{PG}=0$ ($t\omega_{pe}=7200$).

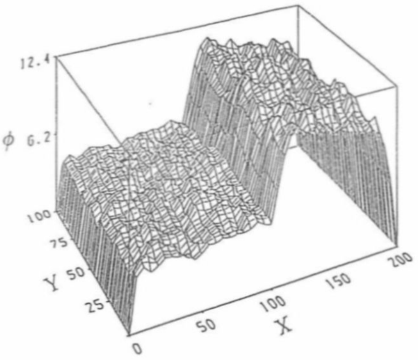


FIG. 5. Potential profile for $\theta=0°$, $\omega_{ce}/\omega_{pe}=2$, and $\phi_{PG}=0$ ($t\omega_{pe}=4200$).

the z axis, it is possible that unstable modes, similar to the drift waves, can be excited through the inverse Landau damping of electrons. Hence the fluctuation level of the low frequency waves can be much higher than the thermal level; the electron transport across the MF will increase drastically. Figure 5 demonstrates this; the potential difference appears in the case of $\theta=2°$ even for $\omega_{ce}/\omega_{pe}=2$.

IV. CONCLUSIONS AND DISCUSSION

Two-and-one-half dimensional electrostatic particle simulation was done to simulate the potential formation across the MF. In the collisionless limit, without the anomalous diffusion of electrons, the potential of the diffused plasma will be slightly higher than that of the main plasma because only ions can move across the MF. However electron anomalous diffusion caused by the low frequency fluctuations under the MF plays a dominant role to create the state that the potential of the main plasma is higher than that of the diffused plasma. The actual experimental devices are three dimensional; many unstable modes can contribute to the low frequency turbulence. Also the mode coupling of the unstable modes can create the convective cell modes which is purely perpendicular to the magnetic field; anomalous diffusion of electrons will increases furthermore. It is found that the potential of the PG can control the potential of the diffused plasma; it will be effective to optimize the extraction of negative ions. Finally, it is to be noted that by the combination of MF and PG we can produce the ion beam in the diffused plasma with the energy comparable to the potential difference. It can be used to produce a low energy neutral ion beams if we assume charge exchange in the diffused plasma.

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