

Particle simulation on extraction of positive and negative ions from a volume source

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A two dimensional electrostatic particle simulation was done to study the extraction of positive (negative) ions from a volume plasma source. The simulation model is a rectangular system which consists of an extraction grid (left wall), a plasma grid, and a grounded wall (right wall). Upper and lower boundaries are connected by the periodic boundary condition. Full dynamics of charged particles are followed. Positive (negative) ions are extracted from the plasma region through a slit in the plasma grid to the extraction grid. Electrons are reflected by the magnetic filter and confined in the region to the right of the magnetic filter. Simulation results are compared with the Child–Langmuir law where the extracted ion current is proportional to the three-halves power of the potential of the extraction grid. In the case of the positive ion extraction, simulation results agree quite well with the Child–Langmuir law. Whereas, in the case of the negative ion extraction, simulation results agree with the law only for the lower value of extraction grid potential.

I. INTRODUCTION

To optimize the extraction of negative ions from the plasma, it is a key issue to know the physics of the potential formation around the plasma–vacuum and plasma–wall interfaces. Because of the presence of negative ions in addition to electrons and positive ions, the system is too complicated to be treated by a simple theory. Particle simulation is very powerful to treat such a highly nonlinear system. However, a conventional particle code usually simulates only a simple rectangular system bounded or essentially infinite by using the periodic boundary condition (for example, fast Fourier transform is used for the Poisson solver).¹ To simulate a system of complicated geometry, we developed a PSEG (particle simulation with electrostatic grids) code which include various electrostatic grids in the system. The Poisson solver in the PSEG code is written by using the successive over-relaxation (SOR) method which can include various boundary conditions. With the PSEG code, we studied negative ion extraction from the volume plasma source by using a realistic geometry including a plasma grid (PG), an extraction grid (EG), an acceleration grid (AG), and a magnetic field in the EG region.^{2,3}

In this article, we employed a simpler geometry including only PG and EG. The extraction of positive ions is studied by using the same geometry as well as the extraction of negative ions. By comparing both results, we can see the effects due to the existence of negative ions. Also, simulation results are compared with the Child–Langmuir law where the extracted ion current is proportional to the three-halves power of the potential of the extraction grid.

II. SIMULATION MODEL

The simulation model is depicted in Fig. 1. Charged particles move in the x – y plane. Full dynamics of charged

particles are followed in the simulation. There is a magnetic filter in the system (indicated by B_y in the figure). The direction of the magnetic field is in the y direction. The magnetic filter is used to reflect electrons. Ions are not affected by the magnetic field because of large inertia. Initially, charged particles are located in the region to the right of the magnetic filter. We will call this region the plasma region. The system is bounded by walls at $x=0$ and $x=L_x$. The wall at $x=0$ is used as the EG. The wall at $x=L_x$ represents a grounded vacuum chamber. A periodic boundary condition is used in the y direction. There is a PG inside the system, the opening of which is defined by a . The space between the EG and PG is represented by d . Electrostatic potentials of the EG and PG are arbitrary and given by ϕ_{EG} and ϕ_{PG} , respectively. Particles reaching the PG, EG, or the wall at $x=L_x$ are absorbed there. Electrons and ions are injected constantly into the source region (SR) inside the plasma region to equal the particle loss to the grids and the walls. To attain the stationary

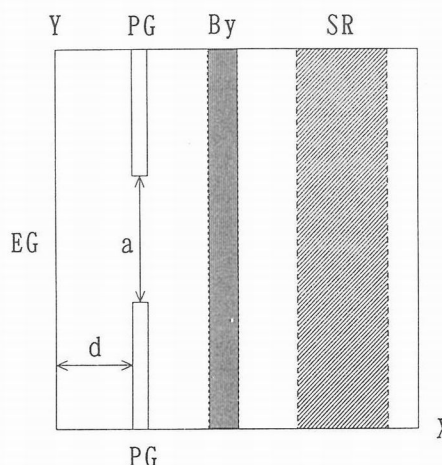


FIG. 1. Schematic diagram of the simulation model.

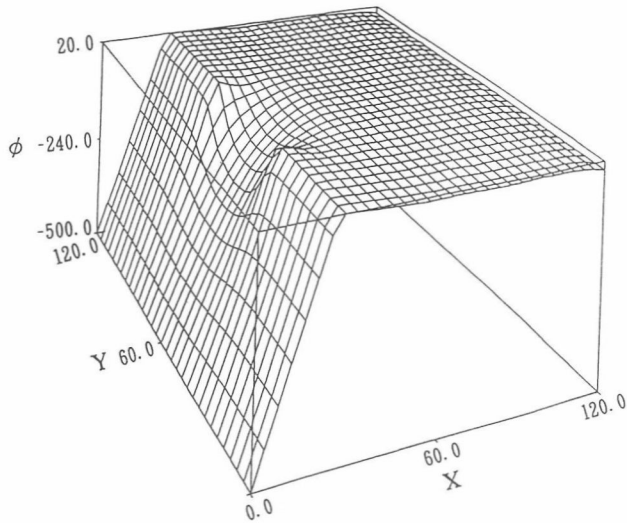


FIG. 2. Three-dimensional view of a potential profile for the case of the positive ion extraction. Parameters are $a=40$, $\phi_{EG}=-500$, $\phi_{PG}=20$, and $t=2000$.

state, the velocity distribution of electrons in the source region is reset to form a new Maxwell distribution in every several tens of time steps. Therefore, electrons entering the SR experience at least one artificial "collision" before leaving the SR (except for very high energy electrons). Without this process, the electron velocity distribution 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 common to the extraction of positive and negative ion extractions are the following: system size: $L_x=L_y=120$ (normalized by the grid size Δ), mass ratio: $m_i/m_e=1836$, temperature ratio: $T_i/T_e=0.1$, electron debye length: $\lambda_{De}=2$ (normalized by Δ), width of

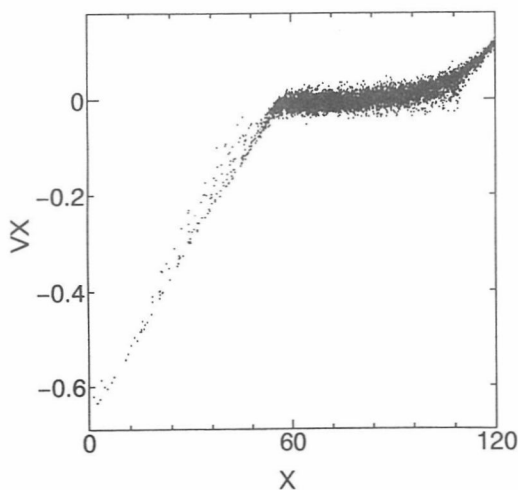


FIG. 3. Phase space (x, v_x) plots of positive ions which are located in the region $40 < y < 80$, for $a=40$, $\phi_{EG}=-500$, and $\phi_{PG}=20$ at $t=2000$.

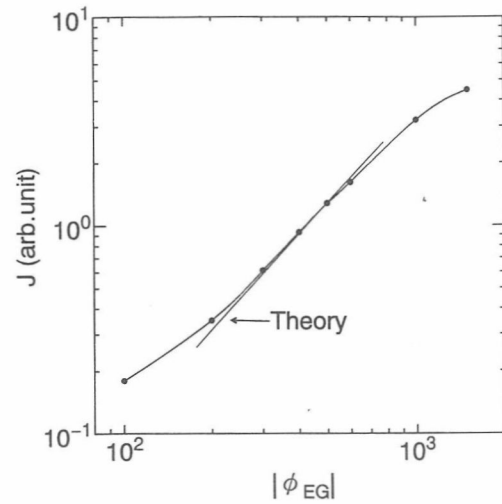


FIG. 4. Positive ion beam currents vs ϕ_{EG} for $a=40$. The line indicated by theory represents the Child-Langmuir law.

time step: $\Delta t=0.2$ (normalized by the inverse of the electron plasma angular frequency, ω_{pe}^{-1}), number of time steps: $N_t=10\,000$. 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 $T_i=0.4$.

A. Extraction of positive ions

The potential of the PG is fixed at $\phi_{PG}=20$. Ions are reflected by this potential and cannot reach the PG. This value of ϕ_{PG} was chosen to compare with the case of extraction of negative ions because usually the plasma space potential is higher than ϕ_{PG} and negative ions cannot reach the PG. Only electrons and positive ions are simulated in this case. About 30 000 particles are used in the simulation.

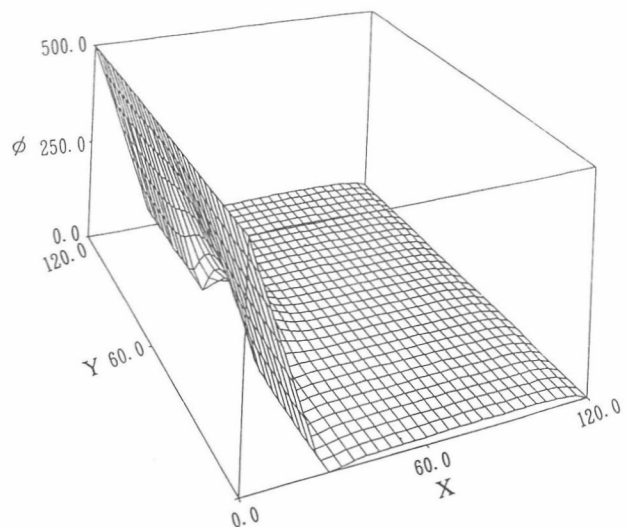


FIG. 5. Three-dimensional view of a potential profile for the case of the negative ion extraction. The parameters are $a=40$, $\phi_{EG}=500$, $\phi_{PG}=0$, and $t=2000$.

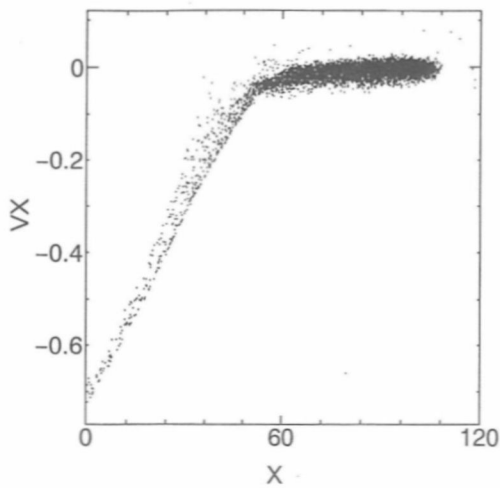


FIG. 6. Phase space (x, v_x) plots of negative ions which are located in the region $40 < y < 80$, for $a=40$, $\phi_{EG}=500$, and $\phi_{PG}=0$ at $t=2000$.

An example of a potential profile is shown in Fig. 2. The two-dimensional structure of the potential is clearly seen. Ion positions in the (x, v_x) phase space are plotted in Fig. 3, where v_x is the velocity in the x direction. We can see that most of ions are confined uniformly in the plasma region. Near the right wall, ions are accelerated to the positive x direction due to the sheath potential around the wall. Some of the ions are accelerated to the direction of the EG. Figure 4 illustrates the ϕ_{EG} dependence of the extracted positive ion current. In this case, the plasma surface (defined by the electron surface) is not affected by ϕ_{EG} . Simulation results agree quite well with the Child-Langmuir law.

B. Extraction of negative ions

In this case, negative ions are followed as well as electrons and positive ions. The initial densities are $n_e = n_{ni} = 0.5n_i$, where subscripts e , i , and ni represent electron, ion, and negative ion, respectively. About 160 000 particles are used in the simulation. The negative ion temperature is $T_{ni}=0.4$. The potential of the PG is fixed to be $\phi_{PG}=0$. Figure 5 shows an example of a potential profile. The phase space plot of negative ions is presented in Fig. 6. The Child-Langmuir law predicts that the extracted current is also inversely proportional to the square of the distance between the EG and the plasma surface. In the case of negative ion extraction, the position of the plasma surface defined by the positive ion surface moves depending on ϕ_{EG} . To compare with the law, we plotted the negative ion current times d_m^2 vs ϕ_{EG} in Fig. 7, where d_m is the

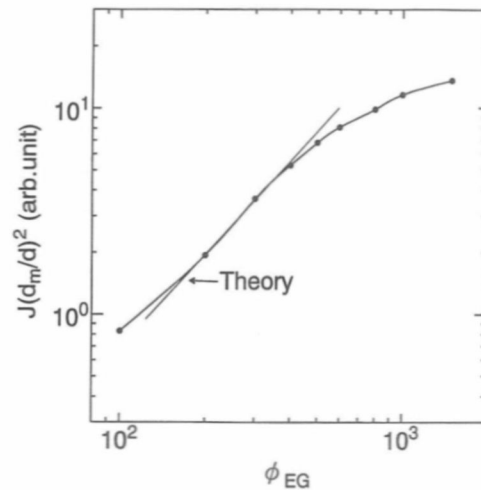


FIG. 7. Negative ion beam currents vs ϕ_{EG} for $a=40$. The correction due to the change of the plasma surface defined by the positive ion surface is done by the factor d_m^2/d^2 . The lines indicated by theory represent the Child-Langmuir law.

measured distance between the EG and the plasma surface at the midplane in y . Simulation results agree with the Child-Langmuir law for the lower value of ϕ_{EG} . While for the higher value of ϕ_{EG} , simulation results do not coincide with the law.

IV. CONCLUSIONS AND DISCUSSION

Two-dimensional electrostatic particle simulation was done to simulate the extraction of positive and negative ions from the volume plasma source. In the case of the positive ion extraction, simulation results agree quite well with the Child-Langmuir law. Whereas, in the case of the negative ion extraction, simulation results agree with the law only for the lower value of extraction grid potential. Further study will be needed to study the physical reason why this deviation from the Child-Langmuir law appears.

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¹ C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulation* (McGraw-Hill, New York, 1985).

² H. Naitou, O. Fukumasa, I. Nomura, and K. Mutou, *Proceedings of the 9th Symposium Plasma Processing* (Division of Plasma Electronics, Jpn. Soc. Appl. Phys., Fukuoka, 1992), p. 229.

³ H. Naitou, O. Fukumasa, and K. Mutou, presented at 6th International Symposium on the Production and Neutralization of Negative Ions and Beams, Brookhaven, Nov. 1992.