REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 71, NUMBER 2 FEBRUARY 2000

Beam instability excited by the magnetic filter

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(Presented on 7 September 1999)

By the one-dimensional electrostatic particle simulation, the ion beam instability is observed in the plasma divided by the magnetic filter (MF). The strength of the MF is selected to influence only electron dynamics; ions move freely across the MF. There are grounded walls at the left and right ends of the system. Particles hitting the walls are absorbed there. The high temperature and high density plasma (main plasma) faces the low temperature and low density plasma (subplasma) across the MF located at the center of the system. The averaged space potential of the main plasma is higher than that of the subplasma. Due to the potential gap at the MF, ions in the main plasma are accelerated into the subplasma. Depending on the extent of the asymmetry of the system, steady or the periodic (dynamic) state manifests. For the periodic state, high density clumps get into the subplasma and excite the strong ion beam instability. The new clump comes into the subplasma when the old clump reaches the wall. © *2000 American Institute of Physics.* [S0034-6748(00)60102-8]

I. INTRODUCTION

The magnetic filter (MF) has been used to control plasma parameters by separating the plasma into two regions of different parameters. For example, in the negative ion source of hydrogen or deuterium, a diffused plasma with low temperature and low density exists next to a source plasma with high temperature and high density across the MF. Most of the negative ion source relies on the two-step process[1,2] the source plasma includes high energy electrons (~20–30 eV) to generate highly excited molecules, whereas the diffused plasma includes only low energy electrons (~1 eV) necessary for the dissociative attachment. This kind of "double plasma" configuration might be useful for the processing plasma since high energy electrons are needed to produce radical species but low electron temperature is preferable to reduce the bombardment of energetic ions accelerated by sheath potential against the substrate surface.

The strength of the MF is high enough to reflect only electrons. Some electrons can move across the MF due to collisional or collisionless (turbulent) transport processes. The effect of the MF on ions is minimal because of the large ion mass. The transport of ions across the MF, however, could be influenced by the potential gap between two plasmas. The plasma divided by the MF was simulated by the two-dimensional particle simulation.[3–6] The importance of electron transport across the MF due to the $E \times B$ drift and resultant potential formation was studied in Refs. 3 and 6. We have believed in the existence of the stationary state (stationary density, temperature, and potential profiles). Recently, we found the nonstationary dynamic state including the ion beam instability by the one-dimensional particle simulation. In this article, we concentrate on the presentation of the newly found nonsteady state in the asymmetric plasma with the MF.

II. SIMULATION MODEL

The one-dimensional particle-in-cell code, visualized particle simulation code in one dimension VSIM1D,[7] is used to simulate the plasma with the MF. The VSIM1D runs on the PC-UNIX operating system and shows the real time portrayal of the phase space and potential, etc., on the X Window system. Full dynamics of electrons and ions are followed under the electrostatic approximations. Physical quantities are allowed to change only in the x direction. Left and right boundaries of the system, $x=0$ and $x=L_x$, are grounded walls. The particles hitting the walls are absorbed there. A MF located at the center of the system (x_{MF}) is represented by the magnetic field pointing in the z axis. The profile of the magnetic field strength is given by

$$B(x)=B_0 \exp[-0.5(x-x_{\mathrm{MF}})^2/a_{\mathrm{MF}}^2], \quad (1)$$

where B_0 is the maximum magnetic field strength and a_{MF} is the characteristic width of the MF. The plasma to the right of

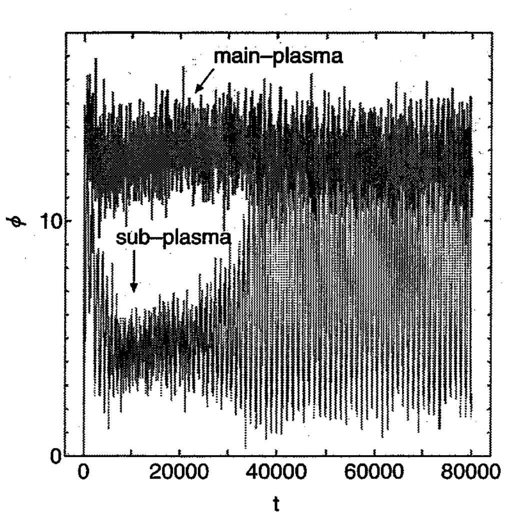

FIG. 1. Time evolutions of potentials at the centers of sub and main plasmas.

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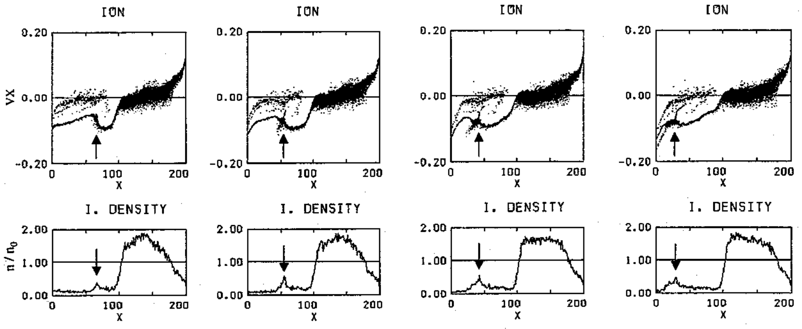

(I) t=40200 (II) t=40400 (III) t=40600 (IV) t=40800

FIG. 2. Photos of phase space plots and density profile of ions.

the MF has high temperature and high density (mainplasma), while the plasma to the left has low temperature and low density (subplasma).

III. SIMULATION RESULTS

The length and time in the simulation are normalized by the grid size Δ and the inverse of the electron plasma angular frequency $\omega_{\mathrm{pe}}^{-1}$. Note that ω_{pe} is defined by the initial electron density ($n_{e0}=n_{i0}=n_0$) in the main plasma. The initial electron Debye length in the main plasma is $\lambda_{\mathrm{de}}=2$. The simulation parameters are as follows. System size: $L_x=200$, $x_{\mathrm{MF}}=100$, $a_{\mathrm{MF}}=12$, $B_0=\omega_{\mathrm{ce}}/\omega_{\mathrm{pe}}=0.5$ (ω_{ce} the cyclotron angular frequency at the center of the MF), mass ratio: $m_i/m_e=1836$, time step size: $\Delta t=0.2$, total number of time steps: $N_t=400\,000$. Temperatures and potentials are normalized by $m_e\Delta^2\omega_{\mathrm{pe}}^2$ and $m_e\Delta^2\omega_{\mathrm{pe}}^2/e$ (e is the electron charge), respectively.

Electrons and ions are injected constantly into the source regions located in the main plasma and subplasmas to equate the particle loss from the respective regions. In the main plasma, one electron and one ion are injected for a time step with given temperatures $T_e=4$ and $T_i=0.4$ in the regions of $120<x<180$. In the subplasma, one electron and one ion are inserted for every 64 time steps with $T_e=1$ and $T_i=0.4$ in the region of $20<x<80$. The velocity distribution of electrons in the respective source region is reset to form a new Maxwell distribution every 75 time steps. Without this artificial "thermalization" 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 walls. The total number of particles in the system varies in time and approaches about 32 000.

The time evolutions of potentials at the centers of the sub and main plasmas are depicted in Fig. 1. At the earlier time ($500<t<30\,000$), the quasisteady gap of the potential is observed. However, the system approaches the periodic state after $t=40\,000$. The potential of the main plasma is almost constant ($\phi\sim 12.5$), while the potential of the subplasma oscillates between $\phi\sim 3$ and $\phi\sim 12.5$. Snap photos of the phase space plot and the density profile of ions are shown in Fig. 2 for different time steps in one period of the potential oscillation. Arrows in the figure designate the position of the ion beam clump. It is clearly shown that a density clump of ion beams entering from the main plasma to the subplasma moves in the negative x direction. The strong change in the phase space around the position of the ion beam clump is observed because of the beam plasma instability. The new clump gets into the subplasma after the old clump gets out of the system; this process continues periodically.

IV. CONCLUSIONS AND DISCUSSION

By executing the one-dimensional electrostatic particle simulation, the ion beam instability is observed in the asymmetric plasma divided by the MF. The main plasma with high temperature and high density faces the subplasma with low temperature and low density across the MF. The potential of the main plasma is almost constant, while the potential of the subplasma oscillates periodically. The maximum value of the potential of the subplasma is close to the potential of the main plasma. When there is a potential gap across the MF, the ion beam clump comes into the subplasma across the MF. The strong ion beam plasma instability is observed as the clump moves into the subplasma. The new clump comes into the subplasma after the old clump is lost at the wall; this periodic process is synchronized with the potential oscillation of the subplasma. Simple theory shows that there is a density threshold for the linear stability of the ion beam plasma instability. This threshold may have some relation to the difference whether the system displays the steady state or the periodic state. Anyway, further study will be needed to explain this nonlinear phenomena.

ACKNOWLEDGMENTS

The authors are grateful to Y. Tauchi (Yamaguchi University) for his assistance in the computer simulation. This work was supported in part by the Grant in Aid for Scientific Research from the Japanese Ministry of Education, Science, Sports and Culture.

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