J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 600–604

Complex Behavior in Asymmetric Plasma Divided by a Magnetic Filter

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(Received: 5 December 2000 / Accepted: 23 August 2001)

Abstract

A bifurcation from the static state to the dynamic state in the asymmetric plasma divided by the magnetic filter (MF) is studied by an one-dimensional particle simulation. A low temperature and low density subplasma is in contact with a high temperature and high density main plasma at the MF. In the dynamic state, autonomous oscillation of the electrostatic potential in the subplasma is observed along with the transit of the shock wave structure [K. Ohi, H. Naitou, Y. Tauchi, and O. Fukumasa, Phys. Plasmas **8**, 23 (2001)]. By changing the control parameter of B_0 very slowly, the existence of the hysteresis in the relation of $\Delta\phi_S$ versus B_0 is verified. Here B_0 is the strength of the magnetic field at the center of the MF and $\Delta\phi_S$ is twice the amplitude of the self-sustained potential oscillation in the subplasma.

Keywords:

self-sustained oscillation, laminar shock wave, limit cycle, Hopf bifurcation, hysteresis

1. Introduction

The magnetic filter (MF) is a localized magnetic field, which can reflect charged particles selectively depending on the mass, the charge, and the energy. The MF is usually located in the vacuum chamber and separates a low density and low temperature plasma (subplasma) from a high density and high temperature plasma (main plasma). In the negative ion source, the MF is used to isolate energetic electrons in the main plasma from the subplasma with low electron temperature [1].

The asymmetric plasma divided by the MF has been investigated [2-4] by the visualized particle simulation code in one dimension, VSIM1D [5]. Complex nonlinear behavior manifested in the simulation. VSIM1D runs on the PC-UNIX operating system and shows the real time portrayal of the phase space plots and the potential profile etc. on the X-Window system. The strength of the MF is chosen to influence only electron dynamics. The effect of the MF on ions is negligible because of the large ion mass. We have observed two bifurcated states. One is the static equilibrium state in which space potentials of the subplasma and the main plasma are $\phi_S \sim 3T_{Se}$ and $\phi_M \sim 3T_{Me}$, respectively. Here, T_{Se} and T_{Me} are electron temperatures in the respective plasmas ($T_{Se} < T_{Me}$). The other is the dynamic state in which the space potential of the subplasma oscillates between $\sim 3T_{Se}$ and $\sim 3T_{Me}$, whereas the space potential of the main plasma is ~

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$3T_{Me}$. The autonomous oscillation of the potential in the subplasma is accompanied by the transit of the laminar shock waves in the subplasma, which are excited by the velocity modulation of energetic ions accelerated by the time varying potential difference at the MF, $\Delta\phi = \phi_M - \phi_S$. The period of the autonomous oscillation is determined by the transit time of the shock wave structure.

One of control parameters of the bifurcated states is the ratio of generation of electrons and ions in the subplasma to that in the main plasma. The production of electrons and ions are needed to keep the density ratio between the main plasma and the subplasma as well as to compensate the particle loss from the respective plasma. The other control parameter is the strength of the MF. Both of the control parameters can govern the asymmetry of the plasma. The transition from the static state to the dynamic state can be understood as the Hopf bifurcation from the stable equilibrium to the limit cycle (periodic attractor). The transition was found to be discontinuous at the boundary (critical point) [4]. So the self-sustained oscillation has a finite radius of the limit cycle even at the critical point. Therefore, if the control parameter is changed slowly in time, hysteresis can be expected between the control parameter and the amplitude of the potential oscillation in the subplasma. This paper extends the simulation of Ref. [4] and concentrates on the verification of the existence of the hysteresis.

The outline of this paper is as follows. The basic simulation model is described in Sec. 2. Simulation results are presented in Sec. 3. Conclusions and a discussion are given in Sec. 4.

2. Simulation Model

Details of the one-dimensional particle-in-cell simulation model with the MF are described in Ref. [4]. We use physical quantities in normalized units. The length is normalized by the grid size Δ. The time is normalized by the inverse of the electron plasma angular frequency ω_{pe}^{-1}, where ω_{pe} is defined by the initial average electron density in the main plasma. Temperatures and potentials are normalized by $m_e\Delta^2\omega_{pe}^2$ and $m_e\Delta^2\omega_{pe}^2/e$ with e and m_e being electron charge and mass, respectively. The normalized magnetic field strength is defined by ω_{ce}/ω_{pe} where ω_{ce} is the electron cyclotron angular frequency. There is a MF at the center of the system ($x = x_{MF} = 200$) and the direction of the magnetic field is in the z-axis. The spatial profile of the magnetic field strength is given by

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

where $B_0 = 0.2$–1.2 and $a_{MF} = 12$. Full dynamics of electrons and ions are followed under the electrostatic approximation. Left and right edges of the system, $x = 0$ and $x = L_x = 400$, are grounded walls. Particles hitting the walls are absorbed there. The main plasma with $T_{Me} = 4$ and $T_{Mi} = 0.4$ exists in $x_{MF} \le x \le L_x$, whereas the subplasma with $T_{Se} = 1$ and $T_{Si} = 0.4$ exists in $0 \le x \le x_{MF}$. Here T_{Mi} and T_{Si} are ion temperatures in the respective plasmas. Hydrogen plasma is assumed. Mass ratio is $m_i/m_e = 1836$. Time step size is $\Delta t = 0.2$. One electron and one ion are injected every one time step in the source region of the main plasma ($220 < x < 380$), while one electron and one ion are inserted every $N_{in} = 64$ time steps in the source region of the subplasma ($20 < x < 180$). Velocity distributions of electrons in the respective source regions are reconstructed to form new Maxwellian distributions every 150 time steps. Without this 'thermalization' process, the electron velocity distributions would be cooled eventually because only low energy electrons are confined by the sheath potential adjacent to the walls.

3. Simulation Results

The physical picture of the dynamic state is briefly summarized here for the case of $B_0 = 0.5$. Figure 1 shows the temporal evolution of (a) the potential profile and (b) the ion density profile for the typical one period of the self-sustained oscillation. Here potentials are time averaged over $\tau = 20$ to eliminate the fluctuating noise concerning electron plasma oscillations. The snap shots of phase space plots of ions, ion density profiles, and potential profiles for the same period can be found in Fig. 8 in Ref. [4]. When the potential difference between the main plasma and the subplasma $\Delta\phi$ is large enough, the high energy and high density ion beam invades the subplasma across the MF. The faster ions overtake the slower ions and excite the laminar shock wave. The shock wave structure includes faster and slower shock fronts. The faster shock front reflects ions in front of the shock wave structure, while the slower shock front throws back ions behind the shock wave structure (see Fig. 8 in Ref. [4]). Between the shock fronts the ion density is higher than that of the ambient plasma. The distance of the two shock fronts increases in time. The slower shock front is clearly observed in Fig. 1 as the peaks of the potential and ion density profiles, while the faster shock front is not so clear. The shock wave

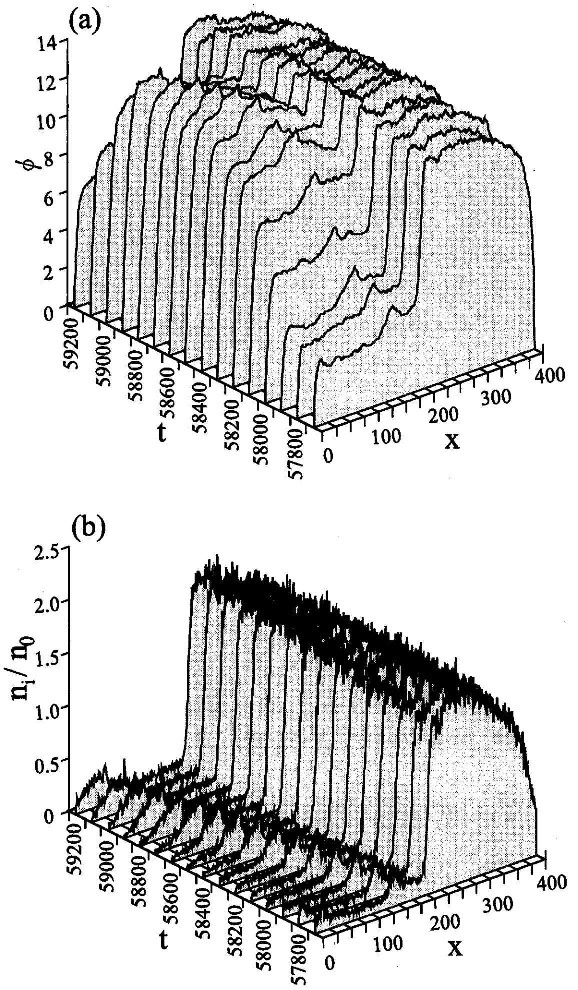

Fig. 1 Temporal evolution of (a) the potential profile and (b) the ion density profile. Typical one period of the self-sustained oscillation synchronized with the transit of the laminar shock wave is shown.

structure shown here is very close to the one experimentally observed by Ikezi et al. [6]. Due to the invasion of the higher density ions, the potential of the subplasma increases to the level of the potential of the main plasma. As the potential gap decreases, the ion beam flux from the main plasma reduces. At this phase, the electrons in the subplasma cannot reach the left wall because of the large sheath potential; the ion sheath without electrons is formed. When the shock wave structure is very close to the left wall, electrons in front of the shock wave are pushed into the ion sheath adjacent to the wall; the ion sheath structure is changed drastically and the space potential of the subplasma reduces to the level of ~ $3T_{Se}$. Owing to the re-built large potential gap, the higher energy and higher density ion beam gets into the subplasma again across the MF. This process is repeated periodically and the limit cycle is established. The period of the limit cycle is determined by the transit time of the shock wave structure.

The parameter range in which the asymmetric plasma with the MF behaves statically or dynamically is identified in Ref. [4]. The control parameters are $1/N_{in}$ and B_0. The averaged electron density of the source region in the subplasma is displayed as a function of $1/N_{in}$ and B_0 (Figs. 13 and 14 in Ref. [4]). It is found that the transition between two bifurcated states is not continuous. Even at the critical point, the dynamic state has the finite radius of the limit cycle. This is because that there is a positive feedback in the subplasma. The process converging to the stable attractor is explained as follows. Due to the thermal noise, the potential difference at the MF is modulated slightly. The weak shock wave produced by the velocity modulated ion beam gets into the left wall. If the reduction of the space potential caused by the approaching shock wave is larger than that of the former potential modulation, the stronger shock wave is formed. This process repeats until the maximum potential of the subplasma goes up to ϕ_M. It is expected that threshold exists for this positive feedback. In the static state, there is no positive feedback because electrons in the subplasma mitigate the effect of the approaching shock. The threshold, which may be the ratio of the ion beam flux from the main plasma to the plasma density in the subplasma, determines the critical point corresponding to the transition of the two bifurcated states. Twice the amplitude of the oscillating part of the potential in the subplasma, $\Delta\phi_S = \phi_{S,max} - \phi_{S,min}$, is depicted as a function of B_0 in Fig. 2. Here $\phi_{S,max}$ and $\phi_{S,min}$ are measured at the center of the subplasma. For $0.38 \le B_0 \le 0.62$, the system behaves dynamically. The static state is observed for $B_0 \le 0.37$ and $B_0 \ge 0.63$. Note that the ion flux across the MF is a decreasing function of B_0. This is because the electron density (and the ion density due to quasineutrality) at the MF reduces as B_0 increases. For the lower value of B_0, some fraction of electrons in the main plasma gets into the subplasma, increasing plasma density in the subplasma.

There is a threshold in order that the initial equilibrium state converges to the dynamic state for the fixed value of the control parameter. However, it is possible that the static state may be destabilized by changing the control parameter slowly from the dynamic regime to the static regime. To investigate this

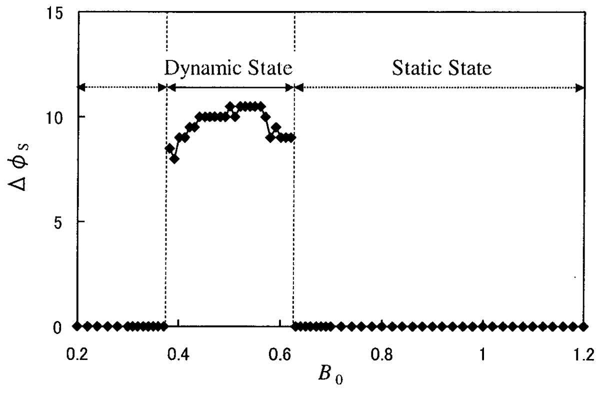

Fig. 2 $\Delta\phi_S$ vs B_0. Here $\Delta\phi_S$ is twice the amplitude of the self-sustained potential oscillation in the subplasma.

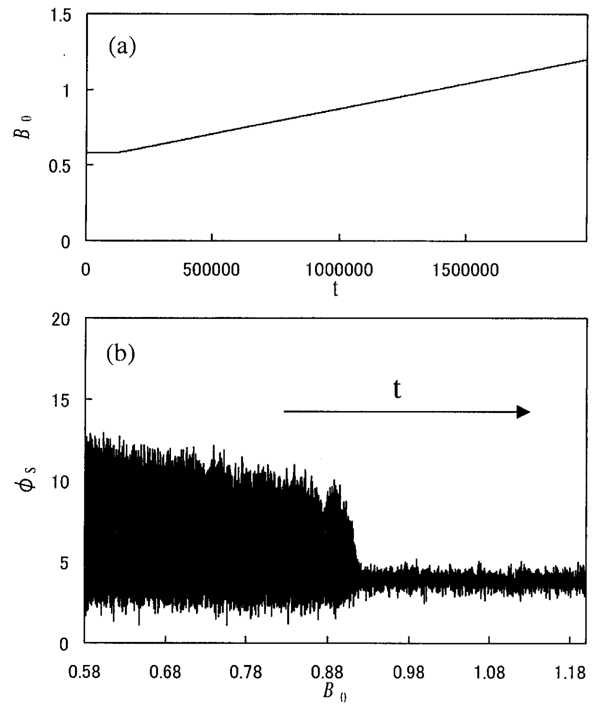

Fig. 3 Time evolution of (a) the control parameter of B_0 and (b) the potential at the center of the subplasma ϕ_S. Time dependence is mapped into the B_0 dependence in (b); $\phi_S[t(B_0)]$. The increasing phase of B_0 is shown.

possibility, the control parameter of B_0 is increased very slowly as shown in Fig. 3(a). Fig. 3(b) displays ϕ_S versus B_0. Time evolution of ϕ_S is mapped into the B_0 dependence. For $B_0 < 0.89$, $\phi_{S,min}$ is almost constant and $\phi_{S,max}$ reduces slightly as B_0 increases. For $0.89 < B_0 < 0.93$, $\Delta\phi_S$ drastically reduces. For $B_0 > 0.93$, no autonomous oscillation is observed. The static state for the fixed value of B_0 is destabilized up to $B_0 \sim 0.91$. The reversed case in which B_0 is reduced very slowly from the static regime to the dynamic regime is shown in Fig. 4. For this case, the critical B_0 is the same as that for the fixed value of B_0.

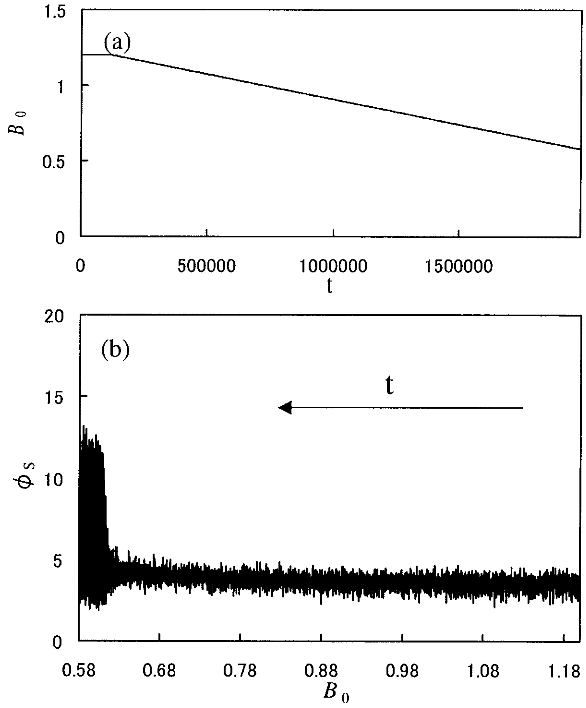

Fig. 4 Time evolution of (a) the control parameter of B_0 and (b) the potential at the center of the subplasma ϕ_S. Time dependence is mapped into the B_0 dependence in (b); $\phi_S[t(B_0)]$. The decreasing phase of B_0 is shown.

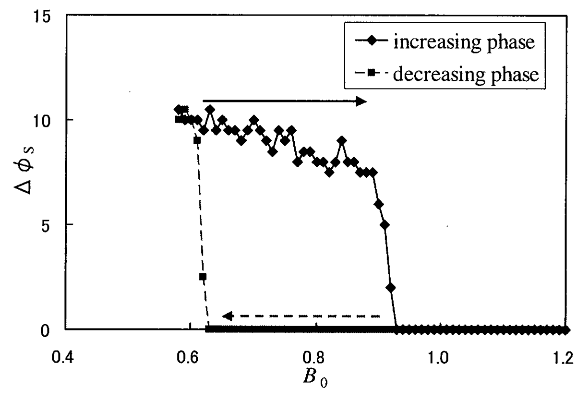

Fig. 5 Hysteresis observed in the relation of $\Delta\phi_S$ vs B_0.

The relation between $\Delta\phi_S$ and B_0 when B_0 is changed very slowly is summarized in Fig. 5. The hysteresis of $\Delta\phi_S$ versus B_0 is clearly observed.

4. Conclusions and Discussion

The asymmetric plasma divided by the magnetic filter (MF) is numerically simulated by the one-dimensional particle-in-cell code VSIM1D [5]. The strength of the MF is chosen to influence only electron dynamics; ions move freely across the MF. The main plasma with the high temperature and the high density is in contact with the subplasma with the low temperature and the low density at the MF placed at the center of the system. Depending on the asymmetry, the system behaves statically or dynamically. In the dynamic state, the electrostatic potential in the subplasma shows the self-sustained oscillation accompanied by the transit of the shock wave structure. The shock waves are excited in the subplasma because the ion flux experiences velocity modulation owing to the time varying potential gap between two plasmas. The Hopf bifurcation is observed at the critical point between the static regime and the dynamic regime. The transition between two bifurcated states is discontinuous at the boundary. As the control parameter of B_0 is changed very slowly in time, this boundary is varied; the existence of the hysteresis in the relation of $\Delta\phi_S$ versus B_0 is verified.

Acknowledgments

The authors would like to express their thanks to Professor T. Kamimura, National Institute for Fusion Science, Professor Y. Kawai, Kyushu University, and Professor K. Saeki, Shizuoka University, Professor Y. Ohsawa, Nagoya University, Professor S. Nishifuji, Yamaguchi University for stimulating discussions.

References

[1] O. Fukumasa, H. Naitou, S. Sakiyama, J. Appl. Phys. **74**, 848 (1993).
[2] H. Naitou, K. Ohi, O. Fukumasa, Rev. Sci. Instrum. **71**, 875 (2000).
[3] H. Naitou, K. Ohi, Y. Tauchi, O. Fukumasa, J. Plasma Fusion Res. **76**, 3 (2000).
[4] K. Ohi, H. Naitou, Y. Tauchi, O. Fukumasa, Physics of Plasmas **8**, 23 (2001).
[5] K. Koga, H. Naitou, Y. Kawai, J. Phys. Soc. Japan **68**, 1578 (1999).
[6] H. Ikezi, T. Kamimura, M. Kako and K.E. Lonngren, Phys. Fluids **16**, 2167 (1973).