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# Electrostatic Shocks Excited by Velocity Modulation of an Ion Beam in a Plasma

Takuma Gohda,[1] Seiji Ishiguro,[2] Satoru Iizuka,[1] and Noriyoshi Sato[1]
[1]*Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan*
[2]*National Institute for Fusion Science, Toki 509-5292, Japan*
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Nonlinear evolutions of electrostatic shocks excited by a velocity-modulated ion beam along a magnetized plasma column are investigated by computer simulation for a $Q$-machine experiment. In the case of a beam velocity modulation, the perturbations grow spatially with subsequent saturation due to an ion bunching of the beam. With an increase in modulation ratio an electrostatic shock is formed, accompanied with a steepening of the propagating front. In the case of a beam density-modulation, however, the initial density jump decays simply. The velocity modulation method is quite effective for an excitation of electrostatic shocks in the $Q$-machine plasma with finite Landau damping. The simulation results using velocity modulation are consistent with the experimental results.

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The nonlinear behaviors of ion beams injected into plasmas are of current interest, particularly in connection with plasma instabilities and plasma heatings. There have been various experiments concerned with wave propagation along the ion beams in plasmas [1,2]. Spatial evolution of density perturbations produced by velocity modulation in an ion beam-plasma system has been demonstrated by Sato *et al.* [3], using a double-ended $Q$-machine plasma. In case of small amplitude modulation, the phenomenon observed was well explained by a linear wave theory with fast and slow beam modes. In discharge plasmas where electron temperature is much larger than the ion temperature as in double-plasma (DP) devices [4], ion acoustic shocks were excited by modulating density of beam ions injected from driver to target plasmas [5]. In order to excite nonlinear waves like shocks in the $Q$-machine plasma with finite Landau damping, several attempts were examined to reduce the effects of Landau damping by increasing the temperature ratio between electrons and ions [6–12].

In this Letter, we investigate the characteristics of nonlinear evolution of density perturbations excited by a velocity-modulated ion beam by employing a particle simulation to understand the phenomena observed in a $Q$-machine plasma [13]. For a comparison we also employ a density-modulation simulation for the nonlinear wave excitation under the same condition as in the $Q$-machine plasma. The simulation results are compared with the experimental results using the velocity modulation in the $Q$-machine plasma [13].

In order to understand the phenomena in the experiments, we have carried out particle simulations. In our simulation the plasma system is divided into two parts as in a double-ended $Q$-machine plasma [13]. One is the positive ion beam generator regarded as a driver plasma, and the other is the beam propagation region regarded as a target plasma. The potential of the driver plasma can be controlled and is varied to modulate the ion beam velocity from $v_b$ to $v_b + v_m$ within a time $\tau$. Therefore, the modulation ratio of beam velocity is given by $v_m/v_b$. In this simulation $v_m$ is normalized by electron thermal velocity $v_{T_e}$, i.e., $v_m/v_{T_e}$ which also has a relation with ion thermal velocity through $v_m/v_{T_p} = [(T_e/T_i) \times (m_i/m_e)]^{1/2}(v_m/v_{T_e})$. Here, the mass ratio of ions to electrons is $m_i/m_e = 400$. The target plasma potential is fixed at ground potential. The length of the boundary region between diver and target plasmas is $200\lambda_{\mathrm{D}}$. Here, $\lambda_{\mathrm{D}}$ is the Debye length. The propagation of perturbation is observed in a moving frame with the beam velocity of $v_b$. Therefore, the beam ions in the target plasma are plotted like stationary ions in the coordinates of $v$-$x$ phase space. Since the electron thermal velocity is much faster than the ion beam velocity, the electrons are regarded as stationary electrons. The normalized space and time coordinates are given by $x/\lambda_{\mathrm{D}}$ and $\omega_{pe}t$, respectively, and the origin of the space coordinate is the edge of the target plasma.

The temperature ratio $T_e/T_i$ of the $Q$-machine plasma is considered to be larger than unity because the ions ionized by contact surface ionization on the hot plate of the $Q$ machine are accelerated by a sheath potential formed in front of the hot plate. The initial velocity difference $\Delta v$ of the ions is reduced by this acceleration. In a $Q$-machine plasma the temperature ratio of electrons and ions is $T_e/T_i \geq 1$, depending on the electron-rich sheath condition in front of the hot plate. In order to evaluate the temperature ratio, we have done several simulations with different temperature ratios to compare with the experiment. The results show that the most suitable ratio is $T_e/T_i \approx 3$ under our experimental condition. Henceforth, we adopt this ratio for performing the simulation.

We also try to excite the density jump and investigate its evolution by using a density-modulation method. In the simulation, the ion density in the driver plasma is set 1.5 times that of the target plasma. Therefore, the density jump appears initially in the boundary region. Here, $T_e/T_i = 3$ as in the case of the velocity modulation. In this case the beam ions in the driver plasma start to diffuse toward the target plasma with almost ion thermal velocity. Therefore, ion density compression toward the downstream region is weak compared to the velocity modulation. Figure 1 shows a comparison of the evolutions of ion beam density perturbation in the density modulation [Fig. 1(a)] and velocity modulation [Fig. 1(b)]. In Fig. 1(a), initial density jump between the driver and the target plasmas is gradually decaying during the propagation, and no clear stable structure with a constant slope is observed. On the other hand, in the velocity modulation, as shown in Fig. 1(b), we observe a formation of density jump like a shock propagating with almost constant front slope and speed. Therefore, the density-modulation method is not efficient for the shock formation in the plasma with finite Landau damping as in the $Q$-machine plasma.

Typical simulation results using the velocity modulation are shown in Fig. 2 with the velocity modulation ratio as a parameter. It is found that the velocity modulation ratio is an important factor for the shock excitation. When $v_m/v_{T_e} = 0.02$, no remarkable growth and formation of the density jump are observed as shown in Fig. 2(a). The initial growth of the density perturbation driven by the ion bunching due to the velocity modulation is simply damped. When $v_m/v_{T_e} = 0.1$, however, the density perturbation grows, and the front of the perturbation starts to move with almost constant velocity, keeping the front shape almost constant as shown in Fig. 2(b). In case of $v_m/v_{T_e} = 0.2$, a clearer and sharper density jump is formed as shown in Fig. 2(c). Therefore, the modulation ratio $v_m/v_{T_e} > 0.1$ is necessary for an evolution of a shocklike structure on the moving front of the density perturbation. Figure 3 shows the evolutions of potential and variations of the phase spaces of beam ions for the case of $v_m/v_{T_e} = 0.1$ and $T_e/T_i = 3$. As shown in Fig. 3(a), the potential grows and finally saturates in a way similar to the ion beam density shown in Fig. 2(b). The maximum of the potential jump is roughly given by $\phi_0 \sim (1/2)m_i(v_m/2)^2/e$. The velocity-modulated beam ions are first accumulated in a narrower region as shown in Fig. 3(b). Then, for $\omega_{pe}t > 1200$ some parts of ions moving ahead of the jump are reflected at the front of the jump due to the evolution of positive potential growth as usually seen in the shock structures. We also observe backward reflection of incoming beam ions by the growing positive potential hump. After the saturation the shocks start to propagate in both forward and backward directions along the beam in the moving frame with $v_b + v_m/2$. Therefore, the ion bunching is very important to create a shocklike structure in the presence of the strong dissipation like Landau damping as in the $Q$-machine plasma. When the velocity modulation ratio $v_m/v_{T_e}$ is reduced, the growth of perturbation is limited and suppressed by the heavy Landau damping.

The simulation results are compared with the experiment carried out in a double-ended $Q$ machine with a vacuum chamber of 20.8 cm in diameter and 167 cm long [13,14]. The schematic of the experimental setup is shown in the top part of Fig. 4. Potassium ion plasmas produced by contact ionization at 52-mm-diameter hot tungsten plates (HP) of 2300 K, placed at both ends of the chamber

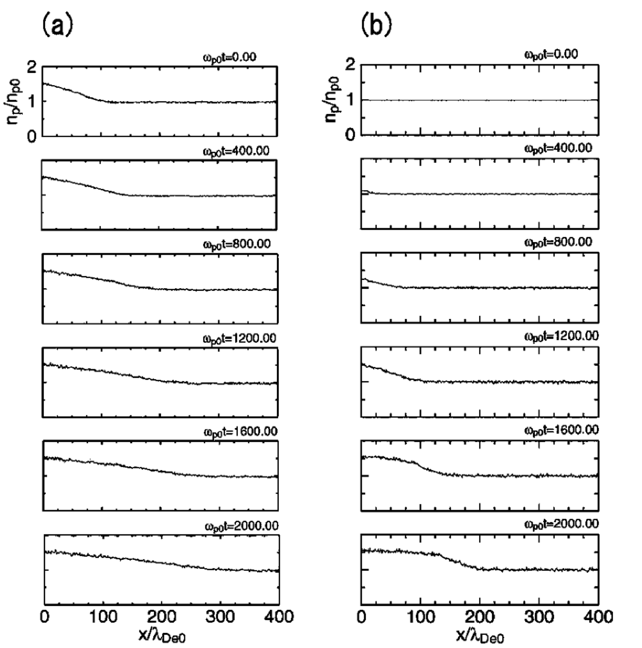


FIG. 1. Evolutions of ion density perturbation excited by (a) density modulation and (b) velocity modulation for temperature ratio $T_e/T_i = 3$.

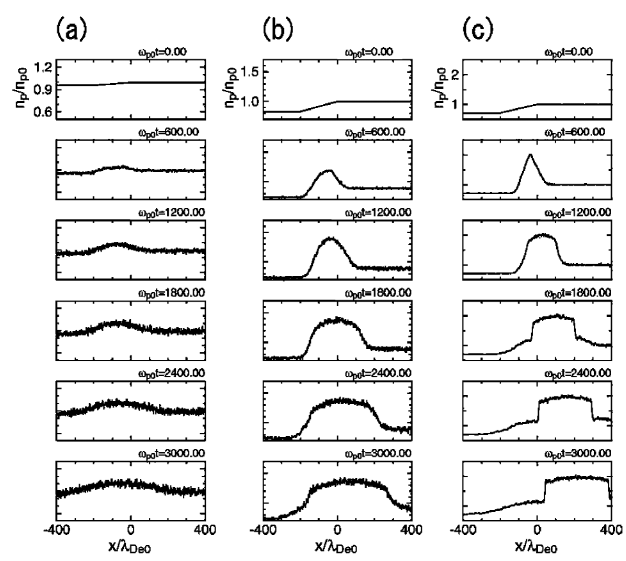


FIG. 2. Evolutions of ion density perturbations excited at different velocity modulation ratios: (a) $v_m/v_{T_e} = 0.02$; (b) $v_m/v_{T_e} = 0.1$; and (c) $v_m/v_{T_e} = 0.2$, for temperature ratio $Te/Ti = 3$.

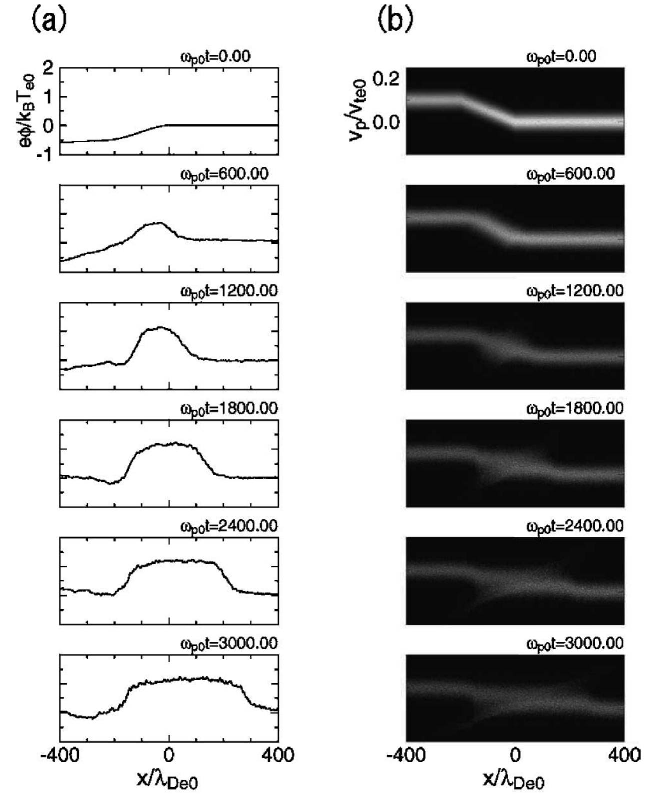


FIG. 3. (a) Evolutions of potential and (b) variations of beam ion phase space when $T_e/T_i = 3$ and $\nu_m/\nu_{T_e} = 0.1$, corresponding to the case of Fig. 2(b).

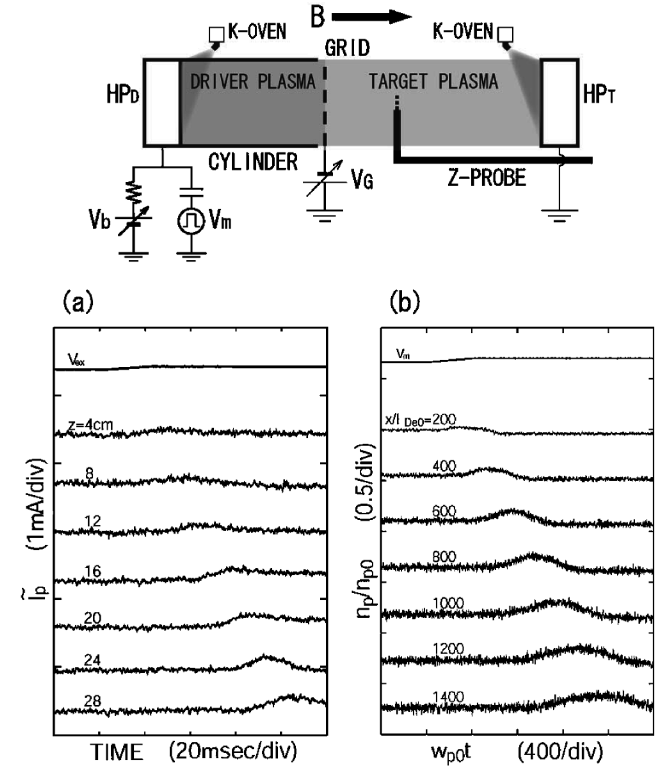


FIG. 4. Evolutions of (a) ion-beam current perturbations in the experiment for $\nu_m = 0.5$ V and (b) ion beam density perturbations in velocity modulation simulation for $\nu_m/\nu_{T_e} = 0.02$ and $T_e/T_i = 3$. Top figure shows experimental setup.

under an electron-rich condition, are confined by an axial magnetic field of 2 kG. The machine is operated as a DP device. One of them, the "driver plasma," is surrounded by a small metal cylinder connected electrically to the hot plate $HP_D$. The other hot plate $HP_T$ in the "target plasma" is grounded. Electrons of the two plasmas are separated from each other by a negatively biased grid of 100 lines/in. By applying positive bias $V_b$ to $HP_D$, ions in the driver plasma flow into the target plasma as a beam. The ramp modulation bias $V_m$ is $-5$–15 V and the rise time $\tau$ is 5–20 $\mu$s. When $V_m > 0$, compressional pulses with positive density slope are excited. Plasma densities of the driver and target plasmas are $5 \times 10^8$–$1 \times 10^9$ cm$^{-3}$ and the electron temperatures $T_e$ are about 0.2 eV which is comparable to positive ion temperature $T_p$. Under our condition, collision mean free paths of charged particles are longer than the plasma column length. The evolutions of perturbations are measured by axially movable mesh probe (6-mm diameter, 200 lines/in.) which is biased negatively to detect ion current.

Figure 4(a) shows the observed ion current variations in the experiment when the beam velocity is modulated by applying ramp voltage $V_{\rm ex} = V_b + V_m$ to the $HP_D$. Here, $\tau$ is 20 $\mu$s, initial beam energy $V_b$ is 4 V, and $V_m$ is 0.5 V. When $V_m = 0.5$ V and $V_b = 4$ V, the bunching position is $L \sim 23$ cm, which is about the middle of the experimental region between the grid and $HP_T$. Here, the bunching position is defined by $L = \nu_1\nu_2\tau/(\nu_2 - \nu_1)$, where $\nu_1$ and $\nu_2$ are the velocities of ions before and after the modulation, respectively. The perturbations excited grow gradually during propagating along the beam. Since the modulation amplitude of beam energy is small, the evolution of perturbation is interpreted by the linear wave theory as in Ref. [5]. Figure 4(b) shows the simulation results of ion beam density perturbation due to the velocity modulation. Although the perturbation grows initially, its front slope decays in time during the propagation as in the experiment. On the other hand, when the modulation amplitude of the beam energy is $V_m = 5$ V in the experiment, a large amplitude density pulse is generated around a bunching position of $L \sim 12$ cm, accompanied by a steepening of the front slope as shown in Fig. 5(a). The temporal evolution of the density perturbation of beam ions obtained from the simulation using the velocity modulation is also plotted in Fig. 5(b), corresponding to the case of Fig. 5(a). A shocklike structure with positive density slope (positive shock) is formed and propagates with an almost constant velocity. We observe similar evolution of perturbation as in the experiment.

In conclusion, we have investigated the evolution of electrostatic shocks by using particle simulations. We find

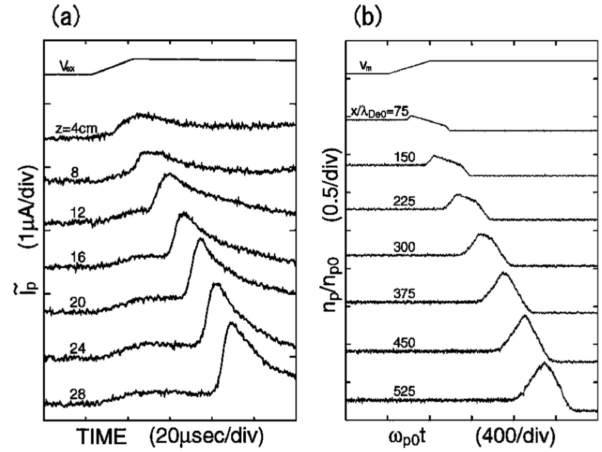


FIG. 5. Evolutions of (a) ion-beam current perturbations in the experiment for $v_m = 5$ V and (b) ion beam density perturbations in velocity modulation simulation for $v_m/v_{T_e} = 0.1$ and $T_e/T_i = 3$.

that the excitation method using velocity modulation is quite effective compared with the density modulation for the plasmas with heavy Landau damping as in the $Q$-machine plasma. This is because of the ion bunching along the plasma column. With an increase in the velocity modulation, density perturbation grows markedly to drive electrostatic shocks propagating along the plasma column. The shocks observed in the experiments are generated by the nonlinear collective effect of the bunching ions provided by the velocity modulation of ion beams.

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