Excitation of Ion Acoustic Waves in Plasmas with Electron Emission from Walls

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Abstract: Various plasma propulsion devices exhibit strong electron emission from walls, either as a result of secondary processes or due to thermionic emission. To understand the details of electron kinetics in plasmas with strong emission, we have performed particle simulations of such plasmas using the EDIPIC code. We show that excitation of ion-acoustic waves is a ubiquitous phenomenon in many different plasma configurations with strong electron emission from bounding surfaces. Ion-acoustic waves were observed to be generated in the vicinity of strongly emitting walls.

Nomenclature

B	=	magnetic field
E	=	electric field
ω	=	frequency of oscillations
γ	=	electron-electron emission yield
n	=	electron density
v	=	wave propagation speed

I. Introduction

Plasmas in cross-field discharge devices exhibit complex nonlinear behavior resulting in a variety of turbulent fluctuations and structures that critically affect operation and performance of these devices. Recent experiments with Hall thrusters and Penning discharges demonstrated that low-frequency (1-10's kHz) spoke oscillations are responsible for anomalous electron cross-field transport that limits the maximum achievable electric field and

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increases power losses in these devices. Our recent measurements in cylindrical Hall thruster[1] and Penning discharge[2] revealed a strong dependence of spoke oscillations on the control parameters of the discharge, including the type of gas, the gas pressure, the magnetic field, and the electron injection from the cathode. In this paper we focus on the effects of electron injection or emission from bounding surfaces upon possible excitation of ion-acoustic waves.

II. Observation of Ion Acoustic Waves in Particle-in-Cell Simulations

Recently, we have performed extensive studies of Hall thruster plasma using the EDIPIC particle-in-cell code. For example, in Ref.[3] we investigated the effect of asymmetric secondary emission in bounded low-collisional E x B plasma on the sheath and plasma properties. We also observed a new regime in which all of the plasma electrons escape and are substituted by secondary electrons[4]. In this regime, there is practically no electric field in the plasma or in the sheath, so that the ions are not drawn towards the wall, the plasma electrons are not confined and the plasma potential is negative. The sheath in those simulations was observed to exist in three different regimes:

(1) regular sheath with a negative wall charge, and a positive space charge in the sheath, when the emission isn't strong;
(2) space-charge-limited sheath with a positive wall charge, and both positive and negative space charge regions present in the sheath, when the emission is stronger;
(3) "inverse" sheath with a positive wall charge, and a negative space charge in the sheath, when the emission is very strong.

The first regime occurs for most cases if the electric field and the electron heating do not exceed critical values. The critical values are determined by the condition that the secondary electrons emitted from the wall can acquire enough energy to emit more than one secondary electron when impacting the opposite wall; that is, the averaged secondary electron emission (SEE) coefficient for these "beam" electrons satisfies

$$\gamma_b > 1 . \tag{1}$$

In the latter case, a positive charge begins to accumulate at a floating wall and to pull back fraction of emitted electrons, to equate the incident and outgoing electron fluxes. Thus a positive space charge will always form if the criterion in Eq.(1) is satisfied. The sheath can be either space-charge-limited, or an inverse kind, depending on the initial state and temporal evolution of the system. The transition between regular space-charge-limited sheath and inverse sheath was observed in our simulations and, e.g., in Ref.[5]. If the ions are accelerated to sonic velocity before a transition to the regime $\gamma_b > 1$ takes place, the space-charge-limited sheath occurs initially, and then transforms into an inverse sheath. In the parameter range where the emission is strong enough to produce SEE beams with the density comparable to that of the plasma we observe excitation of ion acoustic waves.

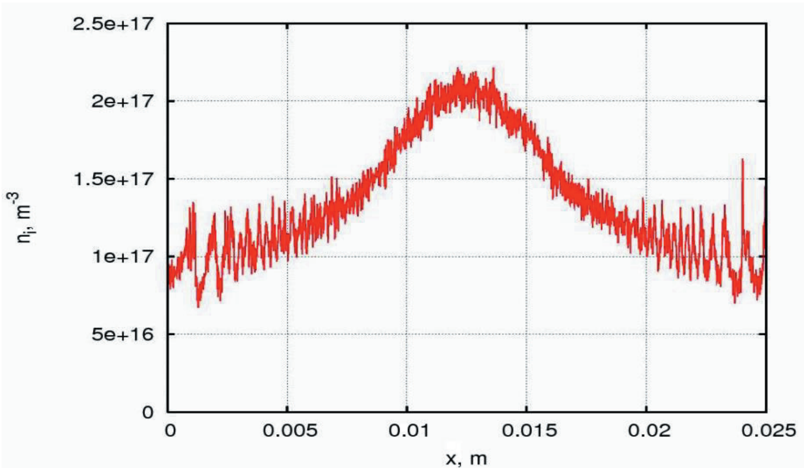

Figure 1. Density profile in the simulated Hall thruster channel. The plasma parameters are given in the text.

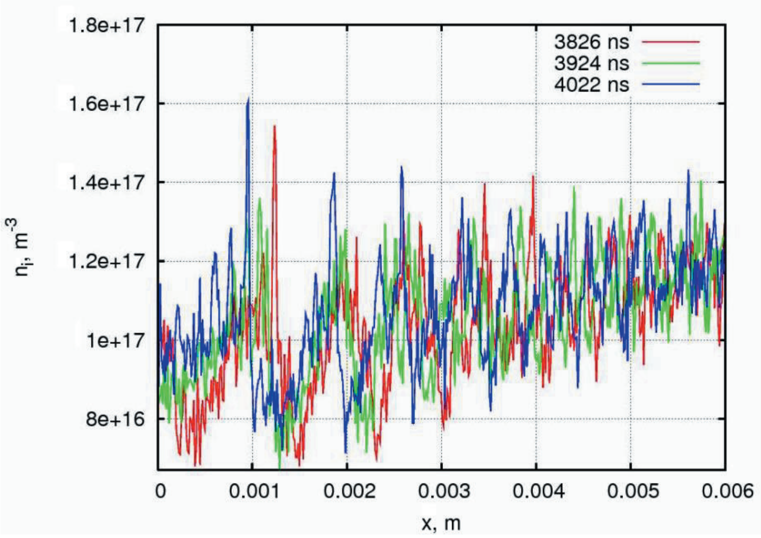

Figure 2. Zoom-in of the ion density profile next to the left boundary at three different moments 3826 ns, 3924 ns, 4022 ns after evolution of a uniform initial profile.

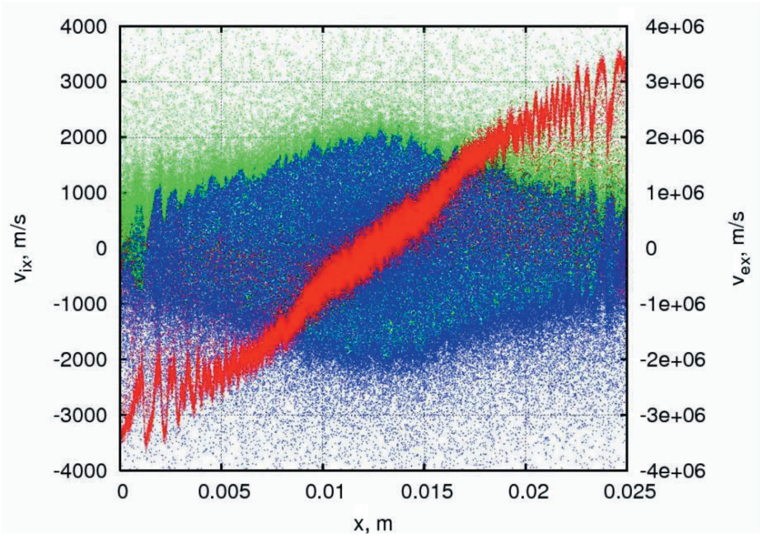

Figure 3. Phase maps for the ions (mapped in red, scale on left) and electrons (scale on right). Secondary electrons emitted from the left are mapped in green and those from the right are mapped in blue. Time t=3924 ns.

Observed excitation of strong ion-acoustic waves is shown in Figs. 1-3. The simulation parameters are as follows: axial electric field E=200 V/cm, magnetic field B=100 G, channel width 2.5 cm, Xe gas with density 10^{12} cm^{-3}, effective turbulent collision frequency $1.12\times10^{7}s^{-1}$; the initial density profile is uniform at $1.1\times10^{11}cm^{-3}$. A detailed description of the simulations can be found in Ref.[6]. Fig. 1 clearly shows the presence of ion-acoustic waves in the ion density profile. The signature of ion-acoustic waves can also be clearly seen in Figs. 2 and 3. In Fig. 2, where a zoom-in of the density profile is shown near the left boundary, one can see that the density perturbation moves about 0.3 mm in about 200 ns; this gives the propagation velocity of perturbation

v = 0.3 mm/200 ns = 1.5×10^{5} cm/s.

Fig. 3 shows the phase-space maps of electrons and ions. There are two ion populations: one of the ions accelerated to supersonic velocities, and the second slow “diffuse” population, made up of the ions generated closer to the walls. The ion-sound velocity for the typical electron temperature in x-direction of 5 eV is 2×10^{5} cm/s, whereas the fast ion velocity can be as high as 3.5×10^{5} cm/s, see Fig.3. If the wave propagates with the sound velocity relative to the fast supersonic ions, its velocity in the lab frame is $(3.5 - 2)\times10^{5}$ cm/s $=1.5\times10^{5}$ cm/s. This is in agreement with what is observed in Fig. 2.

Figs. 4 and 5 show the electron x-velocity distribution functions (EVDF) in the center and in the region close to the left boundary. The intense beams generated by SEE make the EVDF non-monotonic. As studied in Ref.[6], such EVDF may produce a two-stream electron instability and drive electron plasma waves near the center of the plasma. Modulation instability can transfer energy from the electron plasma waves to ion-acoustic waves.

The role of the modulation instability is clearly seen in a simulation of a dc plasma where the dc voltage is 800 V and the flux of electron emission from the cathode is 5×10^{20} $m^{-2}s^{-1}$. The initial plasma density was uniform and equal to 10^{16} m^{-3}. The ion mass selected was 10 amu. The cathode emission was turned on with a delay of 10 μs when the density acquired a smooth profile decaying towards the walls; the time counter was set to zero when the emission started. The electrons accelerated by the dc voltage near the cathode became an electron beam piercing the plasma. The beam excites high frequency eigen mode of the system as shown in the top two panels in Figure 6. In the areas of intense highly-localized high-frequency electric field, the ponderomotive force pushes electrons sideward and

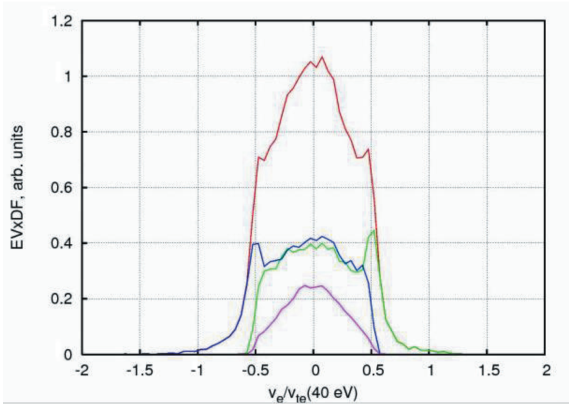

Figure 4. Electron velocity distribution at the center: red-total, magenta-bulk (newly created), blue - SEE from the right wall, and green – SEE from the left wall. Time t=3924 ns; 1.0 cm<x<1.25 cm.

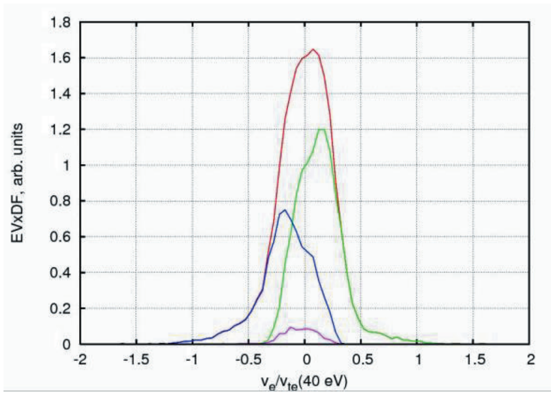

Figure 5. Same as in Fig.4 but for 0<x<0.25 cm.

creates ambipolar electric field which moves ions and forms density cavities (see Figure 6 near 6, 8, and 20 mm). The cavities turn into density pulses propagating with the velocity close to the ion acoustic speed (see Figure 7).

Generation of ion-acoustic waves was also observed in simulations of another bounded plasma configuration with a cold electron beam, namely a Penning discharge used to study spoke phenomena in E×B devices[2]. Lastly, we note that a finite plasma size by itself can strongly affect the instability process, as was recently shown in Ref.[7], where it was demonstrated that subsonic ion flows in a bounded plasma result in ion-acoustic instability.

III. Theory of Ion Acoustic Instability Excited by Electron beam due to Negative Pressure

The main cause of ion acoustic instability is "negative pressure" contribution of the untrapped electron beams propagating from one wall to another. Indeed if the beam with velocity n_b and velocity v_b is affected by a small potential perturbation $\delta\phi$, the density perturbation is given by

$$\delta n_b = \frac{n_b v_b}{\sqrt{v_b^2 + 2\delta\phi / m}} - n_b = -\frac{n_b \delta\phi}{m v_b^2}. \tag{3}$$

That is a positive perturbation of potential will accelerate electrons and reduce their density. Effective pressure that drive acoustic waves is then modifies from standard case of the trapped Boltzmann distribution as following. The density perturbation of ions as a function of the potential perturbation is

$$\delta n_i = \delta n_e = \delta n_p + \delta n_b = \frac{n_p \delta\phi}{T_e} - \frac{n_b \delta\phi}{m v_b^2}. \tag{4}$$

The effective pressure is given by

$$p_{eff} \equiv \frac{n_i e \delta\phi}{\delta n_i} = \frac{n_p + n_b}{\dfrac{n_p}{T_e} - \dfrac{n_b}{m v_b^2}}. \tag{5}$$

Therefore if the beam density is above critical value given by

$$n_b > \frac{mv_b^2}{T_e} n_p \,. \qquad (6)$$

This criterion is verified in simulations.

IV. Conclusion

In conclusion, Hall thruster plasmas may exhibit ion-acoustic waves driven by electron beams produced due to electron emission from the channel walls. The likely cause is onset of ion-acoustic instability when the emission current is sufficiently strong. Another possible process is a two-stream ion-ion instability, due to the distinct groups of ions, moving with supersonic and with subsonic velocities, present when the sheath evolves from the space-charge limited to the inverse regime. Yet another mechanism that can excite ion-acoustic waves is the electron two-stream instability between the bulk and secondary electrons. Nonlinear processes such as modulation instability may then transfer energy from the electron plasma waves to the ion-acoustic mode. Further investigations are needed to identify the processes in question.

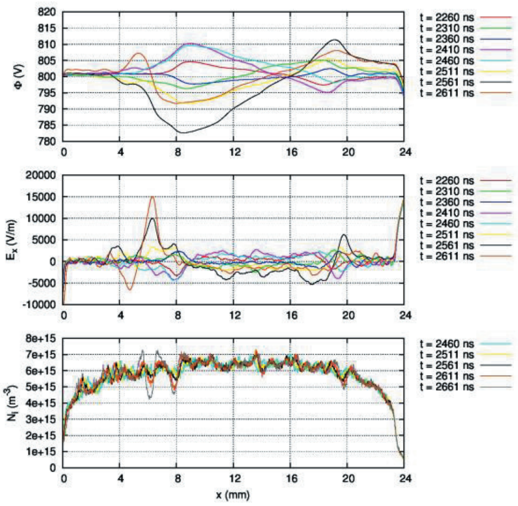

Figure 6. Sequences of profiles of potential (top), electric field (middle), and ion density (bottom) in simulation with 800 V dc voltage. The cathode is at x=40 mm (not shown).

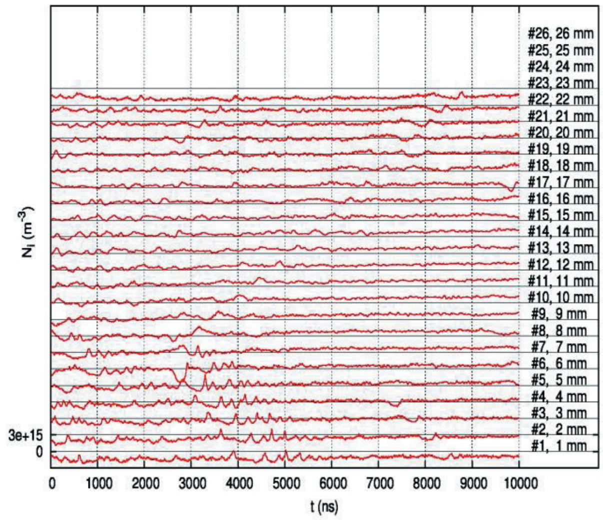

Figure 7. Ion density vs time in points placed with a step of 1 mm along the system in the simulation of an 800 V dc plasma. The curves are shifted upward in proportion to the coordinate of the observation point.

Since the instability depends strongly on ratio of trapped and passing/beam electrons and these densities depend on the way plasma is produced including collisions and ionization processes.

Acknowledgments

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