Excitation of Ion Acoustic Waves in Confined Plasmas with Untrapped Electrons

Hanna Schamis[1]*, Igor Kaganovich[2], Alexander Khrabrov[2], Johan Carlsson[2]
[1] University of Michigan, Ann Arbor, MI [2] Princeton Plasma Physics Laboratory, Princeton, NJ

Introduction

Various plasma propulsion devices exhibit strong electron emission from the walls either as a result of secondary processes or due to thermionic emission. To understand the electron kinetics in plasmas with strong emission, we have performed simulations using a reduced model with the LSP particle-in-cell code. This model aims to show the instability generated by the electron emission, in the form of ion acoustic waves near the sheath. It also aims to show the instability produced by untrapped electrons that propagate across the plasma, similarly to a beam, and can drive ion acoustic waves in the plasma bulk.

Methods

To observe the ion-acoustic instability, a one-dimensional, three-species model is used in the simulations. This simplified model of the bulk of the plasma consisted of an argon plasma (electrons and singly-ionized argon), and a "beam" of electrons. This beam is intended to represent the electrons emitted from the wall that travel past the sheath.

First, the parameters were set up so as to satisfy a reduced expression[1] for the Buneman dispersion relation (Equation 1).

$$1=\frac{\omega_{pi}^2}{\omega^2}-\frac{\omega_{pe}^2}{k^2v_{TE}^2}+\frac{\omega_{pb}^2}{k^2v_b^2}\left(1+\frac{2\omega}{kv_b}\right) \qquad \text{(Eq. 1)}$$

From this equation, the resonant condition, i.e. the fastest-growing mode for the instability, is defined (Equation 2).

$$1=-\frac{\omega_{pe}^2}{k^2v_{TE}^2}+\frac{\omega_{pb}^2}{k^2v_b^2}$$
$$0=\frac{\omega_{pi}^2}{\omega^2}+\frac{2\omega_{pb}^2\omega}{(kv_b)^3} \qquad \text{(Eq. 2)}$$

In the initial simulations, it is difficult to distinguish between the instability and statistical noise (Figure 2).

In the final simulations, the initial conditions (at t=0 ns) are set up in a way that there is a small perturbation in the densities and velocities of each of the three species. This then produces an initial perturbation in the potential (Figure 1). The factor determining the value of the perturbation was arbitrarily chosen at a value higher than the statistical noise.

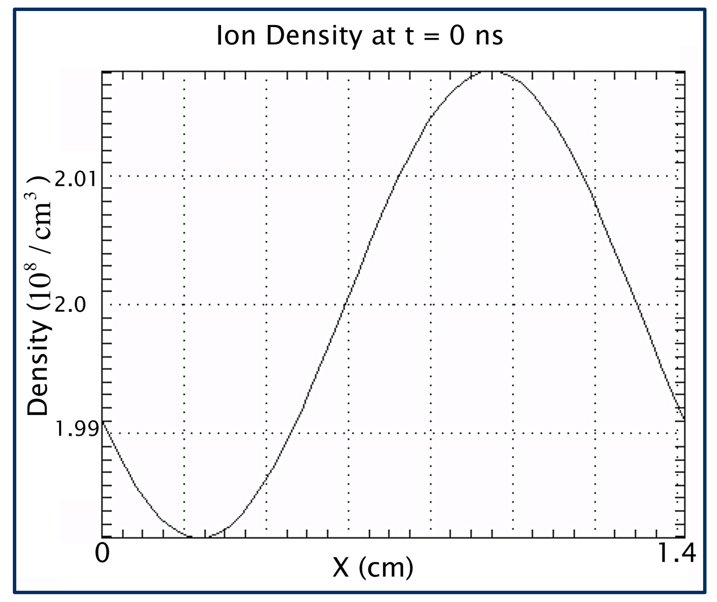

Figure 1(a)

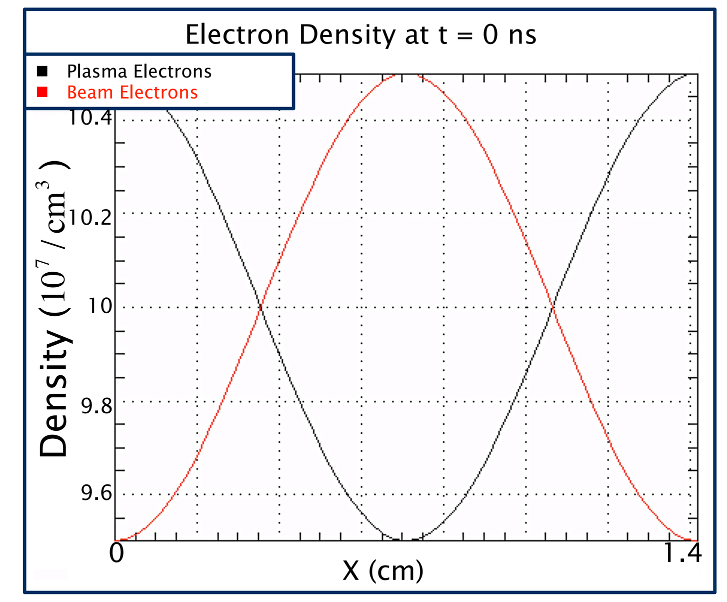

Figure 1(b)

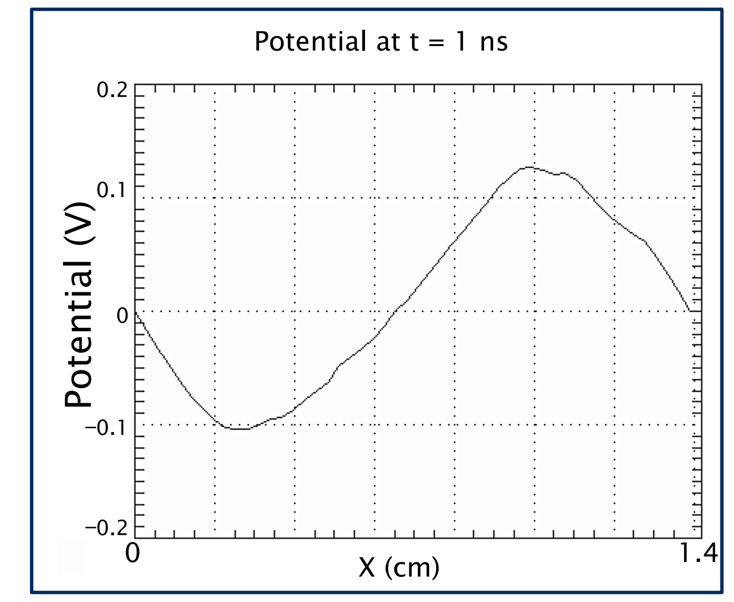

Figure 1(c)

Figure 1: Initial conditions after the perturbations were applied. (a) Density profile for the plasma ions at t = 0 ns. (b) Density profile for the two electron species at t = 0 ns. (c) Resulting potential profile at t =1ns.

Results

Initial results: The first simulations did not have the initial perturbations set up, and although an ion wave seemed to appear (Figure 2), it was difficult to distinguish between noise and instability.

Final results: After applying the initial perturbations, the instability was more apparent, as seen by the phase space of the ions (Figure 3). The growth rate γ for the initial part of the instability (before it saturates) was within 1.6% of the predicted value (Equation 3).

$$\gamma_{max}=k\,v_b\left(\frac{\omega_{pi}^2}{2\omega_{pe}^2}\right)^{1/3}\sin\left(\frac{\pi}{3}\right)\cong 0.02503\ \mathrm{ns}^{-1} \qquad \text{(Eq. 3)}$$

After a short amount of time, the system becomes non-linear, which is expected[2]. The non-linearity can be observed in the phase space plots in Figure 3.

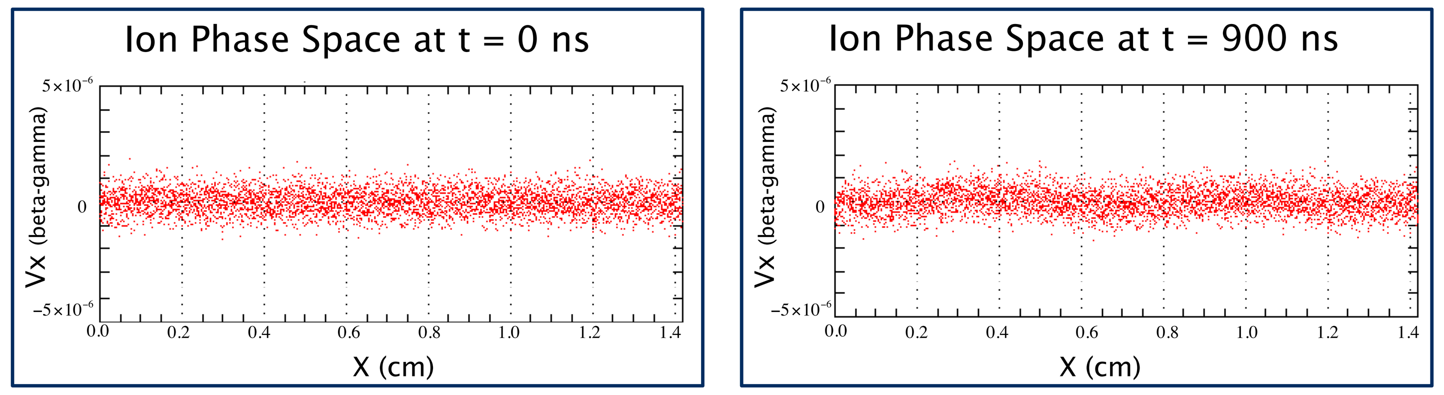

Figure 2: Plots of the ion phase space at t = 0 ns and at t = 900 ns. These simulations were set up without initial perturbations aside from the beam.

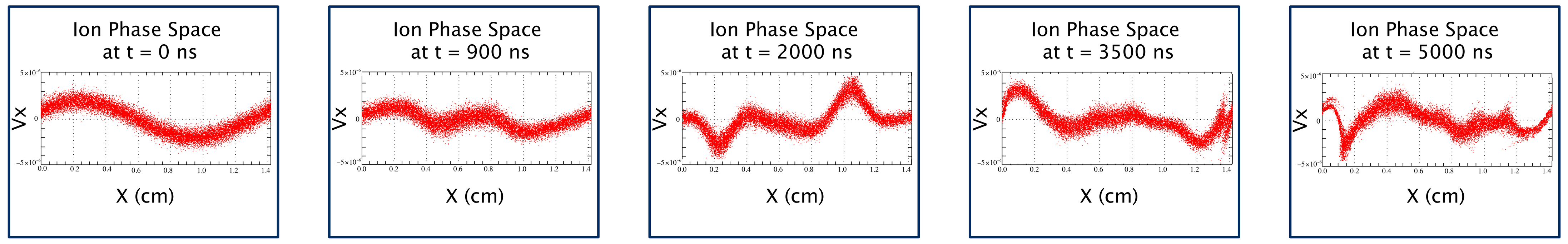

Figure 3: Ion phase space at t = 0 ns, 900 ns, 2000 ns, 3500 ns and 5000 ns.

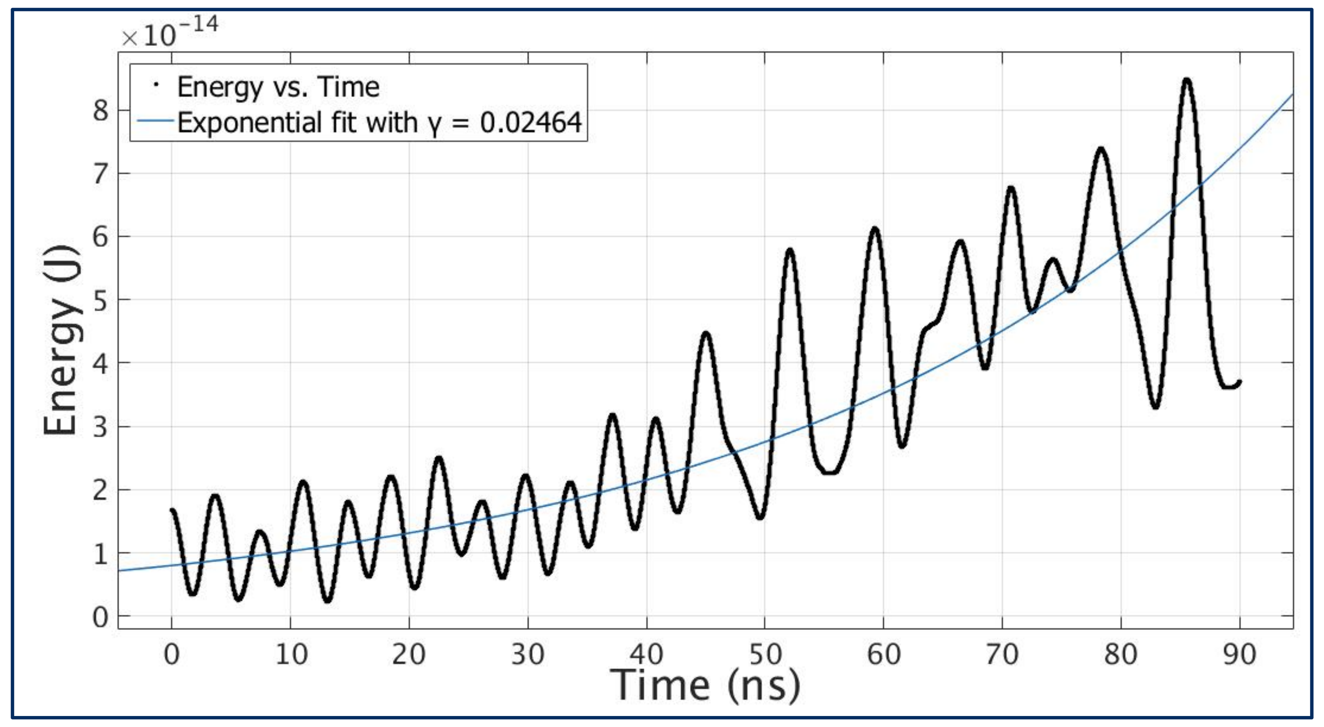

Figure 4: Field energy vs. time. The blue line indicates an exponential fit ($ae^{\gamma t}$ where $\gamma = 0.02464$).

Conclusions and Future Steps

Given that the growth rate measured was within 1.6% of the expected growth rate, we can safely say that the instability has been properly observed.

From the accuracy of the growth rate, we can also conclude that the reduced model for the instability caused by a secondary electron emission is accurate.

After this initial study, the next steps will be to run more simulations varying initial parameters, and eventually simulating an open system (i.e. without boundary conditions).

Acknowledgements

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References:

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*Hanna Schamis, hschamis@umich.edu