Influence of Streaming Instabilities on Transport Near Plasma Boundaries

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A key feature of plasma-boundary interaction physics is that ions are accelerated by a weak presheath electric field to a flow speed exceeding the sound speed at the sheath edge. Most theories, both fluid and kinetic, assume that the flow in this region is laminar. Using theory and particle-in-cell simulations, we give an overview of situations in which the flow gives rise to electrostatic instabilities, which in turn can influence plasma transport. In single ion species plasmas, ion flow can excite ion-acoustic instabilities. In multiple ion species plasmas, differential ion flow can excite ion-ion two-stream instabilities. This work provides a guide to determine the conditions at which these instabilities arise, such as temperature, pressure and concentration, as well as some consequences for how the instabilities influence plasma transport.

1. Introduction

Plasma boundary interactions are an essential feature of all laboratory plasmas. A detailed understanding of this interaction is especially important in materials processing applications, as well as in the interpretation of Langmuir probe diagnostics. A key feature is the formation of a thin sheath with a strong electric field near the material surface. In addition, a weak presheath electric field extends much farther into the plasma This accelerates ions such that the fluid flow is supersonic by the sheath edge. Most theories, both fluid and kinetic, assume that this flow is laminar. Here, we discuss situations in which the flow excites electrostatic plasma instabilities. We also discuss ways in which these instabilities can affect plasma transport properties through wave-particle interactions. The discussion focuses on ion-acoustic instabilities in plasmas with one ion species, and ion-ion two-stream instabilities in plasmas with two ion species. Some connections with electron-electron streaming instabilities that arise when secondary electrons are emitted from surfaces will also be made.

From a practical standpoint, one would like to know the circumstances under which the different instabilities arise. In particular, parameters such as neutral pressure, electron and ion temperatures, and ion concentrations (in the case of two species) affect the threshold conditions. In general, these instabilities tend to be low-pressure phenomena because substantial ion-neutral collisions damp the waves. They also require that electrons be much hotter than ions, otherwise channels exist (both fluid and kinetic) that inhibit wave excitation. In the case of two ion species, wave excitation does not arise if the concentration of one species is too dilute. This work will provide theoretical estimates of the instability boundaries, along with tests using particle-in-cell (PIC) simulations.

If instabilities do arise, one would also like to know what influence they have on plasma transport. In the case of ion-acoustic waves in single ion species plasma, we propose that wave-particle collisions can speed the thermalization rate amongst ions as they traverse the presheath [1]. In the absence of this enhanced collision rate, it is common that ion-neutral charge exchange collisions “pull out” a nonthermal tail. Experimental evidence for this has recently been provided [2]. In two ion species plasmas, we propose that the onset of two-stream instabilities causes a strong friction force between the ions that prevents the differential flow from significantly exceeding the instability threshold [3]. This provides a prediction for the ion flow speeds at the sheath edge that has been confirmed experimentally [4], and with PIC simulations [3].

This presentation will provide a detailed analysis and tests (using PIC) of the instability threshold conditions for different types of wave excitation in the presheath. It will serve as a guide to determine the parameters under which these instabilities can be expected. The talk will also discuss consequences of the instabilities on transport via wave-particle interactions.

2. Electrostatic Instabilities in the Presheath

2.1. Ion-acoustic

As the presheath electric field accelerates ions to the sound speed, they obtain a drift with reference to both the background neutral gas and the electrons. The interaction between ions and neutrals can cause a low energy tail in the ion velocity distribution to form as a result of ionization and charge exchange collisions. A variety of kinetic theories have been developed to model such a situation, starting from the famous Tonks-Langmuir model. All assume that the ion flow is laminar in the sense that any unstable wave generation is neglected.

Ion-acoustic instabilities are excited when the ion drift speed relative to electrons exceeds a threshold value. The threshold is the sound speed divided by a factor determined by the instability wavelength. Since the ion flow in the presheath is subsonic, only wavelengths shorter than an electron Debye length have the possibility for excitation. It was predicted in [1] that these short wavelength ion-acoustic instabilities can enhance ion thermalization in such a way that the low energy tail disappears near the sheath, where wave-particle collisions dominate. This has recently been tested experimentally in [2].

Here, we present further quantitative analysis and tests of the ion-acoustic instability threshold conditions in the sheath, as well as the feedback of the instabilities onto the ion velocity distribution. In particular, we emphasize the neutral pressure threshold and electron-to-ion temperature ratio threshold.

2.2. Ion-ion two-stream

When two ion species are present, the presheath electric field causes the lighter species to drift at a faster speed than the heavier species. A two-stream instability is excited when the differential flow speed exceeds a threshold condition that depends on the ion species concentrations and electron-ion temperature ratio. When instability onsets, wave-particle interactions are predicted to rapidly enhance the collisional friction between ion species. Since the scale length over which this occurs is much smaller than the presheath length scale, it is predicted that the differential ion flow cannot significantly exceed the instability threshold [3]. When this condition is combined with the Bohm criterion for two-ion species plasma, it determines the speed of each ion species at the sheath edge.

The predicted ion speeds have been confirmed experimentally in [4], and measurements of the instability fluctuations have been provided using probes. In addition, recent PIC simulations [3] have also confirmed the presence of instabilities (see Fig. 1), and have provided additional tests of the threshold conditions in the low-pressure limit. In the present work, we extend the analysis to higher-pressure scenarios to determine the threshold at which ion-neutral collisions damp the instabilities. This can occur through direct wave damping as well as distortion of the ion distribution functions.

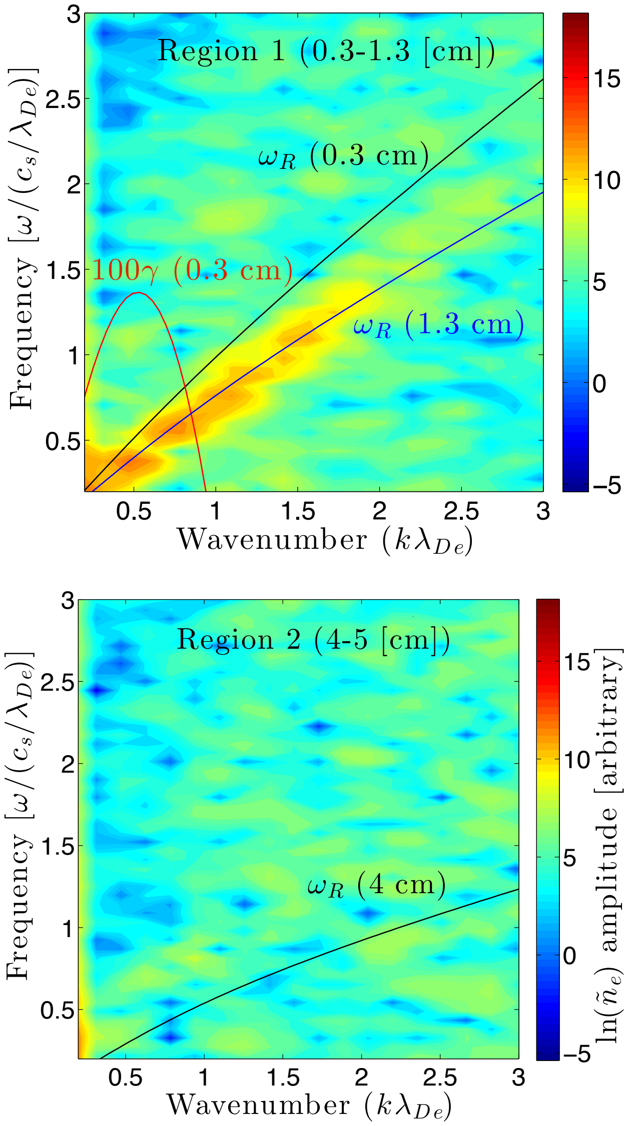

Fig. 1: (Top) Density fluctuation spectrum in a PIC simulation near the sheath of a He-Xe plasma at 7% He ion concentration. Also shown is the frequency spectrum predicted from linear theory at each edge of the box in which the spectrum is taken. (Bottom) A similar density spectrum taken at a location in the bulk plasma, where instability was not observed. Figure adapted from [3].

3. References

[1] S.D. Baalrud, and C.C. Hegna, *Plasma Sources Science and Technology* **20** (2011) 025013.

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