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Impact of Lighter Ion Concentration on Entry Flow in a Multiple Ion-Species Plasma Sheath

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Abstract- In many modern application of positive and negative ion sources, ranging from fusion plasma experiments to surface processing of materials by plasma, substantial increase in efficiency is observed achievable by using complex mixtures of neutral species to generate the source plasma. In the present study we obtain and characterize entry flow combinations from the linear dispersion of the a collisional multispecies plasma, as a function of lighter species' concentration. The entry flow velocity, normalized to acoustic velocity of one the species, shows critical variation in the entry flow velocity of the relatively heavier species whose acceleration is desired by using a mixed concentration of ions in the source plasma.

***Keywords*-** Multiple Ion-Species, Finite Sheath Dimensions, Plasma

I. INTRODUCTION

The plasma sheath is an electrostatic structure ensuring outflow of an equal flux of ions and electrons despite the fact that the ions are much massive than the highly mobile electrons. Clearly, the sheath structure at the boundary must accelerate ions in order to equalize their flux with mobile electrons. In many plasma applications this ion acceleration is exploited for extracting high energy ion flux as well as modifying the target surfaces with desired high ion flow velocities. The study of this plasma boundary region is therefore of great importance and development of theoretical models for plasma sheath and their improvement is an important field of research [3]. The properties and basic structure of electrostatic sheath is determined by the dispersion properties of the plasma which represent collectivelyresponse of all the ion species constituting the plasma depending on their parameters in various unmagnetized and magnetized conditions [1]. The entry flow velocity of ions into sheath structure is governed by standard Bohm criterion [2], which has analytic form of an inequality to to address the cases beginning from the marginal case of sufficiently large sheath dimension ($\lambda_D \ll L_S$) to increasingly sharper structures ($\lambda_D \sim L_S$) covered by the inequality of the criterion, where λ_D is the plasma Debye length. The latter form applies to more realistic cases where a vanishing Debye length ($\lambda_D \rightarrow 0$) is only an approximation. In a multiple ion species plasma the exact values of the entry flow velocities, corresponding to a particular sheath scaling, are obtainable by applying the appropriate form of the criterion and its generalized version which is characterized in this paper. We present results of analysis where an unmagnetized multiple ion species plasma generated sheath is considered with a relatively lighter species. The variation in the relative concentration of the species is allowed to characterize the dependence of entry flow velocity of the plasma on the parameters, including the relative concentration of ions and the sheath thickness. The range of applicability of the analysis covers the studies and experiments where sheath thickness and plasma composition must be optimized to achieve desired results and where wider sheath thickness is preferred for achieving increased spatial resolution such that measurements can be made with enough accuracy in the laboratory conditions [4, 5]. Based on the dispersive properties of the stationary electrostatic modes, often verified by experiments and computer simulations , it is shown that for sheath thickness approaching its limiting value, or the Debye length [6], how the entry velocities attain additional capacity of optimization by varying relative ion concentration. The present analysis is limited by the use of collisional fluid model and excludes the cases where kinetic effects, like those of the particle trapping and non-thermal distributions, become important. We also limit our treatment to the unmagnetized plasmas for simplicity, however the effect of a constant and uniform magnetic field can be addressable by extending the analysis to use a more general magnetized form [7] of the criterion. The present paper is organized as follows. In Sec. II the generalized entry criterion is discussed allowing to treat cases with multiple ion species for the analysis. In Sec. III the sheath structure in plasmas with distinct concentration of two ion species, Ar and Xe, considered for the the present analysis is discussed based on the results. The characterization is done showing the sheath scale length dependence of effective entry velocity of a two-ion- species plasma. Summary and conclusions are presented in Sec. IV.

II. SHEATH ENTRY CRITERION FOR MULTIPLE SPECIES PLASMA

We begin by considering an unmagnetized system of two ion species plasma steadily flowing into an absorbing material boundary with velocities $v_1$and v_2, respectively. In the finite ion momentum balance and negligible electron inertia in limit of low phase velocity perturbations, $\omega/kv_{the} \ll 1$ where $v_{the} = \sqrt{T_e/m_e}$, we write the electrostatic dispersion relation governing the ion perturbation as [7].

$$k^2 + \frac{1}{\lambda_D^2} - \sum_i \frac{\omega_{pi}^2}{(\omega/_k - v_i)^2 - c_i^2} = 0 \qquad (1)$$

where ω_{pi}, v_i and c_i are the plasma frequency, flow velocity and thermal velocity of the i'th ion species, respectively, and $\lambda_D$is the plasma Debye length. The dispersion relation (1) applied to the steadily flowing plasma into a stationary $\omega/k = 0$ electron confining plasma sheath structure variation having $k^2 < 0$ yields the generalized Bohm criterion [3],

$$\sum_j \frac{q_j^2 n_j}{m_j v_j^2 - \gamma_j T_j} \leq \frac{e^2 n_e}{T_e} \qquad (2)$$

The magnitude of k^2in (1) is the linked with inversed squared sheath scale length which must be infinite for the marginal case of vanishing Debye lengths ($\lambda_D^{-2} \gg k^2$) corresponding to equality form of the criterion (2).

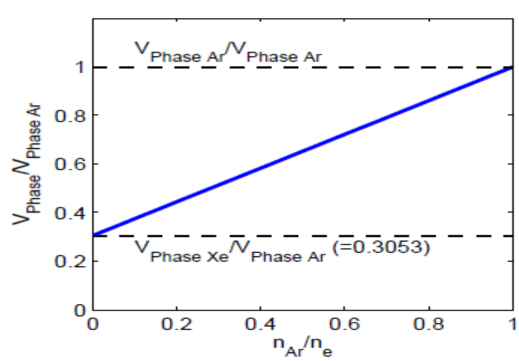

FIG. 1: Reference variation of the effective ion acoustic phase velocity (normalized to pure Ar plasma phase velocity) in a plasma with increasing fraction of the Xe concentration replaced by the Ar concentration n_{Ar}/n_e.

The sheath structure supported by (2) is stationary in the frame of absorbing boundary and the plasma species must have flow velocities satisfying (2). The criterion (2) additionally admits ion species with distinct (non-equal) flow velocities below their instability threshold. However, the present analysis examines only the stable cases of a common entry velocity for both the species and explores solutions with this effective entry velocity of the plasma into the sheath. For a two-ion species plasma with i = 1, 2 substituting V_{Entry}= $v_1 = v_2$ in the cold plasma limit ($T_i \rightarrow 0$) of the expression (1), we get,

$$V_{Entry} = \left[\frac{\sum_s \lambda_D^2 w_{ps}^2}{1 - \lambda_D^2/L_s^2}\right]^{-1} \qquad (3)$$

For a multiple ion sheath structure forming with a finite scale length, the effective ion acoustic phase velocity in the marginal case serves as a good reference for the entry velocities required to produce a finite dimension sheath. We have computed and plotted these entry velocities with variation of the concentration of two species in Fig. 1 where Argon (atomic mass ~40) and Xenon (atomic mass ~131) are used as the first and second species for our characterization, respectively. The solid line in Fig. 1 shows simplistic variation of the effective ion acoustic phase velocity in the bulk plasma where ion species are stationary. Clearly, with increasing concentration of Ar ions, the phase velocity of ion acoustic mode in a pure Xe ion plasma ($V_{Phase\ Xe}/V_{Phase\ Ar}$= 0.3053, indicated by bottom dashed line) shifts towards that of the pure Ar plasma (indicated by top dashed line) and approaches this value at 100 % concentration of Ar ions.

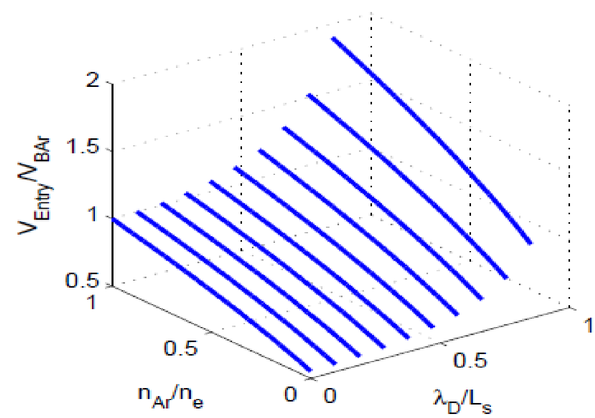

FIG. 2: Variation of common entry velocity of the ion species into the sheath with respect to ratio λ_D/L_s and normalized concentration n_{Ar}/n_e of Ar at the sheath edge.

III. ENTRY FLOW VARIATION FOR FINITE SHEATH DIMENSIONS

We now analyze the effect of the magnitude of sheath thickness on the effective ion entry flow velocity and its variation with the relative ion concentration using the criterion (2). In Fig. 2 we have plotted the variation in the effective entry velocity of the species $V_{Entry} = v_1 = v_2$ into the sheath structure at the plasma sheath edge as a function of both, the relative concentration of n_{Ar}(normalized to total electron density n_e) and the ratio of Debye length λ_D to sheath thickness L_s. The selection of the range of this ratio is motivated by the condition that the ratio λ_D/L_S is bounded between 0 and 1 for all the valid cases of sheath formed in plasma as the Debye length λ_D represents the minimum limit of the sheath thickness in plasma. The profile at $\lambda_D/L_S \rightarrow 0$ corresponds to the nearly linear variation of the effective entry velocity with respect to the increasing relative concentration of Ar. This variation is pronounced and become steeper with increasing ratio of Debye length to sheath thickness L_S indicating that even larger entry velocities are prescribed for the species when Ar concentration is large and sheath thickness begin to be finite and acquire more realistic values in terms of Debye length, rather than being infinity. Note that the usual quasineutral plasma region will not be accessible in the case of this latter limit approached. In most of the applications, therefore, the plasma must be operated away from this limit to have a limited sheath dimension and finite usable bulk plasma volume.

In order to more quantitatively examine the variation in the entry velocity with respect to the sheath thickness, the profiles of V_{Entry} at certain selected values of Ar concentration are plotted in Fig. 3. This can be noted that for sheath length approaching infinity ($\lambda_D/L_S \rightarrow 0$), the entry velocity reduces to phase velocity of the ion acoustic mode for the corresponding plasma presented in Fig. 1.

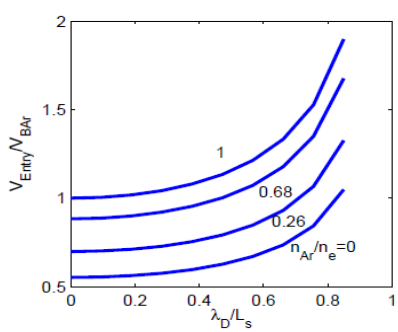

FIG. 3: Entry velocity as a function of ratio $\lambda_D/L_S \rightarrow 0$ in a two species plasma (Ar and Xe) for selected values of relative Ar concentration, n_{Ar}/n_e. = 0, 0.26, 0.68 and 1, respectively. The case n_{Ar}/n_e= 0 corresponds to pure Xe plasma whereas n_{Ar}/n_e = 1 corresponds to a pure Ar plasma.

However a sharper gain is achieved in entry velocity with reducing sheath thickness than with increasing the concentration of lighter Ar ion species. The entry velocities are considerably larger for the sheath thickness approaching its limiting value λ_D.

IV. SUMMARY AND CONCLUSIONS

To summarize, we presented application of linear dispersive property of multiple species plasma to estimate required presheath acceleration of the ion species. The entry velocity of the ions in a two species, Ar and Xe, plasma were characterized to illustrate the dependence of a common entry velocity of these ion species on the relative concentration of the species and on the sheath thickness expressed in terms of plasma Debye length. Results of the analysis were presented to show that the presence of a lighter Ar ion in a Xe plasma results in the increase of the entry velocity of the plasma to the electrostatic sheath. In a realistic laboratory situation with finite dimension of the plasma, the velocities are governed by the version of generalized sheath criterion accounting for the effects of finite sheath thickness. The effect of reducing sheath dimension generate a sharper increase in the entry velocity, as compared to the effect produced by the increasing concentration of the lighter Ar species. The main limitations of present study includes use of linear dispersion relation, neglect of kinetic effects and absence of magnetic field. Inclusion of these effects suggest potential future extension of the present analysis with application of the results to multiple species plasma experiments in the real laboratory set ups.

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