Parametrics for Molecular Deuterium Concentrations in the Source Region of the UW-IEC Device Using an Ion Acoustic Wave Diagnostic

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Abstract:

The ion source region of the UW-Inertial Electrostatic Confinement device consists of a filament assisted DC discharge plasma that exists between the wall of the IEC vacuum chamber and the grounded spherical steel grid that makes up the anode of the IEC device. The plasma characteristics of the source region have been investigated using a planar Langmuir probe and an antenna used for the propagation of ion acoustic waves. Using these diagnostics the average ion mass of the deuterium source plasma has been measured and is consistent with a mostly D_3^+ plasma. These results are consistent with a 0-D theoretical model of the source plasma. Variations in the floating potential, the plasma potential, and the plasma density have been investigated by varying the radial location of the planar probe. Variations in voltage on the IEC cathode have been shown to affect the floating potential in the source region as well as the spatial extent and density of the plasma in the source region.

Source Region Theory

The multi-species ion-acoustic wave dispersion relation has been used to determine the concentrations of molecular ion species in the deuterium plasma used to fuel the UW-IEC device. Computational work done by G.A. Emmert and J. F. Santarius indicates that atomic physics effects, leading to high molecular ion concentrations, have a significant effect on the fusion rate within IEC devices operating at high neutral gas pressures ($>10^{-5}$ torr).

The composition of ions present in the source region of the IEC is treated using zero dimensional rate equations. The rate equations take into account the following processes:

Ionization of D_2:	$e + D_2 \rightarrow D_2^+ + 2e$
Dissociation of D_2:	$e + D_2 \rightarrow 2D + e$
Ionization of D:	$e + D \rightarrow D^+ + 2e$
Dissociation of D_2^+:	$e + D_2^+ \rightarrow D^+ + D + e$
Dissociative ionization of D_2:	$e + D_2 \rightarrow D^+ + D + 2e$
Dissociative recombination of D_2^+:	$e + D_2^+ \rightarrow 2D$
Interchange reactions creating D_3^+:	$D_2 + D_2^+ \rightarrow D_3^+ + D$
Dissociative recombination of D_3^+:	$e + D_3^+ \rightarrow D_2 + D$

The dominant processes for the UW-IEC device are ionizations of D_2, interchange reactions producing D_3^+, and dissociative ionization of D_2 producing D^+. The respective concentrations of D_3^+, D_2^+, and D^+ are dependent on the electron temperature and background neutral gas pressure.

The rate equations used to calculate the concentrations of molecular ion species in the IEC source region are shown below. They illustrate the manner in which ionizations, interchange reactions and flow to the walls and grid all play a role in calculating the ion current that flows through the IEC anode.

$$D^+ \quad \frac{d}{dt}(n_{11}) = n_p n_{20}\sigma_5 V_p - \frac{1}{2} n_{11} C_1 \frac{(A_g + A_w)}{Vol}$$

$$D_2^+ \quad \frac{d}{dt}(n_{21}) = n_p n_{20}\sigma_1 V_p - \alpha_2 n_{21} n_{20} - \frac{1}{2} n_{21} C_2 \frac{(A_g + A_w)}{Vol}$$

$$D_3^+ \quad \frac{d}{dt}(n_{31}) = \alpha_2 n_{21} n_{20} - \frac{1}{2} n_{31} C_3 \frac{(A_g + A_w)}{Vol}$$

Ionization

Interchange reactions

Flow to walls and grid

$$\mathbf{I_{anode}} = e(n_{11}C_1 + n_{21}C_2 + n_{31}C_3)A_g = 2I_{ion}$$

Multi-species Ion Acoustic Wave Dispersion Relation

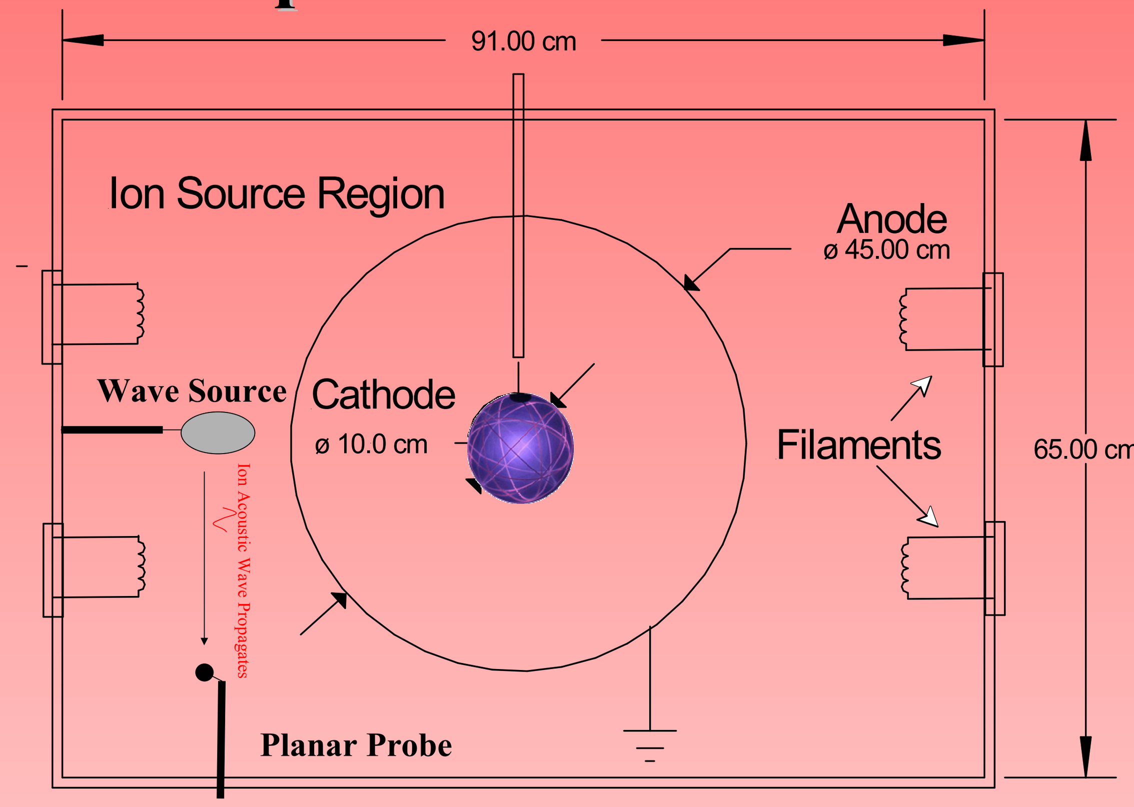
A derivation of the multi-species ion-acoustic wave gives the following dispersion relation where T_e is the electron temperature, M_j is the ion mass of the jth ion species, and c_{sj} is the sound speed of the jth ion species.

$$\frac{\omega}{k} = \sqrt{c_{s1}^2 + c_{s2}^2} \quad \text{where} \quad c_{sj} = \sqrt{\frac{n_j k T_e}{n_e M_j}}$$

This implies:

$$v_{ph}^2 = \frac{\alpha k T_e}{M_1} + \frac{(1-\alpha) k T_e}{M_2} \quad \text{where} \quad \alpha = n_1 / n_e$$

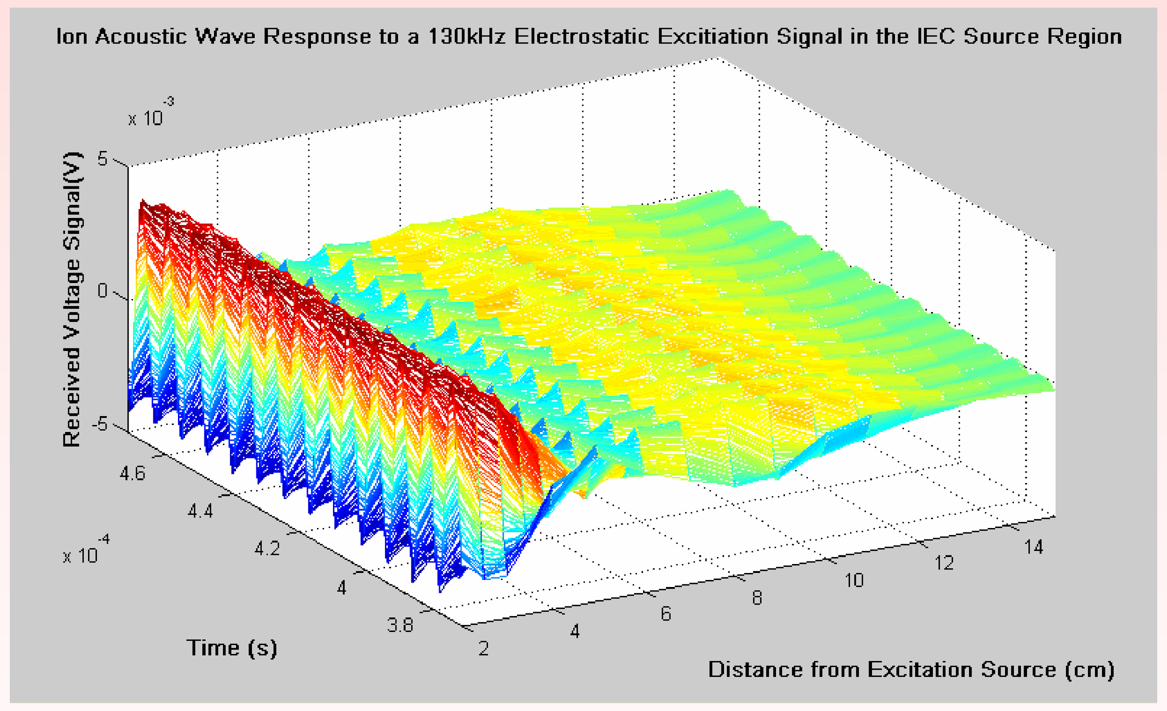
Experiment Schematic



This schematic shows the experimental setup within the UW-IEC Device.

Experimental Method

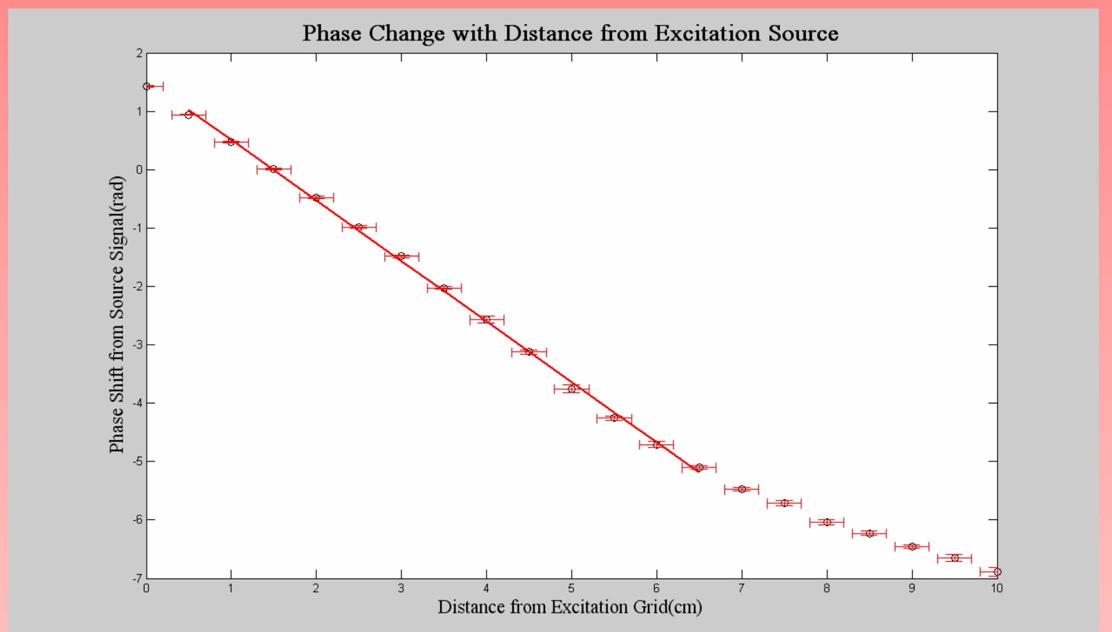
A continuous sine wave with amplitude less than kTe/e was used to excite ion acoustic waves in the source plasma. The position of the planar probe was swept between 1cm and 16cm with the probe voltage held at -100V bias. This allowed the phase dependence of the phase shift between the excitation signal and received signal to be measured. Thus a direct measurement of the phase velocity of the multi-species ion acoustic wave was obtained. The temporal and spatial dependence of the multi-species ion acoustic wave is shown below.



This figure portrays the experimental setup used to verify the molecular ion concentrations calculated to exist in the IEC source region. Excitation signals on the 75cm² mesh were kept to ~2Vpp to ensure the propagation of linear IAW waves.

Experimental Results

The data below illustrates the method used to obtain the phase velocity of the ion acoustic waves. The phase shift between the propagated and received signals is plotted as a function of the separation between excitation source and planar probe receiver. The phase response is linear and slope of the line is the wavenumber of the ion acoustic wave



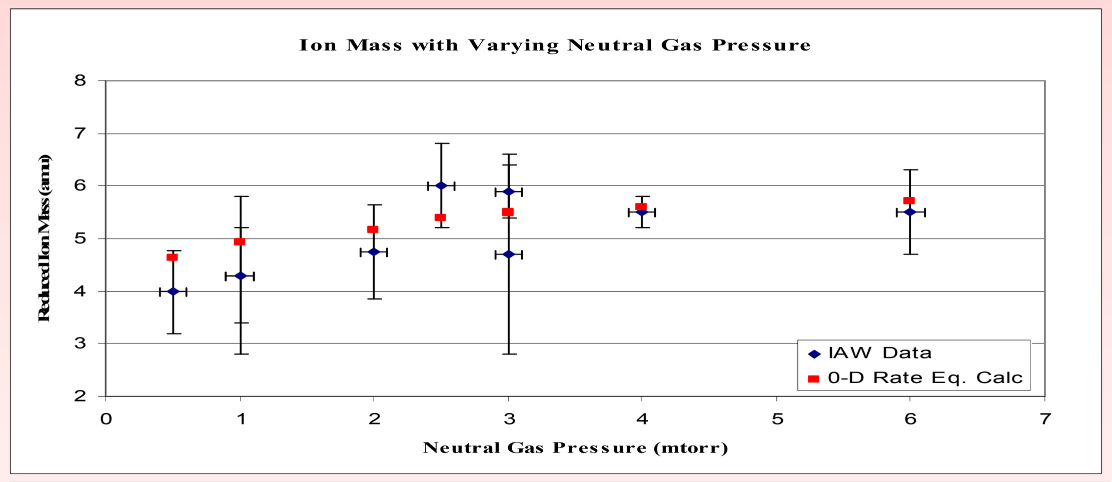
The above data corresponds to the phase shift of a 100kHz wave moving through a plasma with a nominal electron temperature of 2.7 eV. This leads to calculated weighted reduced ion mass of 5.9amu ±0.5amu. The neutral gas pressure for this data set was 3.0 mtorr.

From the phase velocity of the wave and measured electron temperature in the IEC source region a density weighted reduced ion mass can be calculated:

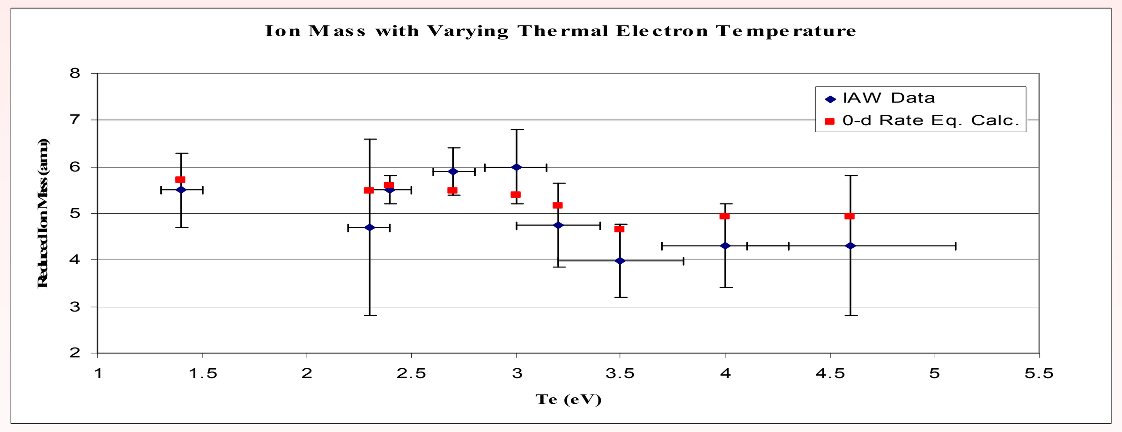
$$M_R^{-1} = \frac{1}{n_e}\left(\frac{n_{D3}}{M_{D3}} + \frac{n_{D2}}{M_{D2}} + \frac{n_D}{M_D}\right)$$

Below the M_R is shown to vary with kTe and neutral gas pressure. The measured values are compared with the M_R values predicted from the ion concentrations calculated by the 0-d rate equation model described previously.

(a)



(b)



In these figures it is shown that (a) at low neutral gas pressure the ion species mix contains a significant fraction of D_2^+ whereas at high neutral gas pressure D_3^+ is the dominant ion type. (b) Similarly low temperature plasmas in deuterium are mostly D_3^+ whereas higher electron temperature plasmas contain larger shares of D_2^+ and D^+.

Conclusion

By examining the propagation characteristics of ion-acoustic waves in the ion source region of the UW-IEC device it has been shown the ion species mix is dependent on neutral gas pressure and electron temperature. Species mixtures vary from, D_3^+ accompanied by a small fraction of D_2^+ , to mixtures where D_2^+ is the dominant ion species. This has significant implications for future modeling efforts on the UW-IEC device.

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