Investigation of effect of excitation frequency on electron energy distribution functions in low pressure radio frequency bounded plasmas

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Particle in cell (PIC) simulations are employed to investigate the effect of excitation frequency ω on electron energy distribution functions (EEDFs) in a low pressure radio frequency (rf) discharge. The discharge is maintained over a length of 0.10 m, bounded by two infinite parallel plates, with the coherent heating field localized at the center of the discharge over a distance of 0.05 m and applied perpendicularly along the y and z directions. On varying the excitation frequency f ($=\omega/2\pi$) in the range 0.01–50 MHz, it is observed that for $f \leq 5$ MHz the EEDF shows a trend toward a convex (Druyvesteyn-like) distribution. For $f > 5$ MHz, the distribution resembles more like a Maxwellian with the familiar break energy visible in most of the distributions. A prominent “hot tail” is observed at $f \geq 20$ MHz and the temperature of the tail is seen to decrease with further increase in frequency (e.g., at 30 MHz and 50 MHz). The mechanism for the generation of the “hot tail” is considered to be due to preferential transit time heating of energetic electrons as a function of ω , in the antenna heating field. There exists an optimum frequency for which high energy electrons are maximally heated. The occurrence of the Druyvesteyn-like distributions at lower ω may be explained by a balance between the heating of the electrons in the effective electric field and elastic cooling due to electron neutral collision frequency ν_{en} ; the transition being dictated by $\omega \sim 2\pi\nu_{en}$.

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I. INTRODUCTION

Low pressure rf discharges are known to have large degree of spatial nonuniformity and nonequilibrium conditions.¹ External control parameters such as the discharge boundaries, neutral pressure, and the excitation frequency play a major role in determining the characteristics of low pressure rf discharges. In the nonlocal regime where the electron energy relaxation length $\lambda_e \gg d$, the discharge length, the plasma electrons are not in equilibrium with the local plasma field.² The excitation frequency can change the dynamics of the discharge considerably by modifying the electron energy distribution function (EEDF). Since a majority of the discharges both for basic research and applications fall under this category where $\lambda_e \gg d$, an investigation of the EEDF with excitation frequency is crucial for an understanding of its role. The present study corresponds to a nonlocal regime since $\lambda_e \sim 3000$ cm $\gg d$ (10 cm). We investigate the effect of rf excitation that mimics inductive heating as different from capacitively coupled plasmas governed by sheath heating.

With the above viewpoint, recently there has been a lot of investigation of EEDFs in low pressure rf plasmas. EEDFs in helicon discharges operated in the double layer (DL) mode^{3–5} have been looked at. These measurements have been carried out to examine the influence of the double layer on the electrons. Measurements of EEDF both upstream and downstream of the DL have been carried out. Godyak *et al.*⁶ investigated the EEDFs in inductively coupled argon plasma

over a wide pressure and power regimes. In another experiment, the paradoxical behavior of the electron temperature in a low pressure rf discharge was analyzed using measurements of EEDF,² where the combined effects of nonlocality and non-Maxwellian EEDFs have been pointed out. Meige *et al.* looked at EEDFs in an inductively coupled plasma,⁷ investigating the origin of the break energy. However, there are not many studies in low pressure rf discharges where the effect of the excitation frequency of the rf heating field on EEDF is investigated. Most of the studies carried out so far have operated at the standard value of the excitation frequency of 13.56 MHz, which is routinely employed in most of the basic research and industrial applications. Some investigations on the effect of $f < 13.56$ MHz (Ref. 4) have been reported. However, there is a definite lack of investigation over a wide range of excitation frequencies for one to be able to make predictions of the effect of the excitation frequency on EEDFs.

The objective of the present research is to investigate the EEDF in a low pressure rf discharge operated at 1 mTorr in argon, where the excitation frequency f is varied over four decades, 0.01–50 MHz. The investigations are carried out using particle in cell (PIC) simulations. The interplay between the excitation frequency and the electron neutral collision frequency ν_{en} is looked at to understand its role in governing the nature of the obtained EEDFs. As electrons transit through the heating region they are locally heated by the antenna electric fields, depending upon the value of f , implying that an investigation of the transit time heating

would be of relevance in predicting their role in electron heating.

The article is organized as follows. In Sec. II, the model used in the PIC simulation scheme is presented. The experimental results from the PIC code are presented in Sec. III. In Sec. IV, the results are discussed. Finally, the results are summarized and conclusions drawn in Sec. V.

II. MODEL

In the following, we discuss the PIC simulation scheme. The plasma is confined between two infinite parallel plates separated by 0.1 m. The neutral gas pressure is maintained at 1 mTorr and typical values of the steady state electron density and the plasma space potential are $\sim 2.5 \times 10^{14} \text{ m}^{-3}$ and $\sim 17 \text{ V}$, respectively. The simulation is based upon a well known PIC scheme^{8–11} with Monte Carlo collisions.¹² The simulation is one dimension (1D) in space (x) and three dimensional (3D) in velocities (x , y , and z). Accurate electron-neutral and ion-neutral collision cross sections are employed to ensure realistic simulations; data can be found in Refs. 13 and 14 for electron-neutral collisions (elastic, exciting, and ionizing), and in Ref. 15 for ion-neutral collisions (elastic and charge exchange). Coulomb collisions are not included in the present study, as their effect on the EEDF would be negligible under the present low density condition.

Until now PIC simulations have been most commonly employed to study capacitive coupling, where the rf voltage is applied to one of the electrodes.^{1,16} Here, the rf heating field is localized at the center of the discharge over a length of 0.05 m. The shape of the rf electric field along the x axis is a top hat and the amplitude is typically $\sim 2.8 \times 10^4 \text{ V/m}$. The electrons are heated with a scheme intended to model “inductive excitation,” similar to that described by Turner,¹⁷ but without solving electromagnetic field equations, and has been recently employed by Meige *et al.*⁷ To simulate the radial electric fields of an actual experiment, the rf electric field is applied in the y and z directions perpendicular to the spatial x dimension where the boundaries are located. This allows us to simultaneously heat electrons in both y and z directions, momentum and energy being transferred to the other directions via electron neutral collisions. The heating current density is maintained at 5 A/m^2 . In the present investigation, the heating scheme differs from the previous work by Meige *et al.*,⁷ where the field was applied only along the y direction. We found this leads to nonsymmetric EEDFs in the y and z directions. The amplitude of the rf electric field is taken as uniform over the length of the heating region and localized within it.

The simulations are allowed to run for several thousand rf cycles in order for the system to reach equilibrium. The initial temperatures of the ions and electrons are taken as 0.026 eV (room temperature) and 3 eV, respectively. It is found that the typical times required to reach equilibrium vary in the range $\sim 20\text{--}30 \mu\text{s}$ after the initiation of the discharge. Each simulation particle is a “macroparticle” representing 2×10^8 actual particles. The number of cells along the x axis are 250 and the time step is $\sim 1 \times 10^{-10} \text{ s}$, which allows the simulation to meet the standard stability and accu-

racy criteria of the PIC scheme:^{8–11} $\Delta t \ll 0.2/\omega_p$ and $\Delta x \ll \lambda_D$, where Δt and Δx are the spatial and temporal increments used in the simulation, and ω_p and λ_D are the plasma frequency and the Debye length, respectively. For a typical value of plasma density of $\sim 2.5 \times 10^{14} \text{ m}^{-3}$ and electron temperature T_e of $\sim 5 \text{ eV}$, $\lambda_D \sim 10^{-3} \text{ m}$ and $\omega_p \sim 8.94 \times 10^8 \text{ rad/s}$.

Depending upon the nature of the obtained EEDFs and the PIC experiments performed here, the results can be grouped in the following frequency regimes: (i) $0.01 \text{ MHz} \leq f \leq 5 \text{ MHz}$, (ii) $5 \text{ MHz} \leq f \leq 20 \text{ MHz}$, and (iii) $20 \text{ MHz} \leq f \leq 50 \text{ MHz}$, although the demarcation at the transition frequencies are not rigorous such as to provide distinctly different EEDFs. The EEDFs are presented for three different velocity components x , y , and z and mainly at three different locations in the plasma; one near the center $x = 0.05 \text{ m}$, near the edge of the plasma $x = 0.012 \text{ m}$ which is closer to the sheath and in the region of the sheath ($x = 0.002 \text{ m}$). The EEDFs are measured along the abscissa and the ordinate is in natural log scale, so that a Maxwellian distribution yields a straight line. For the EEDFs, the electron energies have a resolution of $2 \times 10^{-3} \text{ eV}$ and these have been acquired after the system is well into equilibrium (typically $100 \mu\text{s}$) and run for an additional number of time steps $\sim 5 \times 10^5$ time steps ($\sim 50 \mu\text{s}$) and averaged. To sum up, the system has a finite size in the x direction (0.1 m), while it is infinite in the two other directions y and z . In Sec. III, the results of the simulations are presented.

III. RESULTS

Figures 1(a)–1(c) show typical profiles of the plasma space potential V_p , the particle densities (electron N_e and ion N_i) along the x dimension, and the temporal evolution of the plasma to equilibrium, at an excitation frequency of 20 MHz. From Fig. 1(a), the formation of the sheaths near the boundaries can be seen and the maximum value of the potential at the center is $\sim 17 \text{ V}$. Figure 1(b) shows that the electron and ion densities are $\sim 1.7 \times 10^{14} \text{ m}^{-3}$ at the center of the discharge and decrease uniformly toward the boundaries. The ion densities are higher than the electron densities in the sheath region as expected. The sheath can be approximately taken to begin at a point where the electron and ion densities start to deviate near the boundaries $\sim 0.01 \text{ m}$ from the edge. The sheath thickness is about $10\lambda_D$. Figure 1(c) shows that the discharge attains equilibrium in $\sim 2 \times 10^5$ time steps ($\sim 20 \mu\text{s}$). The discharge was initiated with 1000 simulation particles (electrons and ions) and the equilibrium numbers of particles attained is $\sim 5 \times 10^4$. The characteristic features of the bounded plasma and its time evolution to equilibrium is therefore established.

To show the velocity space distribution, typical equilibrium phase space plots of the plasma (electrons and ions) are shown in Figs. 2(a) and 2(b) at an excitation frequency of 20 MHz. The electrons exhibit the expected filling of phase space indicating a uniform distribution of possible velocities, whereas the distribution of the ions are more nonuniform, indicating directed velocities toward the discharge

FIG. 1. (Color online) (a) The plasma space potential V_p , (b) particle densities (electron N_e and ion N_i) versus the x dimension of the discharge, and (c) demonstrates the initiation of the discharge to equilibrium which is attained in $\sim 3 \times 10^5$ time steps ($30 \mu\text{s}$), for a heating field of frequency 20 MHz. Figure shows the real number of particles.

boundaries as expected, which follow the spatial profile of the electric field.

Figures 3(a)–3(c) show the EEDF in the x direction at an excitation frequency of 5 MHz, 20 MHz, and 50 MHz, respectively, at three spatial locations of the discharge $x=0.05$ m (center), $x=0.012$ m (near the edge), and $x=0.002$ m in the sheath region. It is observed that the typical structure of the EEDFs (two Maxwellian with a step) in the x direction is common to all the frequencies even for $f \ll 5$ MHz (not shown). The case at 20 MHz (Fig. 3(b)) is described first. The plasma space potential V_p at this frequency is shown in Fig. 1(a). It can be seen that as predicted in earlier work,⁷ the break energy of the EEDF shown with dotted lines at the three different spatial locations in the plasma, follow the value of V_p at the corresponding spatial location (Fig. 1(a)), ~ 14 eV at 0.012 m, ~ 16.5 eV at 0.05 m, and 3.8 eV at $x=0.002$ m (cf. Fig. 3(b)). This trend agrees well with the results at 5 MHz and 50 MHz. It may be noted that outward toward the boundaries ($x=0.012$ m and

FIG. 2. (Color online) Plasma (a) electron and (b) ion phase space plots at equilibrium ($t = 100 \mu\text{s}$) for an excitation frequency of 20 MHz.

0.002 m), the EEDFs become deficient in the population of low energy electrons; this is expected because low energy electrons do not have enough energy to overcome the sheath potential barrier. The location $x=0.012$ m is just behind the start of the sheath and does not show as much difference. The characteristic “three temperature structure” of the EEDF has also been reported earlier in some of the EEPFs measured by Godyak *et al.*,⁶ particularly at low pressures (≤ 10 mTorr). The temperature of the two populations of electrons T_{e1} and T_{e2} above and below the break energy E_b has been found and inserted in the figures. It is found that both T_{e1} and T_{e2} are higher for $f=20$ MHz as compared to the results at 5 MHz and 50 MHz. It is considered that the population of electrons representing the temperature T_{e2} is a result of electrons scattered to the x direction from the y and z directions. These electrons are unlikely to be observed in most experiments as there are more than one dimension and boundaries. The only chance of observing them would be in highly magnetized and low collision plasmas.

We now investigate the EEDFs in the other two directions (y and z). Figures 4(a) and 4(b) show the EEDF in the y and z directions, respectively, for an excitation frequency of 5 MHz, taken at the center ($x=0.05$ m) and near the edge plasma ($x=0.012$ m). It may be noted that with the introduction of the heating field in the two directions y and z , the EEDFs have become fairly symmetric in both directions, in contrast to the nonsymmetrical distribution reported by Meige *et al.*,⁷ when the heating field was applied only in the y direction. At 5 MHz, the EEDFs tend to become more convex (Druyvesteyn-like). Here, neither the trapped low energy electrons nor the escaping free electrons have distributions which are perfectly Maxwellian. The findings agree reasonably well with Ref. 6 (at 1 mTorr) where with decrease in frequency a similar behavior in the EEPFs was reported.

FIG. 3. (Color online) (a) EEDF along the x direction at the center ($x = 0.05$ m), near the plasma sheath edge ($x = 0.012$ m), and in the region of the sheath ($x = 0.002$ m) of the plasma for a heating frequency of (a) 5 MHz, (b) 20 MHz, and (c) 50 MHz.

However, the maximum excitation frequency employed there was 13.56 MHz. In Fig. 4, the break energy is not clearly demarcated but appear to be close to the excitation threshold in argon (~ 11.55 eV).

Figures 5(a) and 5(b) show the EEDFs in the y direction at a lower f of 0.5 MHz and 1 MHz, respectively, at the center ($x = 0.05$ m) of the plasma. Similar to the result at 5 MHz (Fig. 4) the EEDFs at these low frequencies have a convex profile (Druyvesteyn-like). The break energy E_b seems to lie in the range of 10–16 eV, i.e., closer to the excitation (~ 11.55 eV) and ionization thresholds (~ 15.76 eV), depending on the frequency, e.g., for EEDF at 0.5 MHz it is closer to the excitation threshold and at 1 MHz and 5 MHz it is closer toward the ionization threshold (~ 15.76 eV for argon). This is expected as there are no boundaries in the two perpendicular directions and V_p should not play a role in dictating the break energy E_b . We compare the convex type of distributions obtained at lower frequencies ($f \leq 5$ MHz) with a standard distribution such as a Druyvesteyn distribution which has a convex shape. Such comparisons have been carried out earlier by other authors [cf. Refs. 2, 6, and 18], with an aim to determine the degree of closeness with Druyves-

FIG. 4. (Color online) (a) EEDF along the y and (b) z direction at the center ($x = 0.05$ m) and near the edge ($x = 0.012$ m) of the plasma for a heating frequency of 5 MHz.

teyn distribution from the value of the exponent r in the fitting with $A\exp(-E^r/B)$. (Here, E is the electron energy and A and B are constants). By fitting each EEDF to the function, $A\exp(-E^r/B)$ as shown in Figs. 5(a) and 5(b), the exponential factor r is estimated to be 1.98 for the two cases,¹⁸ we notice that the depletion of the low energy electrons is less compared to a Druyvesteyn distribution. For a perfectly Druyvesteyn distribution the exponential factor $r = 2$ and the population of low energy electrons is more depleted, we note that the fitting is not particularly good near $E = 0$. The zero slope at $E = 0$ for a Druyvesteyn distribution is difficult to observe even in experiments (e.g., cf. Refs. 6 and 18) and is an ideal situation.

As the excitation frequency is further increased we notice that the EEDFs in the y and z directions transition from a convex type of distribution to a more linear (Maxwellian type) as shown in Figs. 6(a) and 6(b), where the results for 10 MHz and 20 MHz are presented. At 20 MHz (Fig. 6(b)) additionally we observe a “hot tail” in the EEDF, reflecting the manner in which the escaping electrons are heated by the high frequency heating field. It will be discussed later that the development of the “hot tail” is considered to be associated with the transit time heating of the energetic electrons as they pass through the antenna heating field. At frequencies ≥ 10 MHz, the break energy is close to the ionization threshold (~ 15.76 eV). However at 20 MHz, we notice that E_b is ~ 25 eV the point where the “hot tail” appears.

Figures 7(a) and 7(b) shows the EEDFs in the y and z directions at a heating frequency of 30 MHz and 50 MHz, respectively. The measurements are taken at the center of the discharge ($x = 0.05$ m). Similar to the results at 10 MHz and 20 MHz, the distributions are more Maxwellian with E_b

FIG. 5. (Color online) EEDF along the y direction at the center ($x=0.05$ m) and near the edge ($x=0.012$ m) of the plasma for heating frequency of (a) 0.5 MHz and (b) 1 MHz.

closely following the ionization threshold. The effect of the “hot tail” is seen to diminish and is weakly visible at 30 MHz and almost negligible at 50 MHz, indicating that as compared to 20 MHz the heating effect of the high energy electrons diminish at these high frequencies.

FIG. 6. (Color online) (a) EEDF along the y and z directions at an excitation frequency of (a) 10 MHz and (b) 20 MHz, for measurements at the center ($x=0.05$ m) of the plasma. Note the occurrence of the “hot tail” at 20 MHz.

IV. DISCUSSION

As seen from the PIC simulations above the EEDFs become convex (Druyvesteyn-like) at frequencies ≤ 5 MHz. This may be explained using analytical expression for the effective heating field. The transition frequency closely matches with the operating electron neutral collision frequency $\nu_{en} \sim 3$ MHz at 1 mTorr pressure and considering an electron temperature of ~ 5 eV. It therefore seems reasonable to investigate the effect of ν_{en} on the nature of the obtained EEDFs. As ν_{en} or f change relative to each other, the manner in which the electrons are heated would change, which can lead to modification in the shape of the EEDF. The effective heating field as a function of the frequencies can be written as,^{19,20}

$$E_{eff} = \frac{E_o}{\sqrt{1 + \frac{\omega^2}{\nu_{en}^2}}}, \quad (1)$$

where E_o is the amplitude $E = E_o \sin \omega t$. The asymptotic values under very low ($\nu_{en} \ll \omega$) and high ($\nu_{en} \gg \omega$) pressure regimes are $E_{eff} \approx E_o(\nu_{en}/\omega)$ and $E_{eff} \approx E_o$, respectively. Thus, electron heating can get modified due the effect of both f and ν_{en} . At $\omega = \nu_{en}$, we obtain $E_{eff} \approx E_o/\sqrt{2}$. Thus, at high frequencies ($\omega \gg \nu_{en}$) electrons are able to gain energy more efficiently because of the electron-neutral collisions which helps to randomize the directions of the scattered electrons. For the same E_o , the heating efficiency is decided by a square of the ratio of (ω/ν_{en}) , thus in comparison to phenomena for $f \leq 5$ MHz, for a higher frequency of 30 MHz one would expect complementary phenomena

FIG. 7. (Color online) EEDF along the y and z directions at an excitation frequency of (a) 30 MHz and (b) 50 MHz, for measurements at the center ($x=0.05$ m) of the plasma.

FIG. 8. (Color online) (a) Normalized effective electric field (E_{eff}/E_0) versus collision frequency ν_{en} for a set of excitation frequency. (b) EEDF along the y direction at the center ($x=0.05$ m) of the discharge for heating frequency of 30 MHz and collision frequency ν_{en} corresponding to a gas pressure of 5 mTorr and 10 mTorr.

(similar distribution functions) at a higher pressure which is 10 mTorr. This is demonstrated in Fig. 8(a) where the normalized effective electric field (E_{eff}/E_0) is plotted as a function of ν_{en} for various values of f . The vertical dotted lines indicate ν_{en} at 3 MHz and 30 MHz. Considering the collision frequency $\nu_{en}=3$ MHz which is the experimental collision frequency (first vertical dotted line), it can be seen that as the excitation frequency f is increased beyond 3 MHz (e.g., at 10 and 30 MHz) the normalized effective electric field for a set of collision frequency (and over the whole collision frequency range) increases with f but once again reduces at $f=50$ MHz. Similarly, the result imply that if we are to operate at a higher f of 30 MHz, the normalized E_{eff} would be comparable to its value at $f=3$ MHz (for $\nu_{en}=3$ MHz) when operated at $\nu_{en}=30$ MHz (which is $p \sim 10$ mTorr). To appreciate the phenomena the PIC simulations are performed at 30 MHz and at these high pressures (5 mTorr and 10 mTorr). Figure 8(b) shows the plot of the effect of ν_{en} ($p=5$ mTorr and 10 mTorr) on the EEDFs at an excitation frequency of 30 MHz. From the nature of the EEDFs in the y direction we do see a convex type profile at 5 and 10 mTorr similar to those obtained at $f \leq 5$ MHz and at 1 mTorr. It is clear that in order to observe Druyvesteyn-type of distributions at 30 MHz, the operating pressure needs to be increased to ~ 10 mTorr ($\nu_{en}=30$ MHz).

In order to get an insight into the mechanism of the “hot tail” observed at 20 MHz, we calculated the mean energy $\langle E_i \rangle$ gained by an electron as it transits through one end of the heating region of length L to the other, as a function of the excitation frequency of the rf field. By “hot tail” we mean energetic electrons in the tail region of the distribution function. This is quantified by $\langle E_i \rangle$ and is looked at as a function of the excitation frequency of the rf field. The equation of motion of an electron subjected to a localized field of angular frequency ω and amplitude E_0 is

$$\frac{dv_y}{dt} = \frac{qE_0 \sin \omega t}{m}, \quad (2)$$

where, q and m are the charge and mass of the electron and v_y is the y component of the electron velocity at time t . The instantaneous velocity of the electron as it transits through the heating region in time τ_i is given by

$$v_y = \frac{qE_0}{m\omega} [1 - \cos \omega \tau_i]. \quad (3)$$

The mean energy of the particle during the transit time τ_i is given by

$$\langle E_i \rangle = \left(\frac{mv_E^2}{2} \right) \frac{1}{\tau_i} \int_0^{\tau_i} [1 - \cos(\omega t)]^2 dt, \quad (4)$$

where the transit time $\tau_i = L/v_x$ and $v_E = qE_0/m\omega$. At 1 mTorr the transit time is much smaller than the mean collision time. Upon simplification we obtain the normalized heating as

FIG. 9. (Color online) (a) Mean electron energy $\langle E_i \rangle$ gained by the electrons during the transit time τ_i through the antenna heating field region for different excitation frequencies. (b) The mean electron energy $\langle E_i \rangle$ plotted as a function of excitation frequency for electrons with energy of 25 eV.

$$\frac{\langle E_i \rangle}{(mv_E^2/2)} = \frac{3}{2} - \frac{2 \sin \omega \tau_i}{\omega \tau_i} + \frac{\sin 2\omega \tau_i}{4\omega \tau_i}. \quad (5)$$

$\langle E_i \rangle$ given by Eq. (5) is plotted as a function of electron energy in Fig. 9(a). It is noted that depending upon the energy of the electron there is an optimum frequency where the mean energy gained $\langle E_i \rangle$ during its transit time is a maximum. This point is further clarified in Fig. 9(b) where $\langle E_i \rangle$ is plotted as a function of excitation frequency for electrons with energy of 25 eV to clearly demonstrate this effect. Furthermore, it can be noted that at a frequency of 20 MHz, the mean energy gained by the high energy electrons with energies >30 eV are a factor of 10 higher as compared to those at 5 MHz.

V. SUMMARY AND CONCLUSION

In conclusion, an investigation on the effect of the excitation frequency on EEDFs in a low pressure radio frequency bounded plasma was carried out using PIC simulations that is one dimension (1D) in space (x) and three dimensional (3D) in velocities (x , y , and z). The EEDFs have been found out for electrons with velocities (energies) in all the three directions x , y , and z with the excitation frequency varied in the range 0.01–50 MHz. Introduction of the heating field in two perpendicular directions (y and z) result in symmetric EEDFs in both the directions. Results have indicated that at frequencies ≤ 5 MHz the EEDFs in the y and z directions have a convex (Druyvesteyn-like) shape with an exponent of energy, $r = 1.98$ which is close to $r = 2$ for a true Druyvesteyn distribution. However the depletion of the population at very low electron energies ≤ 5 eV does not seem to match with the predictions of a Druyvesteyn distribution. As the frequency is further increased, for $f \geq 10$ MHz the distributions tend to become Maxwellian. For the x directed profiles, almost all the EEDFs have the familiar “two Maxwellian and a step”. The temperature of the Maxwellian tail being lower (e.g., Fig. 3(b), 6 eV and 4 eV for 20 MHz). The EEDFs have been measured at three principal spatial locations in the discharge: at $x = 0.05$ m (center), $x = 0.012$ m (plasma edge near start of sheath), and $x = 0.002$ m (inside the sheath). In regions closer to and in the sheath the populations of the low energy electrons are depleted, which may be understood because low energy electrons do not have enough energy to overcome the potential of the sheath. For the x directed EEDFs the break energy E_b is more distinct and closely follows the plasma space potential V_p , since the electron dynamics for the escaping and trapped electrons is dictated by the boundaries which ultimately sets up V_p . In the y and z directions where there are no boundaries, E_b is not as distinctly visible. However it seems to follow the plasma excitation threshold at $f \leq 0.5$ MHz and the ionization threshold for $f \geq 1$ MHz. At $f = 20$ MHz, a “hot tail” in the EEDF was seen to develop, which seemed to diminish as the frequency was further increased. To understand the convex profiles of

the EEDFs and to see how it is affected by the electron neutral collision frequency ν_{en} , the effective heating field was calculated as a function of ν_{en} and ω . The threshold below which the Druyvesteyn type of EEDF appears seem to happen at $\omega = 2\pi\nu_{en}$. The prediction has been validated with PIC simulations which resulted in convex (Druyvesteyn type) EEDFs at 30 MHz when the pressure was raised to 10 mTorr. The result agrees well with the work of Godyak and Piejak² at 13.56 MHz, where the EEDFs were found to resemble Druyvesteyn type distribution when the pressure was raised from 0.03 Torr to 0.3 Torr. The heating of high energy electrons and the generation of a “hot tail” is explained on the basis of transit time heating of electrons as they pass through the heating region of length L (0.01 m). It is interesting to note that there exists an optimum frequency for which high energy electrons >20 eV can be preferentially heated to give rise to a “hot tail” as observed in the PIC simulations.

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