Modulated plasma potentials and cross field diffusion in a Helicon plasma

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As the input rf power to a helicon plasma is increased there is a discontinuous increase in the density which is identified with a change from a capacitive to an inductive/wave coupling to the plasma. The radial distribution of the density is much narrower in the inductive (high) mode than in the capacitive (low) mode. Although the time average plasma potential \( V_p \) decreases markedly at this mode change, the radial profile of \( V_p \) is flat in both modes. Measurements with an emissive probe show that in the capacitive mode \( V_p \) is strongly modulated (\( \Delta V \) is order of \( V_p \)) at the rf drive frequency indicating the presence of large rf fields in the source. There is also a large radial gradient in the amplitude of this modulation. In the inductive mode the modulation decreases significantly but can still be observed in measurements of the ion energy distribution. It is suggested that in the capacitive mode, the radial diffusion of electrons is driven by the large gradients in the rf fields. As the density increases, the fields are screened out, diminishing the radial electron loss and consequently, the radial ion loss. The reduced radial diffusion of both charged species produces a still higher density as the major loss surface is now reduced to the ends only. © 2002 American Institute of Physics. [DOI: 10.1063/1.1483845]

I. INTRODUCTION

It has been known for some time that cylindrical magnetoplasmas excited with a Helicon antenna exhibit dramatic transitions and discontinuous changes in the plasma parameters when any of the external parameters such as rf power, applied magnetic field, and gas pressure are varied. In particular as the power is increased a point is reached at which the density suddenly increases and the plasma potential decreases. Similar density jumps are observed at constant power when the magnetic field is increased. The jump appears to be related to the capacitive to inductive transition or the dispersion characteristics of the Helicon wave in the plasma and normally has quite an amount of hysteresis. The position of the jump scales with the ratio of the applied axial confining magnetic field \( B \) to the local plasma density, which suggests that a wavelength dependent phenomenon plays a major role.

In the experiments described here, the magnetic field is held at a constant 60 G and is approximately uniform along the axis of the plasma processing reactor. At low power the system is characterized by low densities, high electron temperatures, and high plasma potentials, which are strongly modulated at the rf frequency. These properties suggest that the coupling between the Helicon antenna and the plasma is capacitive in nature. Above the transition, the plasma potential and temperature decrease while the plasma density increases significantly. In this high density mode (where helicon reactors are typically operated) the level of rf modulation is much lower, probably as a result of the decreased skin depth. This is typical of high density inductively coupled plasmas. However, modulation of the ion energy distribution function (IEDF) is still observed with a retarding field energy analyzer (RFEA) in narrow regions where the antenna is directly connected to the observation point by the magnetic field lines.

Rather curiously, the average plasma potential is approximately constant as a function of radius in the diffusion chamber for both the low and high plasma density modes even though the plasma density changes by over an order of magnitude. It is the floating potential which varies and, with a radially decreasing electron temperature in the diffusion chamber, leads to a rather high wall charge.

The very high radial rf fields in the low mode, which can be as large as 500 V m\(^{-1}\), could drive a large cross field diffusion of the electrons thereby contributing significantly to the abruptness of the mode change from capacitive to inductive/wave coupling.

II. EXPERIMENT

The Helicon process reactor used in these experiments is shown schematically in Fig. 1. The plasma source is a 15 cm diam quartz tube, 25 cm long with a 400 \( \text{l s}^{-1} \) turbomolecular pump mounted on the top. The effective pumping speed, however, is closer to 200 \( \text{l s}^{-1} \). A 16 cm long double loop \((m=1)\) Helicon antenna is wrapped around the center section of the source tube and is fed by a 3 kW, 13.56 MHz rf generator via an L-type matching network. Directly above and below the antenna feeds are two solenoid coils connected in series generating approximately 80 G on axis. The lower end of the source opens to a 30 cm diam, 30 cm long
aluminum diffusion chamber which contains the water and helium gas cooled 10 cm diam wafer chuck. Around the midplane of the diffusion chamber, some 15 cm below the exit of the source chamber, are a series of radial ports which allow diagnostic access to the plasma. Above and below the diagnostic ports are two more solenoid coils wound directly onto the chamber circumference. To minimize the possible complications arising from the plasma expanding out of the source, the solenoid currents are adjusted to give a magnetic field configuration with approximately parallel field lines, in essence mapping the source directly into the chamber where the field strength is between 60–70 G on axis.

All the experiments described here are performed with argon gas at a pressure of 2.5 mTorr. It is important to note that these measurements are made in a Helicon system regularly used for plasma processing (SiO₂ etching) and prolonged operation with CHF₃ plasmas have resulted in the metal walls, including the top and bottom surfaces, of the diffusion chamber being coated with layers of insulating polymer. To provide a stable ground reference for the plasma measurements the substrate—silicon wafer—is replaced with a grounded stainless steel plate (see Fig. 1). To maintain this good reference the ground plate requires regular cleaning to remove contamination from sputtering.

Four different diagnostic techniques are used to measure the plasma parameters, principally the plasma potential: (i) single Langmuir probes, (ii) an emissive probe, (iii) an energy selective mass spectroscopy (Hiden HAL, EQP Plasma Probe), and (iv) a RFEA for the ions. All the diagnostics are attached to the same radial port in the diffusion chamber wall to allow direct comparison of results. The Langmuir probes, the emissive probe and the RFEA could be moved across the diameter of the chamber to give the radial profiles of all the main plasma parameters.

Two types of Langmuir probes are employed: a small (area 0.083 cm²) cylindrical tip tungsten probe to measure the floating potential, Vᵣ, and (using a computer controlled probe sweeping circuit and data acquisition system) the plasma potential Vₚ, and secondly, a single-sided tantalum disk probe (3 mm diam) to estimate the perpendicular and parallel electron temperatures. The disk probe is also used to measure the radial distribution of the ion saturation current density.

The emissive probe has a 5 mm long, 25 μm diam thoriated tungsten filament. The probe is operated in two modes. The first is the dc, or strong emission mode where the filament current is supplied by a battery and the probe voltage relative to earth measured using a high impedance voltmeter. For each plasma operating condition the emission current is increased until the probe voltage saturates. This voltage is then interpreted as the average plasma potential, although, as discussed below, there are problems in interpretation when using this method with rf plasmas. The second mode is the low emission swept probe technique which is used to estimate the rf modulation on the plasma potential. The emissive probe is biased with a standard probe sweeping circuit and the measured current differentiated using either an analog differentiator or numerically on a computer via the data

FIG. 1. Schematic of the Helicon plasma etching reactor showing the source, diffusion, and load-lock chambers, together with diagnostic locations. The solid lines show the magnetic field lines for a typical operating configuration.
acquisition system. The voltage at which the two peaks occur in the differentiated signal indicate the lower and upper limits of the modulation of the plasma potential.

The Hiden mass spectrometer is installed with its entrance aperture (100 μm diam) close to (within a few mm) the inner wall of the diffusion chamber. Hence these measurements represent the energy of ions falling through the sheath to the chamber walls. At a pressure of 2.5 mTorr the mean free path for both charge exchange and elastic collisions of Ar⁺ on Ar is between 2 and 3 cm so we can interpret the Hiden energy spectra as a measurement of the local plasma potential (relative to earth or 0 V).

The RFEA is a probe mounted water-cooled, four grid, compact energy analyzer. It is described in detail in Ref. 5. Both the IEDF and the electron energy distribution function (EEDF) can be measured. From the peak(s) in the IEDF the plasma potential can be extracted, and from the exponential high energy tail of the EEDF the electron temperature can be obtained.

III. RESULTS

A. Mode transition

The ion saturation current density, measured with a Langmuir probe in the center of the diffusion chamber, Fig. 2(a), clearly shows a discontinuous jump at an input rf power of about 60 W. The jump appears at quite a low power because of the low magnetic field and gas pressure (2.5 mTorr). Experimentally, we observe that the rf power at which the jump occurs (for a constant magnetic field) usually scales with the pressure \( P \) as approximately \( P^{-0.3} \). Further discussions on the mode transitions have been presented by a number of authors but for our laboratory experiments, we commonly see a transition from capacitive to inductive to wave sustained discharges as the power is increased. At low values of the axial magnetic field (<30 G), the transition generally proceeds directly from capacitive to wave sustained because a 1/2 wavelength Helicon wave can fit into the source axial dimension. This occurs because the Helicon wavelength is proportional to the square root of the axial magnetic field divided by the plasma density and hence, if the axial magnetic field is decreased the density can decrease for the same wavelength. Accompanying the density jump is a sudden decrease in the plasma potential at the chamber axis (measured with the emissive probe in strong emission). Figure 2(b) shows \( V_p \) (solid circles) and \( V_f \) (open squares) measured with the probe in dc strong emission as a function of the rf power with the same plasma conditions. Above 60 W the apparent plasma potential drops from 50 V to <20 V. There is also a change in the floating potential, but this is less dramatic and it remains close to 0 V in the center as the magnetic field line is connected to the earthed stainless steel plate in the chuck. The prejump condition is termed the low density mode, and the post jump condition the high density mode.

![Fig. 2. Variation in (a) the ion saturation current density \( j_i \) and (b) the plasma \( V_p \) (solid circles) and floating potentials \( V_f \) (open squares) measured with a dc emissive probe on the diffusion chamber axis as a function of source rf input power (argon gas, 2.5 mTorr).](image)

B. Potential

The radial profiles of \( V_p \) (solid circles) and \( V_f \) (open circles) measured using the emissive probe (dc strong emission) are shown in Fig. 3 for (a) the high density mode, and (b) the low density mode. In both cases \( V_f \) is a minimum in the center, near 0 V (the potential of the earthed substrate) and rises to a positive value near the walls. Since \( V_f \) is defined as the voltage necessary for ensuring an equal flux of positive and negative species to the probe, and likewise to any insulated surface, these measurements imply that the walls are charged up positively.

In the high density mode plasma \( V_p \) is approximately constant across the plasma radius (with a possible minimum in the center), and the values obtained with the emissive probe, a cylindrical Langmuir probe and the Hiden energy analyzer (which is located at the wall) all agree within ±5%.

In the low density mode \( V_p \) appears to be a maximum in the center and decreases towards the wall. Also the \( V_p \) measured with the emissive probe (dc strong emission) is much higher than from other diagnostics. However, using the emissive probe in the swept voltage mode and determining the potential from the inflection points in the current–voltage
curve\textsuperscript{a} gives the radial profile shown in Fig. 4 for the low density mode. The vertical bars mark the upper and lower limits of the inflection points and so give the degree of modulation in the plasma potential. Time resolved measurements show that the modulation is at a frequency of 13.56 MHz.

From Fig. 5(a) the average plasma potential, measured with the swept emissive probe, for both the low density (38 W) (solid circles) and high density (400 W) (open squares) modes can be seen to be fairly constant across the radius. This is because, in strong emissions, the potential of the emissive probe will float at the maximum value of the plasma potential if it is modulated. Hence great care needs to be taken in interpreting the results of emissive probe measurements and the results presented in Fig. 3(b) are really the maximum value of the rf excursions in the plasma potential and not the average value as we initially assumed.

The flat radial profile for the average $V_p$ for both the low and high density modes is also confirmed by the peak positions in the ion energy distributions obtained with the RFEA. These are plotted in Fig. 5(b) for the low (solid circles) and the high density (open squares) mode plasmas, and show

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**FIG. 3.** Radial profiles of the plasma $V_p$ (solid circles) and floating potentials $V_f$ (open circles) measured with the dc emissive probe for (a) the high density mode (100 W of rf power) and (b) the low density mode (38 W).

**FIG. 4.** The radial distribution of the rf modulation in the low density (38 W) mode measured with the swept emissive probe. The vertical bars mark the extremes of the inflection points in the IV curve.

**FIG. 5.** Radial profiles of the average $V_p$ measured from (a) the swept emissive probe and (b) the ion energy distribution with the RFEA in the low density mode (38 W) (solid circles) and the high density mode (100 W) (open squares).
good agreement with the swept emissive probe results in Fig. 5(a).

C. Temperature

In both the low and high density modes of operation, the difference between the plasma and floating potentials [Fig. 5(a)] imply that the electron temperature is higher in the center of the plasma and much cooler beyond a radius of about 60 mm. The 60 mm radius marks approximately the boundary position (separatrix) between where the magnetic field lines either intersect the top and bottom surfaces of the diffusion chamber, or enter the source. Since the magnetic field basically maps the source diameter into the same diameter in the diffusion chamber, electrons heated in the source can only reach the outer plasma regions by diffusing across the magnetic field lines. As the axial magnetic field in the reactor is constant in all cases, electrons with average energy of 3 eV have a gyroradius of about 0.8 mm while the thermal ion gyroradius will be of the order of 3 cm. Hence the classical cross field diffusion of the electrons is low and important radial electron temperature gradients can be maintained.

Figure 6 shows the radial profiles of the parallel (open squares) and perpendicular (solid circles) electron temperatures measured with a disk probe. For radii >7 cm the orthogonal temperatures are equal, but they diverge significantly from each other in the plasma center. Inside the separatrix \( T_e \) is hotter and anisotropic, which suggests that the electrons are energized parallel to the magnetic field. In addition, the parallel temperature maximum occurs at a radius around 4 cm where we would expect the maximum of the \( E_z \) for the \( m = 1 \) Helicon wave.

Also plotted in Fig. 6 as a solid line is \( (V_p - V_f)/3.9 \), where the potentials are taken from the emissive probe for the high mode [Fig. 3(b)]. The value of the denominator is chosen to be 3.9 to fit the electron temperature data obtained with the disk probe. Traditionally this factor is taken as about 5 for an unmagnetized plasma, however, for magnetized plasmas there is no reliable theoretical model for describing the current collection by the probe and we normally measure factors of around 4 in this reactor. The good qualitative agreement between the disk probe and the emissive probe data imply that the electron distribution is close to Maxwellian over most of the plasma radius in the diffusion chamber. This is also confirmed in the high mode with EEDF measurements from the RFEA which show experimental tails over 1.5–2 decades. We are therefore reasonably confident that \( V_f \) is a true measure of the local current equality condition. The radial profile of \( V_f \) has a minimum at a radius of about 3 cm [Fig. 3(a)] which also suggests that, in addition to the bulk Maxwellian electrons, there may be a hot tail in the electron distribution. Measurements made in a large helicon system\(^6\) have shown bursts of hot electrons associated with axial helicon wave fields, so it is possible that one of the heating mechanisms for the electrons in this processing reactor may also involve wave–particle interactions with a helicon.

D. Density

Radial profiles of the ion saturation current density measured with the disk probe are shown in Fig. 7 for three rf input power levels. The maximum central densities have been normalized to make comparison of the different cases easier. The current density on axis was 0.46, 14, and 50 mA cm\(^{-2}\) at 60, 400, and 1200 W, respectively. In the low density mode the density distribution is broad having a full width half maximum (FWHM) of about 230 mm. In the high density mode, the shape of the distribution is insensitive to the input power and has a considerably smaller FWHM of 140 mm—the same as the inside diameter of the source. To convert these data to ion density, the radial distribution of the electron temperature has to be taken into account, but unfortunately this cannot be measured reliably in the low density mode. However, an estimate of the electron temperature based on the difference between \( V_p \) and \( V_f \) in the low density mode shows that the effect would be to make the density distribution even broader relative to that of the high density mode.

![FIG. 6. Radial profiles of the parallel (open squares) and perpendicular (solid circles) electron temperatures measured with a disk probe. The solid line shows \( T_e \) deduced from emissive probe measurements of \( V_p \) and \( V_f \).](image1)

![FIG. 7. Normalized radial profiles of the ion saturation current density \( J_i \) for three different source rf powers measured with the disk probe showing the changes in the radial distribution between the low mode (38 W) and the high mode (400 W and 1200 W).](image2)
E. Modulation

Evidence of large rf fields in the plasma are seen in both the swept emissive probe and RF data. Figure 8 shows the variation in the modulation of the plasma potential $\Delta V$ measured with the swept emissive probe at the chamber axis as a function of input rf power. The open squares are the minimum voltages and the solid circles are the maximum voltages. Below the mode transition, temporal potential variations of up to 50 V peak to peak are measured (Fig. 4). Above the transition, the modulation decreases by an order of magnitude. This is most probably due to shielding by the skin effect. For low density mode plasmas, the collisionless skin depth (assuming electrons free to move along field lines) is about 3 cm, whereas in high density mode it decreases to around 1 cm. The skin depth across the field is increased as the electron mobility is decreased but this is a tricky problem to solve quantitatively with our parameters and we leave this for more theoretically oriented physicists.

This reduction in the penetration of the rf field between modes is more clearly seen in the radial dependence of the plasma potential modulation. In the low density mode, Fig. 4 shows the rf modulation has a maximum in the center and decays with increasing radius to the separatrix (defined as the last magnetic field line to enter the source) at 7 cm, where its slope decreases somewhat. Just above the mode transition the radial structure changes completely, the overall amplitude of the modulation decreases and a minimum forms close to the plasma center, flanked by two strong asymmetric peaks just inside the separatrix. The position of the peaks correspond with the peak in electron temperature observed with the disk probe (Fig. 6) and adds further weight to the premise that we are coupling to a helicon wave.

IV. DISCUSSION

We begin the discussion by considering the simple case of a magnetized plasma surrounded by a vessel with conducting boundaries. It is well known in this case that radial electric fields can accelerate ions to the walls while the electrons escape axially along the field lines. A self-consistent field structure is formed so that the radial current of ions to the walls is balanced by the axial current of the electrons to the ends. The circuit being closed externally by the conducting boundaries. In the experiment described here however, the only conducting surface is the earthed stainless steel plate in the substrate holder (which is seen to pull the floating potential in the plasma center down toward ground). All the other surfaces of the reactor, including the bottom and top plates of the chamber and the source tube walls are insulating, and, in the steady state the local ion and electron currents must balance at each point on these surfaces. In both the low and high density mode plasmas, the radial electron loss is heavily constrained by the imposed axial magnetic field. Consequently, the radial electric field must be such as to produce an ion flux to balance the low (compared to the magnetic field free case) radial diffusion of the electrons; i.e., if the electrons were confined by a very strong magnetic field in a long cylinder of plasma, then a radial field would have to exist to contain the ions.

The radial variation of $V_p$ shown in Fig. 5 is virtually flat implying the ion loss is due to thermal ions diffusing classically and that there is not a Boltzmann relation between the electron density and the potential. There is also a suggestion that the radial potential has a negative slope which would serve to confine the ions electrostatically, a situation similar to the reflex arc. While the data shows that the plasma potential remains constant across the plasma, the floating potential increases with radius. Parallel to the field, the electrons are free to move so the normal relationship between $(V_p-V_f)$ and the electron temperature must hold, and since the radial electron temperature falls rapidly beyond the separatrix, the value of $V_f$ must increase as the walls of the chamber are approached. The only way that this can occur is if the insulated end surfaces of the diffusion chamber charge up allowing $V_f$ to rise, which in our case is possible since the walls are insulating and so can support a floating potential that is significantly different from ground potential. This hypothesis was further tested by replacing the conducting plate in the substrate holder with an insulator. In this case the whole potential structure, both the floating and plasma potentials, in the plasma dropped by some 10 V but retained its shape, showing that the wall potential (reflected in $V_f$) varies to maintain the difference of about $4kT_e$ between $V_f$ and $V_p$.

Since the radial diffusion is controlled by the axial magnetic field and the radial electric fields, the difference in the radial density distribution between the two coupling modes probably results from a change in the shape of the radial rf electric fields. Although the average $V_p$ has little radial variation in either mode, measurements of the modulation in the plasma potential show large variations both as a function of the input rf power and as a function of radius.

Regarding the transition between the low and high density modes, the observations support the suggestion that there is a change in rf field penetration between the two modes.

The data indicates that in the low density mode the coupling between the antenna and the plasma is capacitive, and that excitation occurs as a result of the penetration through-
out the source of the electrostatic fields established by the antenna. In the high density mode the increased plasma density should confine the near field effects of the antenna to source regions close to the antenna conductors. However, the coupling is in fact strongest close to the axis of the source suggesting that at least some of the input rf energy, even at quite low powers, is being coupled to the plasma via an $m = 1$ helicon wave. In both cases the radial diffusion of the electrons is impeded by the axial magnetic field and the ions can only diffuse radially at the velocity determined by their thermal collision rate.

V. CONCLUSION

The high density mode in typical Helicon processing reactors is characterized by a very small and possibly negative radial electric field. This results in a low cross field diffusion which appears to be the result of the requirement that the ion and electron fluxes to the walls of the different chamber balance for the insulating boundaries.

In the low density mode, the coupling between the antenna and the plasma is poor but is relatively evenly distributed throughout the source as a result of the large skin depth. Measurements in the diffusion chamber show rf modulation if the plasma potential has a maximum in the center where it has the same magnitude as the average plasma potential. It is possible that an anomalously high cross-field diffusion of the electron, related to the large radial rf fields contributes to the broad, low density profile observed at low rf powers.