

Response of the plasma to the size of an anode electrode biased near the plasma potential

E. V. Barnat,¹ G. R. Laity,¹ and S. D. Baalrud²

¹Sandia National Laboratories, Albuquerque, New Mexico 87185, USA ²Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242, USA

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As the size of a positively biased electrode increases, the nature of the interface formed between the electrode and the host plasma undergoes a transition from an electron-rich structure (electron sheath) to an intermediate structure containing both ion and electron rich regions (double layer) and ultimately forms an electron-depleted structure (ion sheath). In this study, measurements are performed to further test how the size of an electron-collecting electrode impacts the plasma discharge the electrode is immersed in. This is accomplished using a segmented disk electrode in which individual segments are individually biased to change the effective surface area of the anode. Measurements of bulk plasma parameters such as the collected current density, plasma potential, electron density, electron temperature and optical emission are made as both the size and the bias placed on the electrode are varied. Abrupt transitions in the plasma parameters resulting from changing the electrode surface area are identified in both argon and helium discharges and are compared to the interface transitions predicted by global current balance [S. D. Baalrud, N. Hershkowitz, and B. Longmier, Phys. Plasmas 14, 042109 (2007)]. While the size-dependent transitions in argon agree, the size-dependent transitions observed in helium systematically occur at lower electrode sizes than those nominally derived from prediction. The discrepancy in helium is anticipated to be caused by the finite size of the interface that increases the effective area offered to the plasma for electron loss to the electrode. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4897927]

I. INTRODUCTION

The near boundary region of a plasma plays a critical role in balancing the injection of charged particles into and out of the plasma and is ultimately responsible for maintaining its quasi-neutral steady-state.^{1,2} Although both ion-rich sheaths (cathodic interface) and electron-rich sheaths (anodic interface) are possible, ion-rich sheaths are far more commonly encountered both in the lab and in nature. The prevalence of ion-rich sheaths stems from the intrinsic asymmetric mobilities of the light electrons to the much heavier ions, where the velocity of the electrons are usually much greater than that of the ions $((m_e/M_i)^{1/2} \ll 1)$.³ To maintain quasineutrality of the plasma, a potential barrier between the boundary and the plasma is established to limit or confine the highly mobile electrons and to drain the ions. As a result, an ion-rich sheath is formed between the wall and the plasma. When the wall is brought to potentials considerably below that of the plasma potential, further suppression of electrons from transiting the boundary is realized. While application of higher (more negative) potentials on the wall may lead to secondary effects such as augmented ionization of the surrounding plasma by energetic electrons liberated from the wall^{4–7} or the formation of virtual cathode in front of the electrode,^{8,9} an ion-rich sheath is almost always anticipated to form at this interface.

Electron sheaths are commonly found near small objects biased more positive than the plasma potential, such as Langmuir probes in the electron saturation region. Typically, such probes are small enough that they do not significantly perturb the bulk plasma. However, if the probe surface area is increased it eventually becomes a substantial perturbation, and can significantly influence global plasma properties. As first postulated by Langmuir¹⁰ the resulting polarity of the plasma with respect to the positive electrode and the distribution of space charge around the grounded wall is intimately correlated with the ratio of the surface area of the two boundaries. Scaling relationships between the area of the electron-collecting (auxiliary) anode electrode (A_E) and the area of the ion-collecting chamber wall (A_W) have been derived from invoking global current balance of the ions and electrons flowing from the plasma.^{11,12} The derived scaling indicated three cases for the distribution of space-charge around the anodic electrode depending on the ratio of A_E/A_W and the ion-electron mass ratio (m_i/m_e) . An ion-rich sheath is anticipated when the anodic electrode is sufficiently large that the ion current to the walls could not alone balance the unimpeded electron current to the anode. This is predicted to occur when $A_E/A_W > 1.7\mu$, where $\mu = (2.3 m_e/m_i)^{1/2}$. Here, the plasma must be more positive then the electrode and the established potential barrier between the electrode and the plasma limits a fraction of the incoming electron flux from being collected by the electrode. Should the anode electrode be sufficiently small, an electron-rich sheath is generated and the plasma potential remains less positive than that of the anode because the electron flux collected by the anode is not sufficient to disrupt the required global balance. The maximum area ratio for this to be possible is predicted to be $A_E/A_W < \mu$. A double sheath is anticipated to form for area ratios between the ion and electron sheath solutions, which consists of both an ion-rich and an electron-rich region. The resulting double layer structure maintains quasi-neutrality of the plasma and establishes a non-ambipolar flow where the entire ion current is collected by A_W and the entire electron current is collected by A_E .

In this study, experiments are described that test the scaling relations outlined in the introduction by investigating how the size of the anode impacts the host plasma it is immersed in. A segmented disk electrode in which individual segments are individually biased to change the effective surface area of the anode is used to examine the impact that the size of the electron collecting electrode has on the host plasma. Trends in the plasma parameters such as the collected current density, plasma potential, electron density, electron temperature and optical emission are identified as both the size and the bias placed on the electrode are varied. Size-dependent transitions in these parameters are identified and are compared with predicted transitions described above. While these measurements do not provide direct evidence of the structure of the interface that forms between the anode and the host plasma, they serve as a means of identifying how changes in the size of the electron-collecting electrode impacts the host plasma it is immersed in. These changes are discussed in terms of the anticipated interface that is predicted by theory. The paper is outlined as follows. In Sec. II, the experimental setup and the procedures to acquire and analyze data are described while in Sec. III, modifications to the initial two electrode theory are described that take into account changes due to a third electrode utilized in the experiments. Key experimental findings are presented in Sec. IV and a discussion of the observations is offered in Sec. V. Concluding remarks are given in Sec. VI.

II. SETUP

To test the impact of the size of the electron collecting electrode on the host plasma, experiments were performed using a segmented electrode assembly depicted in Figure 1(a). The segmented electrode assembly consists of an array of 20 concentric rings 3.18 mm (1/8 in.) wide and separated by 0.1 mm gaps that are fabricated onto a printed circuit board. Electrical connections are made to each of the rings through metalized vias that are routed to contact pads fabricated onto the back side of the circuit board. The back-side electrical connections are shielded from the host plasma and do not contribute to the collection of current. Wires are then run from the pads to one of two 9-pin vacuum feedthroughs. Because only 18 individual electrical connections could be made, two sets of rings are tied together. A pair of 9conductor cables connects the vacuum feedthrough to a break-out box that is used to connect individual rings to the voltage source. A 75 Ω current limiting resistor limits current flow. The total current collecting electrode area spans 32 mm^2 to $1.26 \times 10^4 \text{ mm}^2$.

Measurements are performed in a modified GEC reference cell in which both the upper and lower rf electrode assemblies are removed. A grounded plate with a 115 mm (4.5 in.) diameter hole bored into it containing the segmented electrode assembly is inserted into the lower portion of the reference cell. While the reference cell is nominally a cylindrical chamber 228 mm (9 in.) in diameter and 180 mm (7 in.) in height with multiple side ports, the spacing between lower ground plane and the upper ground plane is $\sim 127 \text{ mm}$ (5 in.). Furthermore, a fine wire copper mesh (0.5 mm opening) is wrapped around the inside of the reference cell to contain the plasma to a well-defined cylindrical region. Holes in front of the 70 mm (2 $\frac{3}{4}$ in.) ports are inserted in the copper mesh to facilitate diagnostics of the plasma discharge. The voids around the probes are filled with ceramic plugs to limit plasma contact in the ports. The total area of grounded surface the plasma contacts is $1.86 \times 10^5 \text{ mm}^2 \pm$ $6000 \,\mathrm{mm}^2$.



FIG. 1. (a) Top-down view of segmented electrode assembly and (b) cross-sectional view of the hollow cathode assembly placed in the modified GEC reference cell. Location of the probes and the imaging configuration are also depicted.

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The upper portion of the reference cell consists of a hollow cathode assembly that housed an electron emitting thoriated tungsten filament that is used for plasma generation. The filament is biased to -65 V below ground and the current emitted from the filament is kept constant at 100 mA. The cylindrical cathode has a 180 mm (7 in.) diameter and is 165 mm (6.5 in.) long and with a total area of 1.5×10^{5} mm². The hollow cathode assembly is connected to ground via a $100 \,\mathrm{k}\Omega$ resistor causing the cathode to acquire a negative potential of 45 V below the plasma potential. A 75 mm diameter (3 in.) hole placed at the bottom of the cathode assembly to allow plasma to flow into the grounded chamber. The cathode is separated from the grounded chamber by a 3 mm gap. The total area of the cathode assembly is 1.59×10^5 mm² ± 5000 mm². Helium and argon gases are fed into the chamber through a feed through placed in the hollow cathode. Gas pressure is regulated over a range of 1-25 mTorr.

The local plasma potential and the electron temperature are ascertained with an electron emitting emissive probe using the floating point method.¹³ The emissive probe consisted of a 0.25 mm diameter thoriated tungsten filament loop 10 mm long and is housed in a 6.35 mm (0.25 in.) double bore alumina tube. Thin wall copper tubes are inserted into each of the bores and ran down the length of the ceramic. Conducting elements of the probe assembly other than the emissive filament are shielded from the plasma. The floating potential is recorded by a high impedance electrometer as a function of current passed through emissive filament, while changes in the floating potential are utilized to determine when the probe became emissive. Typical response of the emissive probe as a function of current is plotted in Figure 2(a). For the measurements on how the bulk plasma properties scale with anode size and bias, emissive probe measurements are made in a region that is 25 mm above the lower electrode at a radial position of 75 mm (3 in.). Gradients in the radial profiles of the plasma potential are relatively small, with a ~ 2 V drop from center of the plasma to where these measurements are made. For spatial measurements of the plasma potential, the probe is moved to the center of the chamber and translated in a vertical plane.

A cylindrical Langmuir probe is used to measure changes in both the density and the energy distribution of electrons in the plasma. For the measurements presented here, the Langmuir probe is a tungsten wire 0.25 mm in diameter and 10 mm long. The probe is shielded in a glass tube to localize the point of charge collection. Analysis of the current-voltage traces consists of using the plasma potential obtained from the floating emissive probes to identify the electron saturation current. From the saturation current, the electron density is computed assuming an average velocity obtained from a Maxwellian electron population possessing a temperature measured by the emissive probe and assuming the collection area is equal to the geometrical area of the probe. Electron current is obtained by subtracting the ion current from the total measured current. Ion current is assumed to have a voltage dependent collection area. The functional form of the ion current scaled as $\Delta V_{\text{Sheath}}^{4/5}$ and is determined empirically from analysis of the measured



FIG. 2. (a) Representative response of emissive probe floating potential as current is passed through the filament for two different discharge conditions. (b) Total (blue curve) and electron (green curve) current-voltage traces acquired with the cylindrical Langmuir probe. The insert depicts the functional form of the ion current (red dashed curve) which subtracted from the total current.

currents as the probe is biased significantly below the floating potential. Representative current-voltage curve is presented in Figure 2(b).

Transient phenomenon that occurs in the segmented electrode current is captured with a 1 GHz bandwidth digitizing oscilloscope. Oscillations in the current extracted from the plasma are monitored on the plasma side of the 75 Ω resistor that limits the current flow to the segmented electrode. The signal is AC coupled into the oscilloscope and terminated with 1 M Ω . Fast-Fourier transformations (FFT) of the current signals are performed in memory and then averaged over 50 to 100 individual scope acquisitions. Signals are acquired over various time bases to capture oscillations spanning below 1 kHz to over 10 MHz. Current waveforms are at sampled at rates of 10 000 MS/s.

Finally, images of the optical emission generated in the 35 mm wide by 45 mm high region above the segmented electrode are acquired using a gated, intensified CCD (ICCD) camera (Andor Istar). The nominal resolution of the imaging system is 90 μ m per pixel. Images are taken at a rate of 200 Hz for a period of 50 μ s. Typical acquisition times

span 5 s to 20 s depending on the brightness of the plasma. Triggering of the ICCD is performed by a free running digital delay generator. Narrow band interference filter centered on 450 nm with a band pass of $\pm 4 \text{ nm}$ are used to suppress the white light generated by the cathode filament. The interference filter transmitted plasma induced emission corresponding to the $3p_7$ to $1s_4$ transitions in argon and the 4^3D - $> 2^{3}$ P transitions in helium. Because there is a significant amount of light generated by the filament that passes through the interference filter, background subtraction is performed. For the results presented here, emphasis is placed on how the plasma structure changes with size of the electron collecting electrode and the bias placed on it. Therefore, for a given electrode size, the reference background image is chosen to be the condition when electrode biased closest to the ground potential as this condition most closely represents a nominally unperturbed plasma.

Data acquisition is performed sequentially and is managed with an in house LabView based routine. Prior to data acquisition, the segmented electrode is configured for the desired number of rings to be biased and the rest are grounded (set to the wall potential). The segmented electrode is initially set to a value of -15 V below ground and incremented to values approaching and exceeding the plasma potential. Typical voltage steps used in these studies are 1 V. After stepping the applied voltage, the routine dwells for 2 s and then proceeds to sweep the current through the emissive probe. Current and voltage traces are then obtained with the Langmuir probe and FFT spectrum of the current are acquired. Images are taken with the ICCD camera and the procedure repeats.

III. MODIFICATION OF GLOBAL FLOW SCALING MODELS TO ACCOUNT FOR ION COLLECTING SURFACES

The sheath that forms near a positively biased electrode must allow global balance of electron and ion currents leaving the plasma. In Ref. 11, a two-electrode model consisting of a reference wall electrode and a biased auxiliary electrode was developed that predicted the polarity of the sheath based on the area ratio of the two electrodes. In the present experiment, a third boundary is present in the form of a hollow cathode, which takes a potential significantly more negative than both the plasma potential and ground. This surface will essentially collect only ions and perhaps emit electrons. Using a similar method as outlined in Ref. 11, current balance can be utilized to predict the plasma potential in the presence of these three boundaries, as well as the bounds on the size of the electrode for the sheath polarities.

The electron and ion flux incident upon a bounding sheath can be expressed as

$$\Gamma_e = \frac{1}{4}n\sqrt{\frac{8T_e}{\pi m_e}}$$
 and $\Gamma_i = 0.6n\sqrt{\frac{T_e}{M_i}}$, (1)

where *n* is the bulk plasma density, T_e is the effective electron temperature and m_e is the electron mass and M_i is the mass of the ion.³ A minimum electrode area for an ion sheath to be present at the electrode can be derived by insisting that the

plasma potential be greater than the electrode potential. In this case, the global electron current lost can be expressed as

$$I_e = e\Gamma_e \left\{ A_E \exp\left[-\frac{e(V_p - V_E)}{T_e}\right] + A_W \exp\left[-\frac{eV_p}{T_e}\right] + A_{HC} \exp\left[-\frac{e(V_p - V_{HC})}{T_e}\right] \right\},$$
(2)

where V_P is the plasma potential, V_E is the electrode potential, V_{HC} is the hollow cathode potential, A_E is the anode area, A_W is the grounded wall area and A_{HC} is the hollow cathode area. The last term on the right (electron loss to the hollow cathode) can be neglected since it is assumed that $V_p > V_E \gg V_{HC}$. The ion current lost from the plasma is given by

$$I_i = e\Gamma_i \{A_E + A_W + A_{HC}\},\tag{3}$$

where it is noted that the hollow cathode area arises. Equating the ion and electron loss currents gives an expression that determines the plasma potential

$$\exp\left(-\frac{eV_p}{T_e}\right) = \left\{\frac{A_E + A_W + A_{HC}}{A_W}\mu - \frac{A_E}{A_W}\exp\left[-\frac{e(V_p - V_E)}{T_e}\right]\right\}, \text{ where}$$
$$\frac{\Gamma_i}{\Gamma_e} \equiv \mu = \sqrt{\frac{2.3m_e}{M_i}}.$$
(4)

The area ratio requirement is derived from the assumption that the electrode, and hence the plasma potential, be biased much more positively than the electron temperature. In this case, the left hand side can be neglected and, the lower bound of the anode size (A_E) can be expressed as

$$\frac{A_E}{A_W + A_{HC}} \bigg|_{Ion\,Sheath} \ge \left(\frac{0.6}{\mu} - 1\right)^{-1} \sim 1.7\mu. \tag{5}$$

In the other limit, conditions for an electron sheath can be derived by requiring that the electrode be more positive than the plasma $(V_E > V_P)$. In this case, the electron current lost from the plasma is

$$I_e = \Gamma_e \left\{ A_E + A_W \exp\left[-\frac{eV_p}{T_e}\right] \right\},\tag{6}$$

where loss to the hollow cathode is here neglected under the assumption that $V_P \gg V_{HC}$. Ion current is assumed lost only to the wall and hollow cathode since the electron sheath blocks all ion current at the electrode $(V_E - V_P)/T_i \gg 1$. Equating the resulting electron and ion currents gives an expression that determines the plasma potential in the case of an electron sheath

$$\exp\left(-V_p/T_e\right) = \left\{ \left(1 + \frac{A_{HC}}{A_W}\right)\mu - \frac{A_E}{A_W} \right\}.$$
 (7)

Once again the area ratio criterion is obtained from the limit that the plasma potential becomes much larger than the electron temperature. The plasma potential increases as the electrode area increases in order to maintain current balance, according to Eq. (7). The limit that all electrons are lost to the electrode provides the upper bound on the electrode area capable of maintaining an electron sheath

$$\left. \frac{A_E}{A_W + A_{HC}} \right|_{Electron\,Sheath} \le \mu. \tag{8}$$

Using the bounds derived in Eq. (5) for an ion sheath and Eq. (8) for an electron sheath along with the charge collecting areas present in the experiment, predictions can be made about the size of the anode and the type of sheath that will be formed above the anode. The resulting predictions are presented in Table I for helium and argon discharges. Electron sheaths are anticipated to form below electrode areas smaller than $\sim 6200 \text{ mm}^2$ in helium and smaller than 1960 mm² in argon. Likewise, ion sheaths are anticipated to form above electrode areas greater than 10500 mm² in helium and greater than 3300 mm² in argon. For all cases, transitions from one type of interface to another type of interface occur at smaller electrode sizes in argon than they do in helium. This is a direct result of the differences in the mass of the two species (Eq. (4)). Finally, we note that although the hollow cathode area contributes to the plasma potential in a non-trivial way, it simply adds to the total wall area in the area ratio criteria. This because the area ratio criteria represent the extremum in which all electrons are lost to the electrode. The resulting area ratios are identical to those in Ref. 2, if the grounded wall area A_{w} from Ref. 2 is simply replaced by the total ion collecting area $A_w + A_{HC}$.

IV. RESULTS

A. Bulk plasma behavior with anode bias and anode size

In Figure 3, the behavior of bulk plasma properties such as (from top to bottom) electron current density collected by

TABLE I. Calculation of anticipated anode-plasma interface configuration for helium and argon plasmas generated in the experimental setup that is described in Sec. II.

Anode ring	R _o (mm)	$A_{AE} (mm^2)$	Anticipated Sheath type (He)	Anticipated Sheath type (Ar)
6	19.1	1145.5	Electron	Electron
7	22.2	1547.5	Electron	Electron
8	25.4	2025.8	Electron	Double
9	28.6	2568.4	Electron	Double
10	31.8	3175.3	Electron	Double
11	34.9	3824.6	Electron	Ion
12	38.1	4558.1	Electron	Ion
13	41.3	5355.9	Electron	Ion
14	44.5	6218.0	Double	Ion
15	47.6	7114.5	Double	Ion
16	50.8	8103.2	Double	Ion
17	54.0	9156.2	Double	Ion
18	57.2	10273.6	Ion	Ion
19	60.3	11417.3	Ion	Ion

the anode (J_e) , the plasma potential (V_{Plasma}), electron density (n_e) , electron temperature (T_e) and changes in light emitted from the plasma are plotted as functions of the difference between the anode potential and the localized plasma potential (the sheath potential). This sheath potential is utilized as it is the potential that ultimately regulates current flow to the biased anode and governs how the plasma responds to the anode. The left hand column corresponds to trends observed in a 1 mTorr argon discharge, while the right hand column corresponds to trends observed in a 20 mTorr helium discharge. Symbol shapes correspond to the size of the electrode while the colors of the symbols are chosen to delineate general trends in the observed behavior of the bulk plasma parameters to changes in the anode potential. Green symbols correspond to electrodes defined as "small," blue symbols correspond to electrodes defined as "intermediate" and red symbols correspond to electrodes defined as "large." For both discharges, the open green circles correspond to "very small" electrode sizes where little impact on the bulk plasma is observed by the biasing of the anode. To simplify the amount of information that is presented, six consecutive anode sizes (plus one for the very small anode) are chosen based on the collective behavior of the bulk plasma properties with the applied anode potential. It is important to emphasize that the delineation of data into the various size categories is based on the observed trends in the current density to the anode and the behavior of the plasma potential as a function of the sheath potential (upper plots, Figure 3) as the sheath potential approaches or exceeds (becomes more positive than) the local plasma potential. It is further noted that while these trends are clearly identifiable in argon, they are less-so in helium, especially for the larger anode sizes. Furthermore, trends obtained for electrode sizes near transitions near anticipated transitions can exhibit mixed characteristics that make it difficult to absolutely state which size class the electrode should be placed in.

Electron current densities (J_e) to the anode, as computed by the measured current to the anode divided by the geometrical area of the anode, demonstrates three characteristic trends in scaling with increasing potential between the anode and plasma. For all electrode sizes and for both argon and helium discharges, the current densities demonstrate the same dependence on the applied anode bias until the anode potential begins to exceed that of the grounded chamber walls ($V_{Anode} - V_{Plasma} > -5$ V). Smaller electrodes (green symbols) demonstrate rapid growth in the current density followed by decreasing current growth as the anode potential exceeds the plasma potential. Both discharges trend towards saturation over the range of voltages presented here. Furthermore, current densities extracted from both the argon plasma and the helium plasma demonstrate negligible dependence in the small electrode limit. This size-independent behavior of the extracted current density is utilized to define these electrodes as "smaller electrodes." As the anode size is increased, there is a deviation from this size-independent behavior of the current density in both argon and helium discharges. For argon, the intermediate sized electrodes (blue symbols) the extracted demonstrate characteristically different sheath voltage scaling than the larger sized electrodes red

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20 mTorr Helium



FIG. 3. Measurements of bulk plasma parameters such as (top to bottom) electron current density to the anode, plasma potential, electron densities and electron temperatures and optical emission emanating from a 1 mTorr argon discharge (a) and a 20 mTorr helium discharge (b) as functions of the anode size and bias (with respect to the plasma potential) placed on the anode. The color of the symbols is used to delineate different scaling observed in the voltage-dependent trends.

symbols do). The electron current density to the intermediate electrodes is nearly linear with applied sheath voltage $(J_e \sim \Delta V_{Sheath}^{\gamma}, \gamma \sim 1)$ whereas the electron current density to

the larger electrodes scales super-linearly with applied sheath voltage ($J_e \sim \Delta V_{Sheath}^{\gamma}$, $\gamma > 1$). While there is a clear transition from smaller sized to intermediate sized electrodes

in the helium discharge, there is not a clear transition in the extracted current densities from intermediate to larger electrodes. Therefore, the placement of electrode size into either intermediate or large category is not clearly defined by the current density alone.

The localized plasma potential (V_{Plasma}) of both the argon and helium discharges demonstrate similar characteristic trends that the current density demonstrated as the anode potential approaches and exceeds the initial plasma potential. To aide in clarifying these trends, the black dashed lines having a slope of one are included in the plots. When the anode potential is sufficiently below the plasma potential, the plasma potential is observed to be independent of the applied bias, the size of electrode, and the gas used to generate the plasma. Deviation in the similarity of the behavior of the plasma potential begins to occur when the anode potential is \sim 5 V below the plasma potential for both argon and helium discharges. As the anode becomes more positive than the grounded walls, the response of the plasma is observed to depend on the size of the anode. For smaller sized electrodes immersed in both argon and helium plasmas, the plasma potential is a sub-linear function of the sheath potential. Unlike the current densities, the plasma potential demonstrates size dependence of the electrode. The size dependence is more pronounced in the helium discharge. For the smaller electrode to intermediate electrode transition, both discharges demonstrate stronger dependence (near-linear) of the plasma potential on the sheath potential. Likewise, the larger sized electrodes demonstrate super-linear scaling of the plasma potential with the sheath potential. This sublinear to super-linear transition is used to define the transition from intermediate to large sized electrodes.

The behavior of the bulk electron density (n_e) and average electron temperature (kT_e) as obtained from the Langmuir probe current-voltage sweeps are discussed together. With the exception of the very small electrode, the bulk electron density rapidly decreases as the anode potential exceeds the potential of the grounded wall (VAnode - $V_{Plasma} \sim -5$ V), while the average electron temperature increases. Electron density depletion is observed to reverse for the large electrodes at higher anode potentials. On the other hand, size dependent electron heating trends show similarities to the scaling trends observed in both the plasma potential and the electron current densities extracted from the plasma by the anode. Distinct changes in the scaling in the average electron densities and the average electron temperatures are not as apparent as they had been for both the plasma potential and current densities.

Finally, changes in the optical emission emanating from the bulk plasma (referenced to the light emitted from the plasma when the electrode is grounded) further demonstrate distinct transitions in scaling with anode potential as the size of the anode is changed. For smaller electrodes, there is little change in the emitted light from the plasma while for the larger electrodes the plasma becomes much brighter. Both argon and helium plasma induced emission demonstrate an anode potential scaling behavior that is analogous to trends in the plasma potential and anode current density.

B. Spatial structure of the anode-plasma interface

To ascertain the nature of the interface formed above the electrodes, the spatial distribution of the localized plasma potential is plotted as a function of height above the electrode in Figure 4. As had been presented in Figure 3, symbols are used to identify the physical size of the electrode while colors are used to delineate different sets of behavior and correspond to the same electrode sizes discussed in the previous section. The open red symbols correspond to the condition when all 20 electrode rings are shorted to ground and serve as the nominal reference for how the plasma is configured in an unperturbed state. For all electrode sizes, the anode potential is kept constant at +15 V above the grounded chamber wall. While the localized plasma potential increases with increasing electrode size, the localized plasma potential for all but the largest electrodes remains below that of the biased electrode. Gradients in the potential are observed for the smaller electrode cases when the potential across the interface (the sheath potential) is the greatest. On the other hand, no discernable potential gradient could be resolved for either the intermediate or the large electrode configurations as access to the first few mm in front of the electrode is restricted.

The structure of the interface is also interrogated by examining changes in optical emission as the potential applied to the anode is increased. Changes in the averaged axial intensity (± 10 mm about the center of the anode) as a function of the anode potential with respect to the plasma potential are plotted in Figure 5 for various electrode configurations. The left hand column corresponds to changes in



FIG. 4. Measured plasma potential as a function of height above the anode immersed in (a) 1 mTorr argon plasma and (b) 20 mTorr helium plasma.



FIG. 5. Changes in the optical emission emanating from the 1 mTorr argon discharge (a) and the 20 mTorr helium discharge (b) as both the size of the electrode (top to bottom) and the potential across the sheath is increased. Red shaded areas indicate inaccessible parameter space.

light emitted from the 1 mTorr argon discharge, while the right hand column corresponds to changes in light emitted from the 20 mTorr helium discharge. Color coded labels above the images indicate the geometrical area of the anode,

while the shaded regions in the larger anode area plots correspond to inaccessible operating space where the anode potential does not exceed the plasma potential by the values indicated on the x-axis of the figures.

The evolution of plasma induced emission above the smaller electrodes demonstrates some growth in the bulk plasma (20 mm above the electrode), but the growth appears to remain detached from the electrode. The plasma front initially evolves towards the electrode as the anode bias exceeds the potential of the plasma and tends to stagnate at a distance of 5 mm from the electrode in the argon discharge and 10mm from the electrode in the helium discharge. Furthermore, at higher anode potentials (V_{Anode} - V_{Plasma} >10 V), a secondary region of plasma excitation forms on the electrode and the width of this secondary region grows with increasing bias. By contrast, the expansion of the bulk plasma to the anode no longer seems to stagnate as the electrode size transitions from a small size to an intermediate size, while the secondary glow on the anode is still observed to form at higher anode potentials. Finally, the plasma front rapidly comes into contact with the anode for the large electrode cases and the secondary glow is no longer observable.

C. Energetics of plasma electrons

In Figure 6, the natural log of the electron current, normalized to the electron saturation current measured by the probe when the anode array is grounded, is plotted as a function of probe potential below the plasma potential. By plotting the current in this manner, qualitative comments about energy distribution of the electrons in the plasma can be made. Curves plotted in the left hand column are obtained from the 1 mTorr argon discharge, while curves plotted in the right hand column are obtained from the 20 mTorr helium discharge. The colored labels in the plot correspond to the size of the anode, while the colored lines correspond to the potential of the anode with respect to the potential of the host plasma.

For the smaller electrodes the electron population is initially non-Maxwellian as indicated by a non-linear current voltage trace. As the anode potential increases, the temperatures tend towards a more Maxwellian-like distribution. For the intermediate sized electrodes immersed in argon discharge, modest heating over the entire electron population occurs while preferential deposition of energy into the higher energy electrons in the helium discharge is apparent. This preferential heating is indicated by increased population of higher energy electrons. For both of the discharges, heating of the plasma electrons does not appreciably occur until the anode potential exceeds the plasma potential by ~ 5 V. Similar behavior is observed for both plasma discharges interacting with the larger electrode sizes.

D. Oscillations in anode current

In addition to characteristic changes in both the bulk properties and the spatial distribution of the plasma, subtle changes in oscillations in the current collected by the anode are observed as the electrode size is changed and as the anode bias is changed with respect to the host plasma. Fast-Fourier transforms (FFT) of the power spectrum of the current collected by the bias anode immersed in the 1 mTorr argon discharge and 20 mTorr helium discharge are presented in Figures 7(a) and 7(b), respectively. For the argon

1 mTorr Argon



Probe potential below plasma potential (V)



FIG. 6. Log of the normalized electron current collected by the Langmuir probe immersed in (a) the 1 mTorr argon discharge and (b) the 20 mTorr discharge. The electron current is normalized to the current collected at the plasma potential when the anode is grounded (unperturbed plasma case). The colored labels in the plot correspond to the size of the anode, while the colored lines correspond to the potential of the anode with respect to the potential of the host plasma.

discharge, prior to biasing the electrode, sharp oscillations near 18 kHz are observed to be present as indicated by the black traces (-5 V corresponds to the grounded electrode). While there is little change in the location or amplitude of this oscillation with bias or size, there are some notable changes at higher frequencies. Specifically, the oscillation at 37 kHz becomes better defined and a broad, diffuse structure develops in the region spanning 45 kHz to 65 kHz. The oscillation near 30 kHz is observed to initially grow as the anode is biased to the plasma potential (0 V, blue curve) but becomes suppressed at higher biases. By contrast, the most notable change in the frequency spectrum of the current



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FIG. 7. FFT spectrum of electron current extracted from a (a) 1 mTorr argon and a (b) 20 mTorr helium discharge. The colored labels in the plot correspond to the size of the anode, while the colored lines correspond to the potential of the anode with respect to the potential of the host plasma.

oscillations induced by increased bias placed on the intermediate sized anode occurs at frequencies below 10 kHz. As is the case for the smaller anode, there is a diffuse peak that develops at higher frequencies but spans a range from 35 kHz to 55 kHz. Finally, as the bias is increased on the 3830 mm² anode, the low frequency structure is suppressed and the higher frequency structure becomes stronger and more diffuse, washing out the 37 kHz peak present for the other two smaller electrode sizes. Unlike Argon, The 20 mTorr helium plasma does not demonstrate any strong characteristic oscillations present in the discharge prior to the application of the electrode bias. On the other hand as the bias placed on the $4560 \,\mathrm{mm}^2$ electrode increases, strong oscillations near 140 kHz and 190 kHz are observed to develop. The oscillations are present when the anode bias exceeds the plasma potential by ~ 10 V (red curves) and shift to lower frequencies as this difference is increased. For the intermediate electrode case (5360 mm²), the oscillations are not particularly well defined until the anode exceeds the plasma by ~ 15 V (dark red line). Instead, a more diffuse structure initially forms over frequencies spanning 100 kHz to 200 kHz. For the larger electrode sizes, the well-defined oscillations never form, but the diffuse structure spanning lower frequencies forms in their place.

V. DISCUSSION

A. Anode size and mode transitions

In general, the experiments indicate that there are (at least) three modes of behavior that are observed in bulk plasma properties, spatial configuration of the plasma, and energetics of the electrons contained in the plasma as the size of a biased electrode is increased. Furthermore, the delineation of these modes by electrode size agrees rather well with predictions for changes in the sheath structure as described in Sec. III and tabulated in Table I. For comparison, the predicted transitions obtained in Sec. III and

measured transitions observed in Sec. IV are tabulated in Table II. As the anode rings are discretized, average areas are used for the observed areas.

While there is no direct measure of the sheath structure for the current sets of measurements, trends in the spatial distribution of the plasma potential and the spatial distribution of optical emission above the electrode indicate that the nature of the electrode plasma interface is changing. For smaller electrodes, the plasma potential does not track the anode potential. As the bias placed on the electrode becomes more positive than the host potential $(V_E > V_P)$, an electron sheath must be present at the interface between the anode and plasma. By contrast, for the large electrodes, the plasma potential tracks the anode potential by a few volts. Likewise, the development of a secondary excitation region (glow) just above the small sized electrodes indicates that energetic electrons are present there. No such glow is observed for the larger electrodes. Finally, for intermediate-sized electrodes, the anticipated double layer is not observed in the potential profiles plotted in Figure 4. The reason that there is an absence of a non-monotonic sheath structure is unclear. While the region close to the anode was not observable with the emissive probe, the observed structure indicates that the potential is rising (as opposed to first decreasing) as the anode is approached. Oscillations observed in the current for these intermediate sized electrodes may be indicative of a transition between an ion rich and electron rich sheath. Such oscillations could serve to wash out the appearance of a double sheath. As pointed out by Forest,¹⁴ the depth of the double layer depended on a balance between ions being trapped in the potential well and the loss of those ions from the well. It was demonstrated that the geometry of the electron collecting electrode and the loss offered to the ions played an important role in the structure of the double layer. Finally, computational simulations of the experiment describe here likewise indicate that double layers are not forming on-axis above the intermediate sized anode. Instead, the structure is

TABLE II. Comparison between measured and anticipated interface transition areas in helium and argon discharges.

	Helium o	lischarge	Argon discharge	
	Small to intermediate	Intermediate to large	Small to intermediate	Intermediate to large
Anticipated area (mm ²)	6200	10 500	1960	3300
Observed area (mm ²)	$\sim \! 5000$	$\sim\!\!6200$	$\sim \! 1770$	~ 2900
Percent difference	-20	-40	-13	-12

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observed to form around the outer edge of the interface, in a region where the biased anode and the grounded wall are in close proximity. Subsequent studies are planned to better understand why the double layer is not observed.

For both discharges, the size-induced transitions occur at smaller electrode sizes than those predicted by the model. Differences in the helium discharge span 20% (Small to intermediate sized electrodes) to 40% (intermediate to large sized electrodes) below anticipated values while differences in the argon discharge are only 12% below anticipated values for both transitions. A likely explanation of this difference stems from differences in the geometrical area of the electrode to the actual size of the electron collecting interface.¹⁵ Specifically, as the bias placed on the electrode increases, space charge around the anode (electron sheath) is likely to expand to buffer the host plasma from the applied fields. As a result, the plasma interacts with a larger area than the geometrical area offered by the actual anode. This effect is present in both the spatial distribution of the plasma potential above the anode (Figure 4) as well as the spatial distribution of the plasma induced emission above the anode (Figure 5). For the helium discharge, the interface between the anode and the host plasma is $\sim 5 \text{ mm}$ whereas for argon, the interface is more localized ($\sim 3 \text{ mm}$). Assuming an effective area (A_{Effective}) described by a cylindrical area of $\pi r^2 + 2\pi r l$ where r is the radius of the anode and l is the thickness of the interface, differences between effective area and nominal area scale as $A_{Effective} = A_{Nominal}(l + 2r/l)$. For the electron to double sheath transition in both helium (r = 44 mm and l = 5 mm) and argon (r = 25 mm and l = 5 mm)l = 3 mm), the difference can approach 20%. Twodimensional diagnostics capable of resolving this structured interface will be investigated in subsequent studies.

Finally, beyond the differences in effective collection area, the oscillations in the anode current are indicative of a plasma instability. Because the frequency spectrum of the instability tends to show the most change around the electron sheath to double sheath transition, particularly at higher electrode biases, there is likely a relationship between the stability of the interface and the observed oscillations. For example, as the bias is increased and the interface between an electron collecting (small) electrode and the plasma expands, the size of the interface can exceed the limit described by Eq. (8) and a transition in the configuration of the both the interface and the plasma potential will occur. As the interface transitions, the effective area is likely to revert to a smaller area as the potential between the electrode and plasma is no longer as large as it had initially been and the interface reverts back to its original electron-sheath configuration, completing the cycle of the instability. Similar types of oscillations have been reported in studies on anode spots and "fireballs."16-21

B. Electron energy and plasma potential

Both the depletion of low energy electrons and the heating of the higher energy electrons can be correlated to changes in the plasma potential. As outlined in Sec. III, the plasma potential is related to the electron temperature and the geometry of the system bounding the plasma (Eq. (7)). For small electrodes where the low energy electrons are lost through the electron-collecting interface and the electron temperature effectively increases, there must be a corresponding increase in plasma potential to maintain quasineutrality of the host plasma. With this increase in the plasma potential, there is an increased barrier to electrons that are lost to the (larger area) grounded wall. Electrons with energies comparable to and less than the new plasma potential, but more energetic than the initial plasma potential are now bound in the plasma system. For the smaller sized electrodes, changes in plasma potential are $\sim 2-4$ V in argon and $\sim 5-10$ V in helium. The change in plasma potential for the two discharges correlates well with the observed heating of the electrons.

Confinement of the modest energy electrons and increase of the plasma potential continues with increase in electrode size. When the plasma potential begins to lock to the anode potential as is the case for the intermediate and large sized electrodes (Figures 3 and 4), additional heating of the electrons occurs. This heating is likely caused by increased energy imparted to the electrons injected into the plasma from the grounded walls (induced by energetic particle bombardment) and is best demonstrated by the augmentation of higher energy electrons in the measured electron energy spectrum obtained in plasmas generated above intermediate and large sized electrodes (Figure 6). Better confinement of the lower energy electrons due to the establishment of a potential barrier between the host plasma and the anode is also expected to occur above both the intermediate and larger sized electrodes. Confinement of these electrons scales with the depth of the potential barrier. For intermediate sized electrodes that are expected to possess a double layer, the depth of the potential barrier is a fraction of kT_e deep. On the other hand, for larger sized electrodes that are anticipated to possess an ion sheath, the depth of the potential barrier is a few kT_{e} deep. Therefore while both interfaces are capable of confining lower energy electrons, the ion sheath does a much better job. Finally, the strong growth in optical emission with increasing anode size and bias likely results from the higher energy electrons injected into the plasma as the plasma potential rises. Greater excitation (and ionization) occurs with increased potential difference between the plasma and the bounding walls.

VI. CONCLUSIONS

The size dependency on the bulk plasma properties between an electron collecting electrode (anode) and the host plasma it is immersed in is investigated using a segmented electrode array. Characteristic size-dependent modes of behavior in the bulk properties of the plasma such as the plasma potential, electron current density, electron density and electron temperature are observed as the bias placed on the anode is varied. The size of the anode that induces a transition between the various modes is compared to predicted scaling relationships outlined in Sec. III. While our observations do not provide a direct measurement of the interface that is formed between the electrode and the host plasma, it is found that the observed transitions in the scaling of these bulk properties were indicative of the anticipated changes in the configuration of the interface formed between the anode and the host plasma.

It is observed that the plasma in contact with smaller sized anodes demonstrated saturation in the bulk properties such as the extracted current while changes in the plasma potential with increasing anode potential were on the order of the electron temperature. These scaling trends are consistent with the presence of an electron rich interface (electron sheath). On the other hand, the plasma in contact with larger sized electrodes did not demonstrate any such saturation and the plasma potential became "locked" to the potential applied to the anode, behavior consistent with the presence of an ion rich interface (ion sheath). Changes in the spatial structure of both the plasma potential and optical emission emanating from the plasma are used to support this conclusion. Discrepancies between the anticipated and measured transitions are consistent with differences between the nominal area of the anode and the effective are of the anode. Due to the non-planar structure of the interface that develops above the anode, the effective area offered to the plasma for electron loss is 10% to 20% larger than the nominal or geometrical area of the anode. Scaling is tested for both helium and argon discharges.

In addition to observations made on the bulk properties of the plasma, intermediate frequency oscillations (10-50 kHz in argon and 100-500 kHz in helium) are observed in the current collected from the plasma by the anode. The oscillations are postulated to be formed by transitions between the interface configurations as the size of the effective anode approached a predicted interface transition. Changes in the electron energy spectrum are likewise observed. The reduction of the potential barrier to low energy electrons caused a depletion of these low electrons from the plasma causing an increase in the effective temperature of the plasma electrons. Furthermore, increases in the plasma potential by the loss of these low energy electrons leads to additional heating of the electrons by the better confinement of intermediate electrons. These observations have important implications on the ability to tailor the targeted portions of the electron energy distribution. For the smaller sized electrodes where an electron sheath is anticipated to be present and the anode potential is comparable to or greater than the host plasma, there is some additional ability drain low energy electrons by permitting them to escape from the plasma and to "heat" the electrons population through better confinement of modest energy electrons. The size of the electrode with respect of the host plasma can be used to balance the two effects.

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