Comparison of Hollow Cathode Discharge Plasma Configurations

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Hollow cathodes are used in plasma contactor and electric propulsion devices to provide electrons for sustaining plasma discharges. Based on previous cathode life tests where erosion was observed on hollow cathode assembly components, it is desirable to understand the plasma flow field downstream of hollow cathodes. Plasma flow field measurements are presented herein for hollow cathode generated plasmas using both local and remotely located plasma diagnostics. Two cathode discharges are presented: 1) an open, no magnetic field configuration and 2) a setup simulating an ion thruster discharge chamber. In the open cathode configuration, large amplitude plasma potential oscillations, ranging from 20 V to 85 V within a 34 V discharge, were observed using a floating emissive probe. These oscillations were observed over a dc potential profile that contained a clear potential hill structure. A remotely located electrostatic analyzer (ESA) was used to measure the energy of ions produced within the plasma, and energies were detected that met and in some cases exceeded the peak plasma potentials detected by the emissive probe. In the prototype NSTAR-like discharge chamber configuration, plasma potentials from the emissive probe agreed with ion energies recorded by the remotely located ESA. A correlation model was used to compare the local and remote measurements in both cathode discharges.

Nomenclature

ESA	=	electrostatic analyzer
E	=	energy or electric field
ϕ	=	voltage or potential
IEDF	=	ion energy distribution function
$\dot{m}$	=	xenon flow rate
n_e	=	electron density
r	=	radius or radial distance
R	=	resistance
σ	=	xenon electron-ion cross section
T_e	=	electron temperature
V	=	voltage/potential
w	=	ion weight
z	=	ion charge state (1,2,3, etc.) or axial distance

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I. Introduction

PREVIOUS ion thruster and hollow cathode life tests have shown erosion of hollow cathode components that could lead to failure of a thruster during a long mission [Patterson et al.¹ 1995; Polk et al.² 1999; Soulas et al.³ 2004; Vaughn et al.⁴ 2004]. It is presumed that ions created in the plasma regions downstream of the cathode were those that caused the cathode surface wear [Domonkos and Williams⁵ 2001; Mikellides et al.⁶ 2007]. The erosion is dependent on the number of ions that hit the surface, ion species, ion charge state, incidence angle, energy at which the ions strike the surface, etc. [Sigmund⁷ 1969; Yamamura and Tawara⁸ 1996]. These factors are all directly dependent on the conditions within the plasma where the ions are created. Therefore, as a first step toward investigating cathode erosion mechanisms, it is of interest to examine the plasma structure near hollow cathodes. Comparisons of the spatial and temporal information from various local and remote probes are made in an attempt to explain the nature of the potential structures in the plasma and expose mechanisms whereby energetic ions are created that can limit the life time of hollow cathode based plasma contactors devices.

II. Experimental Apparatus

We first describe the discharge chamber configurations and diagnostic tools that were used to probe plasmas. Two discharge chamber configurations were used that had different geometries, which resulted in very different plasma environments. Diagnostics included an emissive probe, a triple Langmuir probe, and a remotely located electrostatic analyzer (ESA). All tests were performed at the CEPPE Lab at Colorado State University in a 1.2 m diameter by 4.6 m long vacuum chamber that was pumped with a 0.9 m diameter, 20 kW diffusion pump equipped with a refrigerated baffle. The base pressure of this facility with no flow was 7×10^{-7} torr. The vacuum pressure was in the low to mid 10^{-5} Torr range at typical xenon flow rates of 3 to 15 sccm.

In both configurations, the same hollow cathode was used to produce and sustain the plasma. The hollow cathode was a 6.3 mm diameter tube that contained a low-work-function impregnated, sintered tungsten insert. The hollow cathode tube was capped with an orifice plate that had a 0.55 mm diameter orifice on its centerline. The cathode tube and insert were heated by a resistive coil wrapped around the outside of the tube, which was insulated by a multiple-layer, tantalum-foil radiation shield. The enclosed keeper used with the cathode was equipped with an orifice plate fabricated from 0.635 mm thick tantalum. The keeper orifice plate had a 2.54 mm diameter orifice positioned about 0.5 mm downstream of the cathode orifice plate. It is noted that the cathode and keeper orifice diameters were similar to but not exactly the same as the discharge cathode and keeper features used in the NSTAR ion thruster [Mikellides et al.⁶ 2007]. All of the xenon propellant required to operate the cathode and the discharge chamber plasma were supplied through the cathode. In case 2, because high voltages were not applied to extract ions and propellant was lost only through the relatively small slot in the chamber side-wall and the pseudo-grid surface, the flow through the cathode was sufficient to produce NSTAR-like neutral densities throughout the discharge plasma.

A. Case 1: Open Cathode (Zero Magnetic Field) Configuration

A photograph of the hollow cathode plasma configuration examined in this study is shown in Figure 1. The axis of the cathode assembly (consisting of the hollow cathode, heater, and enclosed keeper) was aligned with the axis of a stainless steel ring anode. The hollow cathode was connected to the vacuum chamber ground during all testing described in this study. To produce the plasma discharge, electrons were drawn from the cathode to the positively biased ring anode. The hollow cathode was equipped with an enclosed keeper electrode, but this electrode was connected to ground during all testing described in this study. No magnetic field was applied, but we note that the geomagnetic field (of magnitude 0.5 G) could penetrate the stainless steel vacuum chamber and did so at an angle of 70 degrees relative to the cathode and anode axis. The ring anode was 19.5 cm in diameter and 9 cm in length. Each plasma diagnostic probe discussed below was mounted to two linear positioning stages (labeled radial and axial) to allow for movement to different locations within the plasma.

Figure 1. Open cathode (zero magnetic field) configuration. The anode was 19.5 cm in diameter and 9 cm in length.

B. Case 2: Prototype NSTAR Discharge Chamber Configuration

The second experimental setup consisted of a hollow cathode mounted within a discharge chamber as seen in Figure 2. The discharge chamber had a 30-cm diameter cylindrical section attached to a conical central section which was capped by a back plate and was, therefore, similar in size, shape, and magnetic field geometry to the NSTAR thruster [Rawlin et al.⁹ 1999; Farnell and Williams¹⁰ 2004]. The discharge chamber was made from sheet aluminum with an inner stainless steel lining and three magnet (samarium cobalt) rings. The first ring was located near the exit of the source (where the ion optics would be located on an actual NSTAR ion engine) at one end of the cylindrical sidewall section, the second was placed at the intersection of the cylindrical and conical anode sections, and the third behind the cathode on the back plate. A pseudo-screen grid fabricated from stainless steel and biased to cathode potential was used to simulate the neutral flow restricting behavior of an actual ion optics system. Ions produced in the plasma were allowed to flow directly from the discharge chamber through a 6 mm wide slot cut in the side wall of the discharge chamber and pseudo-screen grid so they could be sensed by remotely located probes. The discharge chamber/hollow cathode system was mounted within a fixture so that it could be rotated about an axis centered at the cathode orifice thereby enabling measurements at angles from 0 to 90 degrees with respect to the cathode centerline. This was done to investigate the size and shape of the dense plasma region produced near the hollow cathode orifice. In all tests, the hollow cathode was connected to vacuum chamber ground.

Figure 2a Side view of the prototype NSTAR discharge chamber showing the three rings of magnets and 6 mm wide viewing slot. Upper right shows plasma discharge at a 90° viewing angle.

Figure 2b Top view schematic of the discharge chamber. Bold/blue highlighted region indicates the 6 mm wide slot cut in the discharge chamber sidewall for remotely located probe investigations.

C. Floating Emissive Probe

An emissive probe, shown in Figure 3a, was used to measure the plasma potential of the discharge plasma. When the emissive probe filament is heated to high temperature, the probe will float near plasma potential [Hershkowitz and Cho¹¹ 1988; Hass and Gallimore¹² 2001; Beal et al.¹³ 2005]. Some error in emissive probe measurement can come from incorrect heating current and voltage drop across the filament; and even when very hot, an emissive probe will float slightly below true plasma potential; a condition which becomes progressively worse when the probe is positioned in dense plasma. With care typical errors are less than ~2-3 V and, hence, the emissive probe is very useful due to its direct nature of plasma potential measurement. Figure 3b shows a plot of the measured plasma potential as a function of heating current at a selected location within the plasma. A standard procedure during a given test was to start the plasma discharge and then position the emissive probe at a few different locations and repeat the potential versus heating curve until an acceptable heating current was identified that could be used to perform the entire plasma potential mapping operation.

Figure 3a. Emissive probe used to measure potential (3.5 mm long, 0.127 mm dia. tungsten filament).

Figure 3b. Plot of probe floating potential versus emissive probe heating current.

For the measurements presented herein, plasma potential was measured using a voltmeter connected to the probe through a high-impedance, low-capacitance, active filter [Goebel et al.¹⁴ 2005]. The filter was necessary to reduce the effects of the meter on the floating probe and allow the detection of high frequency plasma potential oscillations. The data acquisition system was capable of measuring voltages from ~ 0 to 85 V at a sampling frequency of 3 MHz. The 3 dB roll off point of the overall low pass filter and emissive probe circuit was measured to be ~ 600 kHz.

D. Triple Langmuir Probe

Langmuir probes consist of electrodes (single, double, or triple) placed in a plasma to collect ion and electron currents under imposed biases [Chen and Sekiguchi¹⁵ 1965; Beal et al.¹⁶ 2004; Diamant¹⁷ 2006]. The triple Langmuir probe uses the same principle of operation as the single Langmuir probe but has three electrodes rather than one. From the measured current and voltages on the electrodes, the electron temperature (T_e), plasma potential (V_p), and electron density (n_e) can be determined. The main advantage of this probe is that, unlike the single probe, there is no need for a voltage sweep. Instead a single voltage bias is used. A diagram of the triple probe is shown in Figure 4. Three cylindrical tantalum electrodes 4 mm long and 0.381 mm in diameter were used. The electrodes were housed in aluminum-oxide tubing and the electrode separation distance was 1.0 mm. Four voltages were monitored. The floating potential, V_3 , was measured on one of the three electrodes while the other two electrodes were biased in a double probe arrangement using a fixed voltage power supply. In the double probe arrangement, the net ion and net electron currents collected on the negatively and positively biased electrodes, respectively, are equal and $I = V_1/R$. The bias voltage, V_4 , was held constant at 20 V, but was monitored to ensure that the power supply set point didn't change during a test. Finally, the voltage between the positive leg of the fixed voltage power supply and the floating electrode, V_2 , was also recorded.

There are certain requirements for the triple probe relations to be valid. The probe geometry must be small such that the three electrodes are exposed to the same plasma environment. However, the electrodes must be spaced far enough apart (many Debye lengths) so the sheaths around each electrode do not affect the other electrodes. For the triple Langmuir probe analysis, quasi-neutrality is assumed and the electrons are assumed to be Maxwellian [Chen and Sekiguchi¹⁵ 1965].

Figure 4. Triple Langmuir probe schematic and photograph.

E. Electrostatic Analyzer

A Comstock model AC-901 electrostatic analyzer (ESA) was used to measure the energy of the plasma ions [Comstock Inc.¹⁸ 1973]. The ESA, shown in Figure 5, consisted of two spherical sectors nested in a 160 degree arc. The ESA has collimators at each end of the spherical sectors to allow for narrow solid angle acceptance of ions moving toward the detector. The collector electrode was located immediately downstream of the exit collimator. To yield the ion energy distribution function, IEDF, the constant transmission mode was used whereby a constant voltage bias, $\Delta\phi$ was applied to the spherical segments and the entrance and exit collimators were swept with respect to the plasma. At each voltage bias setting, an ammeter was used to measure the ion current that flowed to the collector electrode. The voltage difference on the spherical plates was converted to ion energy-to-charge ratio (E/z) using equation (1), where r_1 and r_2 were the inner and outer radii of the ESA spherical segments and $\Delta\phi$ was the voltage difference applied between r_1 and r_2 [Comstock Inc.¹⁸ 1973; Moore et al.¹⁹ 2002].

$$\frac{E}{z} = \frac{\Delta\phi}{\frac{r_2}{r_1} - \frac{r_1}{r_2}} = 2.254 \cdot \Delta\phi \quad (1)$$

III. Experimental Results and Discussion

F. Case 1: Open Cathode (Zero Magnetic Field) Configuration

Three operating conditions were chosen for detailed investigation and they are described in Figure 6. At each operating condition, the xenon flow rate and discharge current were held constant and the discharge voltage was allowed to adjust to a steady state value. The vacuum tank pressure was 4.8×10^{-5} Torr. Figure 6 shows a plot of the mapped region for the emissive and triple Langmuir probes, as well as the location of the ESA relative to the mapped region.

Condition	J_D (A)	V_D (V)	Flow Rate (sccm Xe)
1	7.5	33.0	7.6
2	11.25	34.0	7.6
3	15.0	33.5	7.6

Figure 6. Test conditions and setup showing the region mapped by the emissive probe, triple Langmuir probe, and the relative position of the electrostatic analyzer (ESA) with its line of sight. The diamond points represent locations where temporal measurements of plasma potential were made.

1. DC Emissive Probe Profiles – Open Cathode

Figure 7a shows DC potential profiles taken with the floating emissive probe (along with triple Langmuir probe measurements discussed in the next section). The potentials ranged from about 16 V to 50 V, with potentials dropping off as the emissive probe was positioned farther away from the hollow cathode discharge (axial distances greater than $z \sim 10$ cm). The DC plasma potential also decreased as the probe was moved close to the cathode, to within a couple of cm radius from the cathode/keeper orifice. At the 7.5 A discharge condition, a clearly defined potential hill region was observed to exist just downstream of the hollow cathode where the peak plasma potential was significantly above the cathode to anode voltage. As the discharge current was increased to 11.25 A and 15.0 A, the potential hill spread out, dropped in magnitude, and moved farther downstream of the cathode.

2. Triple Langmuir Probe Profiles – Open Cathode

Figure 7b shows potential profile plots calculated from triple Langmuir probe measurements. Similar to the emissive probe measurements, plasma potential decreased as the triple probe was positioned farther away from the discharge region (axial distances greater than $z \sim 10$ cm). In addition, low plasma potentials were observed when the triple probe was moved to within a couple of centimeters of the cathode/keeper orifice. The triple probe results also indicate the existence of potential hills (i.e., potential maximums occurring at locations downstream from the cathode), especially at condition 1, but the potential hill location and structure were found to differ from the emissive probe. One possible cause of error with a triple Langmuir probe is when significant numbers of primary electrons are present, as could be the case within the potential hill region. Another factor in triple probe error could be caused by the presence of intense plasma potential oscillation, which was detected within the potential hill region.

Although similar in general characteristics to the emissive probe, the triple probe measurements were also not as symmetric about the cathode centerline. It is believed that the non-symmetry could be due to the orientation of the triple probe with respect to the cathode and anode axis where one of the electrodes could be affecting the ion and electron currents flowing to the other two electrodes. A similar effect is described by Tilley et al.²⁰ [1994] in regard to the orientation of the triple probe with respect to flowing ion currents that perturbed measurements of plasma properties. The main result of these comparisons is that the trends in the potential profiles in regions outside of the potential hill measured with the triple probe were similar to the emissive probe data.

Figure 7a. Emissive probe potential measurements at condition 1- $J_D = 7.5$ A, $V_D = 33.0$ V, condition 2- $J_D = 11.25$ A, $V_D = 34.0$ V, and condition 3- $J_D = 15.0$ A, $V_D = 33.5$ V. The diamond points correspond to locations where temporal plasma potential measurements were made that are presented in Figure 8.

Figure 7b. Triple Langmuir probe plasma potential measurements at operating conditions 1, 2, and 3.

3. Temporal Emissive Probe Potential Measurements – Open Cathode

In addition to time-averaged, DC potential measurements there is an obvious desire to determine if any significant plasma potential fluctuations are present since plasma potential fluctuations can result in energetic ion formation similar to how potential hills form energetic ions. The emissive probe was connected to a high speed (~1 MHz) data acquisition system to monitor the time-varying plasma potentials.

Five locations were chosen for the oscillation measurements. Their locations are shown in Figure 7a (diamond points) and correspond to $r = -0.5$ cm, $z = 0.5, 1.25, 2.0, 3.5, 5.0, 9.5$, and 20.0 cm relative to the keeper. Figure 8 shows the resulting potential waveforms at each location for conditions 1, 2, and 3 where large potential oscillations were observed near the cathode from about $z = 1$ cm to $z = 6$ cm. At some locations, potentials varied from about 20 V to over 85 V, which was the maximum potential that the emissive probe circuit was capable of accurately measuring. We consider it likely that the plasma potential could have been fluctuating to potentials higher than 85 V. Similar to the time-averaged emissive potential trend, as the discharge current was increased from 7.5 A to 15.0 A, the location of the largest potential oscillations moved farther downstream from the cathode (from $z = 1.25$ cm to 3.5 cm). However, we note that the location of the time-averaged potential peak did not correspond to the location of the maximum oscillation amplitude. The largest amplitude oscillations were observed at locations between the cathode and time-averaged potential peaks.

Figure 8. Potential oscillations for test conditions 1, 2, and 3 at radius $r = 0.5$ cm and axial distance (z) measured from keeper. The y-axis is plasma potential (0 V to 85 V scale) and the x-axis is time (s).

The frequency of the oscillations ranged from 5 to 100 kHz with no definite single frequency component in the signal, although there was a slightly more defined frequency component in the 40 to 50 kHz range. Similar plasma potential measurements have been made nearby hollow cathodes by Goebel et al.¹⁴ [2005] and by Fitzgerald²¹ [1983]. Although the discharge chamber conditions and cathode and keeper assembly dimensions of these studies were different from the measurements presented herein, both observed potential oscillations that had similar frequency content in the 50 to 500 kHz range.

4. Electrostatic Analyzer (ESA) Measurements – Open Cathode

The ESA was used to characterize the energy distribution of ions flowing from the discharge plasma. Figure 9 shows measured IEDFs at the three operating conditions of this study. Ion energies were measured relative to the hollow cathode which was tied to vacuum tank ground. The entrance to the ESA was located about 45 cm downstream of the keeper. Each of the three IEDFs corresponds to a radial location of the ESA relative to the

cathode ($r = 0$ cm, $r = -3$ cm, and $r = -6$ cm). A main ion signal was present in all cases that had a most probable energy near the discharge voltage. In addition, there was an energetic ion signal that indicated the presence of ion energies exceeding 100 eV. As the discharge current was varied from 7.5 A to 15 A, the relative number of higher energy ions increased, especially in the 50 eV to 100 eV energy range. The magnitude of the high energy ion signal decreased when the ESA was moved to the $r = -3$ cm and $r = -6$ cm locations. This was somewhat expected since the emissive and Langmuir probes showed the largest plasma potentials and plasma potential oscillations occurring near the axis of the cathode.

G. Case 2: Prototype NSTAR Discharge Chamber Configuration

In the ion thruster discharge chamber configuration two operating conditions will be discussed, both having a relatively high discharge current of 18.0 A. In the first operating point, the xenon flow through the cathode was 13.0 sccm and the corresponding discharge voltage was 24.9 V. For the second operating point, the flow was reduced to 8.3 sccm which produced a higher discharge voltage of 36.0 V. The vacuum tank pressures were 5.6×10^{-5} Torr and 3.9×10^{-5} Torr, respectively.

5. DC Emissive Probe Profiles – Prototype NSTAR

Figure 10 shows time-averaged potential profile plots taken with the emissive probe at each of the operating points. Measurements were taken from $z = 0.5$ to 29.0 cm from the keeper orifice and $r = -29.5$ to 5.0 cm from the cathode centerline axis. Inside the main region of the discharge chamber the plasma potentials were 20 to 25 V for the 24.9 V operating point (point A) and 30 to 37 V for the 36.0 V operating point (point B). The plasma potential decreased at locations within a couple of centimeters of the orifice of the hollow cathode. Also, plasma potential dropped off as the emissive probe was moved outside of the discharge region (axial distances greater than $z \sim 10.5$ cm), however, plasma potential near the cathode centerline remained slightly higher than the potentials off centerline at locations just downstream of the pseudo-screen grid. The time-averaged potentials were highest near the anode (measured in the viewing slot cut in the conical portion of the anode). The plasma potentials dropped off gradually at radial positions outside of the anode. An outline of the discharge chamber is presented in all contour plots to help guide the eye of the reader.

It is noted that due to the viewing slot cut in the anode, there was some undesirable coupling of the discharge plasma to the outside of the anode wall to the magnet rings, especially when operating at high discharge currents. It is reasonable to assume that the fraction of discharge current carried to the outside of the discharge chamber was small compared to the fraction of current flowing to the interior wall of the discharge chamber since both the plasma density and accessible coupling area were a couple orders of magnitude higher inside the discharge chamber.

Figure 9. IEDF's measured with the ESA at operating conditions 1, 2, and 3 (open cathode configuration).

Figure 10a. Prototype NSTAR point A. Emissive probe potential measurements at $J_D = 18.0$ A, $\dot{m} = 13.0$ sccm Xe, $V_D = 24.9$ V.

Figure 10b. Prototype NSTAR point B. Emissive probe potential measurements at $J_D = 18.0$ A, $\dot{m} = 8.3$ sccm Xe, $V_D = 36.0$ V.

6. Triple Langmuir Probe Profiles – Prototype NSTAR

Figure 11 shows potential profile and electron density plots taken with the triple Langmuir probe for the 24.9 V discharge (operating point A). Low plasma potential was observed near the cathode/keeper assembly and the plasma potential was also low as the probe was moved outside of the discharge chamber. The highest potentials were observed near the anode walls and at off axis locations near the cathode.

In comparison to the emissive probe, the triple probe plasma potential structure was similar to, but higher at most locations. Note that the potential scale on the contour plots is different for the triple probe than the emissive probe. Inside the discharge chamber, the plasma potential was 20 to 32 V compared to the discharge voltage of 24.9 V. Unlike the emissive probe measurements, the plasma potentials went up to 50 V at some locations outside of the discharge chamber near the anode. As mentioned in the sections above, the triple probe is prone to errors and may have been affected by electrode shadowing and sheath interactions at the low plasma densities expected within the anode slot and in the regions outside of the discharge chamber. Both the triple Langmuir probe and the emissive probe indicated that the potentials at locations just outside of the pseudo-screen grid remained slightly higher near the chamber centerline compared to the potentials off centerline. Consistent with visual observation and the emissive potential measurements, the triple probe indicated that some plasma was being produced outside the anode region.

Figure 11a. Triple probe potential, operating point A ($J_D = 18.0$ A, $\dot{m} = 13.0$ sccm Xe, $V_D = 24.9$ V).

Figure 11b. Triple probe electron density, n_e (#/m³) ($\cong$ ion density, n_i) at operating point A.

In addition to plasma potential, the triple probe yields information about the electron temperature and electron density. At both operating points, the electron temperatures inside the discharge chamber ranged from 2 to 5 eV. A plot of the electron density for operating point A is shown in Figure 11b. The electron densities are plotted on a logarithmic scale from 1×10^{14} to 1×10^{19} particles/m³. The highest electron density was observed just downstream of the cathode. The plasma densities agree in magnitude with measurements on similar NSTAR-like discharges [Herman and Gallimore²² 2003].

7. Temporal Emissive Probe Potential Measurements – Prototype NSTAR

Temporal measurements of plasma potential are shown in Figure 12 where low amplitude potential oscillations on the order of 5 to 15 % of the discharge voltage were observed. The maximum amplitude of oscillations occurred near the cathode and was ± 2.5 V relative to the time-averaged values. The oscillations were found to be higher for lower flow rate, higher current and higher voltage conditions. In general, the oscillation amplitudes for the prototype NSTAR configuration were much lower than for the open cathode configuration. However, as with the open cathode configuration, potential fluctuation amplitudes increased at locations close to the hollow cathode.

Figure 12. Potential versus time at selected locations using the emissive probe at condition A ($V_D = 24.9$ V) and condition B ($V_D = 36.0$ V). The y-axis is plasma potential (0 to 50 V) and the x-axis is time (s).

8. Electrostatic Analyzer (ESA) Measurements – Prototype NSTAR

The remotely located ESA was used to investigate the discharge plasma produced in the prototype NSTAR configuration. Figure 13 shows the measured IEDF for each operating condition at selected zenith angles from 0 to 90 degrees. The entrance to the ESA was located about 55 cm away from the keeper plate. The most probable energy of the ions occurred at or just below the value of the discharge voltage. The magnitude of the ion current to the ESA was about 5 to 10 times less at 90 degrees compared to 0 degrees. At most operating conditions and zenith angles, there were a small number of ions that had energies above the cathode-to-anode voltage difference and the largest fractions of energetic ions were usually observed at off-axis zenith angles, usually from 15 to 30 degree angles.

Figure 13. IEDFs for angles of 0, 15, 30, and 90 degrees relative to the cathode centerline for operating points A (left) and B (right). Most ions had energies near the cathode-to-anode voltage difference.

IV. Correlation Model for Local and Remote Probes

Experimental results have been presented from a combination of locally and remotely located probes. Emissive and triple Langmuir probes yielded local spatial information such as the plasma potential, electron temperature, and electron density within the plasma while the remotely located ESA yielded information about the energy of ions flowing from the plasma region. It would be useful to correlate and compare measurements from the different probes, both to verify probe measurements and to investigate effects occurring in the plasma. To compare probe measurements, a model was created to use the locally measured plasma properties as input to generate output IEDFs. The generated IEDFs from the model were compared to the IEDFs measured with the remotely located ESA.

The model flow processes included the following steps:

1. Input steady state plasma profile geometry and create a two-dimensional mesh (r,z coordinates). The plasma potential values were used to estimate the electric field, E (V/m), at each (r,z) location and to calculate ion trajectories through the simulation region.
2. Input ion density spatial map. An equation was used to describe how the ion density varied experimentally with position.
3. Input time-varying plasma potential information. An equation was used to describe how the plasma potentials varied with time (one oscillation cycle) along with a second equation to describe how the potential (both dc and ac components) varied with position.
4. Calculate ion trajectories through the simulation region over a period of one oscillation. Ion weighting (ion density) and energy was varied over the entire mesh according to the measured plasma properties at each starting location.
5. For each ion tracked in the model, record the initial location, initial trajectory, exit location, energy, and weight to determine the resulting IEDF. In this model, the particles were assumed to travel along their starting trajectories and not be affected by the time-varying potential field. Future models could be improved by including the effects of varying electric fields as the particles accelerated from their creation points and moved through the simulation region.

H. Geometry Model

The simulation region consisted of a two dimensional array with limits corresponding to the measured emissive probe regions in each case. Figure 14 shows the mesh used for both cases. In the prototype NSTAR case, two regions were considered; one mesh was used when looking for ions that exited through the pseudo-screen grid (0 to 30 degrees with respect to the cathode) and another mesh was used when looking for ions that exited through the anode (90 degrees with respect to the cathode).

Figure 14a. Simulation region for the open cathode configuration. The cathode and anode are shown for reference.

Figure 14b. Simulation regions for the prototype NSTAR configuration. The cathode, anode, and pseudo-screen grid are shown for reference.

I. Ion Density Model

The ion density was modeled by fitting a power equation to the electron density data from the triple Langmuir probe. Due to the quasi-neutrality of the plasma, the ion density is equal to the electron density ($n_i \cong n_e$) at each location. The peak of the ion density was centered near the hollow cathode orifice and dropped as the distance was increased away from the cathode. The power fit equation was:

$$w_{avg}(x) = w_0(x)^{w_1} \quad (2)$$

Where $w_{avg}(x)$ was the weight, or density, of the ions, x was the distance from the peak ion density location (near the cathode/keeper orifice), and w_0 and w_1 were constants to describe how the ion density varied with distance. The ion density was limited to a maximum value close to the cathode when the distance, x , was small.

The temporal ion density for a particular location was then modified from its steady state value according to the electron-ion ionization cross section, which is a function of the potential, $\phi(r,z,t)$. This was done to account for higher ionization rates that will occur when the plasma potentials were high due to the increased electron-ion ionization cross section. The equation used was:

$$w_{particle}(r, z, \phi) = w_{avg}(r, z) \cdot \sigma(\phi) \quad (3)$$

Where $w_{particle}$ was the weight of a test particle, w_{avg} was the weight according to position, and σ was the electron-ion cross section determined by the potential at the initial particle location. Also note that the potential, ϕ , was a function of position and time. This modification to the weight of the particle results in a slight preference to particles being born at higher potentials.

J. Plasma Potential Model (Time-Varying + Position)

The plasma potential was observed to vary as a function of time and position in the emissive probe measurements. In general, the potential at a given position was calculated as the average potential at that location plus an oscillation potential:

$$\phi(r, z, t) = \phi_{avg}(r, z) + \phi_{osc}(r, z, t) \quad (4)$$

The average potential at a particle location, $\phi_{avg}(r,z)$, was sampled directly from the time-averaged emissive probe measurements at the chosen operating condition. Two equations were used to describe the potential oscillations: one equation described how the potential varied with time (over one oscillation cycle) and a second equation described how the potential magnitude varied with position:

$$\phi_{osc}(r, z, t) = \phi_{osc-p}(r, z) \cdot \phi_{osc-t}(t) \quad (5)$$

To describe how the plasma potential varied with time, equation (6) was used:

$$\phi_{\text{osc}_t}(t) = \begin{cases} \frac{1}{2-b} \cdot \left(1 - b - \cos\left(\frac{t}{b} \cdot 2\pi\right) \right) & \text{if } t < b \\ \frac{-b}{2-b} + \frac{1}{M} \cdot \sin\left[2\pi \cdot \left(\frac{t-b}{1-b}\right)\right] & \text{otherwise} \end{cases} \quad (6)$$

Where ϕ_{osc_t} was the potential at time, t . For the simulation, the time was varied from 0 to 1 to simulate one oscillation cycle and particle trajectories were calculated over the entire cycle. The variables b and M were constants and were chosen to approximate how the potential varied with time by looking at the emissive probe time-varying data. The potential oscillation profile was chosen such that the integral from time 0 to 1 was equal to zero. This means that on average the potential at each location was equal to the measured steady-state potential value from the emissive probe.

A second equation (7) was used to describe how the magnitude of the potential oscillations varied with position:

$$\phi_{\text{osc}_p}(d) = A \cdot \frac{C_1 \cdot e^{-C_2 \cdot \frac{d}{d_0}} + C_3}{C_1 + C_3} \quad (7)$$

Where ϕ_{osc_p} was the potential as a function of position, d . The value d_0 was a reference value of the maximum distance from the origin to the farthest point in the simulation:

$$d_0 = \sqrt{(r_{\text{max}})^2 + (z_{\text{max}})^2} \quad (8)$$

The variable, d , was the distance from the center of the peak oscillation to the particle location:

$$d = \sqrt{(r_{\text{particle}} - r_{\text{center}})^2 + (z_{\text{particle}} - z_{\text{center}})^2} \quad (9)$$

Consequently, the ratio, d/d_0 , could vary from about 0 to 1 over the simulation region. The maximum oscillation potential amplitude, A , was established from the time-varying emissive measurements. The constants C_1 , C_2 , and C_3 were found from fits to the emissive probe data that determined the envelope of the potential oscillations with distance from the maximum.

Another effect that was included in the simulation was the effect of differences in the oscillation phase between different locations in the plasma. This effect was modeled as a small amplitude, random modification to the time, t , in the potential oscillation function, $\phi_{\text{osc}_t}(t)$:

$$t = t_i - R \cdot t_{\text{phase}} \quad (10)$$

Where t was the time used to determine the potential at which the particle was generated, t_i was the time along in the cycle, R was a random number between 0 and 1, and t_{phase} was the maximum allowable phase difference between points. The value t_i was determined in the simulation by dividing up the oscillation cycle into an even number of increments and then generating particles at each of those points in the cycle. The value t_{phase} was determined from the time-varying emissive probe measurements and could vary from 0 to 1. A value of zero for t_{phase} meant that all of the potentials in the simulation were rising and falling at the same time. Generally, it was found that for the open cathode case, some phase value other than zero (but less than 0.3) was needed to make the simulation results agree with the measurements, whereas for the prototype NSTAR case, a phase of zero was suitable. Table 1 shows the values used for the potential oscillations in each case. Notice that the main difference between the cases is in the magnitude of the oscillations which were controlled by variables M and A that were obtained from curve fits to probe measurements.

Figure 15 shows plots of the potential versus time for each simulation case along with sample measurements from the time-varying emissive probe data. The values for b , M , and A were chosen to reproduce the general shape of the oscillations. The magnitude of the potentials in the open cathode was much higher than the magnitude in the prototype NSTAR case. Also, as seen in the emissive probe measurements, the magnitude of the potentials was made to drop off as the distance from the oscillation center point increased.

Table 1. Model values used to describe plasma potential variations.

Variable	Case 1	Case 2
b	0.18	0.00
M	10.0	1.0
A	120.0	2.5
C_1	1.0	1.0
C_2	5.0	5.0
C_3	0.1	0.1
t_{phase}	0.25	0.00

Figure 15a. Simulated maximum potential oscillation profile (one cycle) versus time for the open cathode configuration ($b = 0.18$, $M = 10.0$, $A = 120.0$, $\phi_{avg} = 30$ V, $r = r_{osc_center}$, $z = z_{osc_center}$).

Figure 15b. Sample time-varying emissive probe measurements for the open cathode configuration (Cond. 1c, $J_D = 11.25$ A, $\dot{m} = 7.6$ sccm Xe, $V_D = 34$ V, $r = -1.5$ cm, $z = 2.0$ cm). Note that the emissive probe was not capable of measuring voltages above 85 V.

Figure 15c. Simulated maximum potential oscillation profile (one cycle) versus time for the prototype NSTAR configuration ($b = 0.00$, $M = 1.0$, $A = 2.5$, $\phi_{avg} = 25$ V, $r = r_{osc_center}$, $z = z_{osc_center}$).

Figure 15d. Sample time-varying emissive probe measurements for the prototype NSTAR configuration (Cond. 2d, $J_D = 13.0$ A, $\dot{m} = 13.1$ sccm Xe, $V_D = 25.2$ V, $r = -0.5$ cm, $z = 2.0$ cm).

K. Open Cathode Configuration - Simulation Results

Operating conditions 1, 2, and 3 were examined for the open cathode setup. Figure 16 shows the basic setup of the simulation region along with the relative locations of the cathode, anode, and remotely located ESA. The ESA was positioned about 45 cm downstream of the keeper at radial locations of 0.0, -3.0, and -6.0 cm relative to the cathode centerline. It was estimated that the ESA had an acceptance angle of about 3 degrees based on the aperture dimensions. In reality, the ESA has a conical acceptance because ions can enter the ESA if they have small tangential velocity components and still travel through the spherical ESA segments to the collector plate. However, for this two dimensional simulation, all tangentially directed ions were ignored.

Figure 16. Setup of the ESA relative to simulation region. The ESA was positioned 45 cm downstream of the keeper (Cond. 3, $J_D = 15.0$ A, $\dot{m} = 7.6$ sccm Xe, $V_D = 33.5$ V). Time-averaged profile is shown for reference.

Figure 17 illustrates the ion weighting and peak potential oscillation profiles used in the simulation. The ion density profile was modeled as a power fit equation with the peak ion density located near the cathode/keeper orifice. Constants in the power fit were determined from the triple Langmuir probe electron density profiles. The potential oscillation profile was modeled as an exponential function with the peak located a few centimeters downstream of the cathode/keeper orifice. The potential profile in Figure 17b is modified according to the time during the oscillation cycle and added to the average potential at each location.

Figure 17a. Ion weighting profile. The peak density was located near the cathode/keeper orifice at $r = 0.0$ cm, $z = 1.0$ cm.

Figure 17b. Profile of the maximum potential oscillation ($A = 120$ V). The oscillation peak was centered at $r = 0.0$ cm, $z = 2.5$ cm from the cathode.

Once the ion density and potential profile was determined for a particular time during the cycle, ions were placed throughout the simulation region and their trajectories were calculated. Each ion trajectory was determined from local electric fields that were calculated from gradients of the plasma potential profile. Figure 18 shows the starting point of ions that had trajectories toward the ESA over the entire oscillation cycle for condition 3. If the calculated trajectory indicated that the ion would travel toward the ESA, and the ion was within the required acceptance angle, the particle was binned according to ion energy to create the IEDF. In most cases, the simulation was run where the initial trajectory of each ion was calculated and the ions were not tracked further. This was done due to the long simulation times required if each ion path was calculated. The energy of the ion was assumed to be equal to the potential difference between the ion starting point and the ESA, which was assumed to be at 0 V.

Figure 18. Plot of the locations and peak potentials of ions that were created in the simulation region that were directed toward the ESA and were within the ESA acceptance angle. The ions were binned according to ion energy. Three ESA locations of $r = 0.0$, -3.0 , and -6.0 cm are shown at condition 3 ($J_D = 15.0$ A, $\dot{m} = 7.6$ sccm Xe, $V_D = 33.5$ V).

After the particles had been monitored and recorded over the oscillation cycle, the binned particles were used to create the resulting IEDF. The ions were grouped according to energy and the particle weights were added to determine the relative strength of particles with different energies. Then, the distribution was normalized to the peak value, which typically occurred near the discharge voltage similar to the experimentally measured IEDF.

Figure 19 shows IEDFs from a simulation along with the measured IEDFs from the ESA for operating conditions 1, 2, and 3. Both the simulation and the ESA measurements showed a main group of ions with energies from about 20 to 50 eV, near the discharge voltage. This is expected since a large portion of the oscillation cycle was spent where the potentials in the discharge plasma were near the value that would result in these ion energies. There was also a second group of ions having energies above 50 eV for both the ESA measurements and the simulations. These more energetic ions were produced when the potentials were in the higher portion of an oscillation cycle.

Figure 19a. Simulation results for condition 1 at radial locations of 0.0, -3.0, and -6.0 cm.

Figure 19b. Measured IEDF using the ESA for condition 1 ($J_D = 7.5$ A, $\dot{m} = 7.6$ sccm Xe, $V_D = 33$ V).

Figure 19c. Simulation results for condition 2 at radial locations of 0.0, -3.0, and -6.0 cm.

Figure 19d. Measured IEDF using the ESA for condition 2 ($J_D = 11.25$ A, $\dot{m} = 7.6$ sccm Xe, $V_D = 34$ V).

Figure 19e. Simulation results for condition 3 at radial locations of 0.0, -3.0, and -6.0 cm.

Figure 19f. Measured IEDF using the ESA for condition 3 ($J_D = 15.0$ A, $\dot{m} = 7.6$ sccm Xe, $V_D = 33.5$ V).

The agreement between general trends in the simulated and measured IEDFs is considered to be good. Specifically, the simulation results suggest there were more energetic ions present when the ESA was positioned closer to the cathode centerline (at $r = 0.0$ cm). This result agrees with both the experimental IEDFs and the emissive probe measurements in which the highest plasma potentials were measured on the cathode centerline. Also similar to

the measured distributions from the ESA, the amount of energetic ions in the simulated IEDFs increased relative to the main ion group as the discharge current was changed from 7.5 to 15.0 A (1-3). In a more detailed comparison, one can see that the simulated IEDFs slightly overestimate the high ion energy component when the line of sight is along the cathode centerline. The drop in energetic ion content with radial position was more pronounced for the simulated IEDFs.

The shape of the distributions obtained from the simulations could be varied by adjusting the values for the weighting, oscillation profile, oscillation magnitude, or phase. The values used in these simulations were chosen because they gave a reasonable representation of the measured plasma properties from the emissive and triple Langmuir probes. In addition, the chosen simulation parameters also yielded reasonable agreement between the simulated IEDFs and the ESA measurements. The floating emissive probe showed large amplitude plasma potential oscillations having values ranging from 20 V to 85 V when the discharge voltage was near 34 V along with the existence of a DC potential hill that existed downstream of the hollow cathode, with peak plasma potentials up to 55 V above the cathode to anode voltage. Resulting from the large amplitude potential fluctuations, the simulations and measurements showed groups of ions with energies well above the cathode-to-anode voltage. The data suggests that the large amplitude plasma potential oscillations are the likely mechanism responsible for the creation of high energy ions.

L. Open Cathode Configuration - Simulation Results

The simulation was also exercised for condition B of the prototype NSTAR discharge chamber configuration. The simulation was run with the ESA positioned at angular locations of 0, 15, 30, and 90 degrees relative to the cathode centerline. The ESA entrance point was positioned at 55 cm from the cathode in all cases. Figure 20 shows the simulation setup with the approximate angles of acceptance to the ESA. Binned particles are shown that had the proper position and trajectory to be accepted into the ESA over the entire oscillation cycle.

The amplitude of the oscillations, A , was set to 2.5 V based on the time-varying emissive probe measurements. Although the amplitudes of the potential oscillations were relatively small in prototype NSTAR case compared to the open cathode case, the oscillations were included because they would affect the widths of the IEDFs. The phase value, t_{phase} , was set to zero based on the time-varying multiple emissive probe experiments, which showed only small variations of the potential oscillations with position. The ions were binned according to energy and the particle weights were added to determine the relative strength of particles with different energies.

Two different regions were used in the simulation for the prototype NSTAR configuration. One region was used for the 0, 15, and 30 degree angles and a separate region was used for the 90 degree angle. At the 0, 15, and 30 degree angles, ions were accepted to the ESA from both inside and outside the discharge chamber. Although it appears more ions came to the ESA from outside the discharge chamber, especially in the 15 and 30 degree cases, these ions carried much less weight (corresponding to density) than the ions created closer to the cathode region. At the 90 degree angle, most of the accepted ions originated from either near the anode or outside of the discharge chamber. This was because ions formed inside the discharge chamber were directed on paths toward the center of the discharge chamber.

The resulting distributions are shown for operating point B in Figure 21 along with ESA measurements made at the same positions relative to the cathode. Looking first at the simulation results, the IEDF was much stronger at the 0 degree zenith angle. As the simulated ESA position was varied to 15 and 30 degrees, the distribution magnitude dropped. The magnitude of the distribution was also lower at the 90 degree angle. In all cases, the widths of the IEDFs were similar.

Figure 20. Simulation setup at condition B for the prototype NSTAR discharge chamber ($J_D = 18.0$ A, $\dot{m} = 8.3$ sccm Xe, $V_D = 36.0$ V). Binned particles are shown that had the proper position and trajectory toward the ESA to be measured.

Figure 21a. Simulation results for prototype NSTAR condition B at zenith angles of 0, 15, 30, and 90 degrees.

Figure 21b. ESA measurements for prototype NSTAR condition B.

Trends observed in the simulations were also observed in ESA data. One example is the similarity between the most probable energies of the ions. Corresponding to the 36 V discharge voltage, ions with energies in the 25 to 40 eV range were recorded. It appears that ions were able to leave the discharge region and enter the ESA most readily at the 0 degree zenith angle. Also, in both the simulation and measurements, the most probable energy of the distribution increased slightly as the ESA was moved from 0 to 30 degrees. This may be because ions created at slightly lower energies (15 to 30 eV) near the pseudo-screen grid were not directed toward the ESA (when positioned at a zenith angle of 30 degrees) in a manner that would allow them to flow through the ESA collimators.

Another similarity between the simulation and measurement was at the 90 degree angle for condition B where two groups of ions were seen. One ion group had an energy near 26 eV and the second ion group had an energy near 36 eV. This makes sense if one re-examines Figure 20 for the time-averaged plasma potential profile. The plasma potential near the anode was about equal to the discharge voltage of 36 V and the potential farther outside of the anode was near 26 V.

V. Conclusion

Herein we presented data on plasma structures and fluctuations occurring nearby hollow cathode devices. The prototype NSTAR discharge configuration showed plasma potentials near the discharge voltage along with low amplitude potential fluctuations (5-15% of the discharge voltage). Remotely measured ion energies were in good agreement with locally measured plasma potentials and very few highly energetic ions were detected. Hence our measurements do not identify a cause for the observed erosion of cathode and keeper structures located within quiet discharge chamber plasmas. Conversely, in the open cathode discharge configuration, very large amplitude plasma potential fluctuations (~ 80 V p-p) and DC potential hill structures are reported nearby a hollow cathode when emitting ampere level plasma electron current. Data and simulations based on local plasma property measurements presented herein suggest that large amplitude plasma potential oscillations are the likely mechanism responsible for the creation of high energy ions in open hollow cathode configurations. Both the DC potential structures and the potential fluctuation levels are cause for concern when hollow cathodes are considered for long term operation in open configurations because energetic ions will be created that will sputter erode hollow cathode assembly components.

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