DIRECT AND REMOTE MEASUREMENTS OF A HOLLOW CATHODE DISCHARGE

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Abstract

Results are presented from measurements made on a hollow cathode generated plasma using direct and remotely located probes. Based on previous life tests where erosion was seen on hollow cathode assembly components, it is necessary to understand the plasma flow field downstream of hollow cathodes. Experiments have been performed where large amplitude plasma potential oscillations were seen from measurements made using a floating emissive probe (potentials ranging from 20 V to 85 V within a 34 V discharge). In addition to the emissive probe, results are presented from a direct measurement triple Langmuir probe. Also, a remotely located electrostatic analyzer (ESA) was used to measure the energy of ions produced within the plasma.

I. INTRODUCTION

Previous ion thruster and hollow cathode life tests have shown erosion to hollow cathode components that could lead to failure of a thruster during a long mission [1,2]. It is presumed that the wear was caused by ions that were created somewhere in the downstream plasma that sputter eroded the cathode surfaces. Therefore, it is of interest to examine the plasma structure near the hollow cathode.

In this paper, direct and remotely located probes were used to make measurements on a plasma produced by a hollow cathode. Direct measurement emissive and triple Langmuir probes were used to estimate the plasma potential (V_p), electron density ($n_e(\sim n_i)$), and electron temperature (T_e) at different locations within the plasma. Also, a remotely located electrostatic analyzer (ESA) was used to measure the energy of the ions coming from the plasma (E/z). The goal of this activity is to correlate spatial and temporal information from the various probes to obtain a better understanding of the nature of the potential structures and erosion-causing mechanisms in the plasma.

II. EXPERIMENTAL APPARATUS

A. Hollow Cathode Produced Plasma

A picture of the cathode plasma configuration is shown in Fig. 1. The cathode assembly (consisting of the hollow cathode, heater, and enclosed keeper) was setup in the center of a stainless steel ring anode. To produce the plasma discharge, electrons were drawn from the cathode to the ring anode. The plasma was produced in a relatively open configuration and no magnetic fields were applied. The ring anode was about 19.5 cm in diameter and 9 cm in length. Each probe was mounted to two linear positioning stages (radial and axial) to allow for movement to different locations within the plasma.

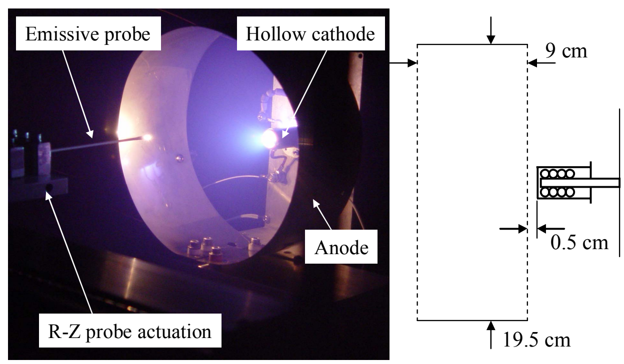

Figure 1. Experimental setup showing the hollow cathode assembly and ring anode used to produce the plasma.

B. Floating Emissive Probe (Direct)

An emissive probe, shown in Fig. 2, was used to measure the potential of the discharge plasma. When the filament is heated to a temperature hot enough to emit a sufficient rate of electrons, the probe will float near plasma potential [2]. Some error in the emissive probe measurement can come from incorrect heating current, voltage drop across the filament, and even when hot enough, the probe will float slightly below the true plasma potential [3], which becomes worse in dense plasma. However, the emissive probe is very useful due to the quick and direct nature of measurement.

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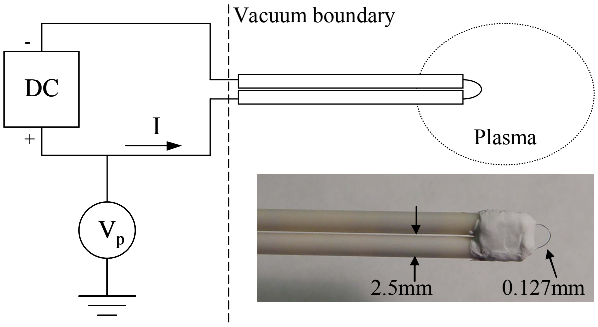

Figure 2. Floating emissive probe used to measure plasma potential (0.127 mm filament).

For the measurements presented here, the plasma potential was measured using a voltmeter connected to the probe thorough a high-impedance, low-capacitance filter. The filter was necessary to reduce the effects of the meter on the floating probe [4]. The data acquisition system was capable of measuring voltages from ~ 0 V to 85 V at a rate of up to ~ 2 MHz.

C. Triple Langmuir Probe (Direct)

Langmuir probes consist of electrodes (single, double, or triple) placed in a plasma to collect ion and electron currents under imposed biases [3,5]. 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, 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. A diagram of the triple probe is shown in Fig. 3. Three tantalum electrodes with diameters of 0.381 mm were used. The electrodes were housed in an aluminum-oxide, four-bore tube with a separation distance of about 1.0 mm. With this setup, four voltages were recorded. The floating potential was measured on one of the three electrodes while the other two electrodes were biased using a power supply to measure ion and electron currents. The bias voltage, V_4, was held constant at 20 V.

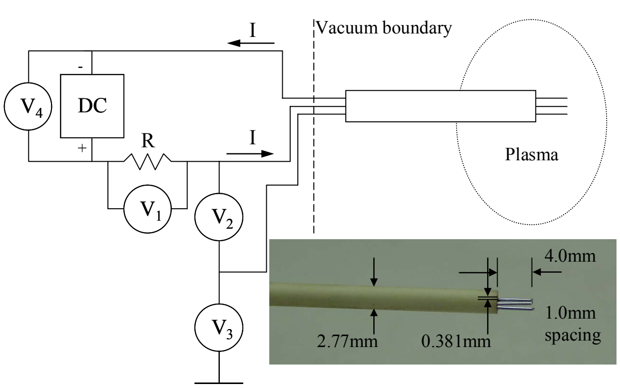

Figure 3. Triple Langmuir probe schematic.

There are certain requirements for the triple probe relations to be valid [5]. 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, quasineutrality is assumed and the electrons are assumed to be Maxwellian.

D. Electrostatic Analyzer (Remotely Located)

A Comstock model AC-901 electrostatic analyzer (ESA) was used to measure the energy of the plasma ions [6]. The ESA consisted of two spherical sectors nested in a 160° arc. The ESA had collimators at each end of the arc to allow for very narrow solid angle acceptance of ions moving toward the detector. The collector electrode was located downstream of the exit collimator. To yield the ion energy distribution function (IEDF), 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, a picoammeter was used to measure the ion current that flowed to the collector electrode.

III. DATA AND RESULTS

Three operating conditions were chosen for analysis (Table 1). At each operating condition, the xenon flow rate and discharge current were held constant while the discharge voltage was allowed to self regulate.

Table 1. Test Conditions.

Cond.	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

A. Emissive Probe Profiles (Steady State)

Figure 4 shows potential profiles taken with the emissive probe. The potentials generally ranged from about 16 V to 50 V, with the potentials dropping off as the emissive probe was moved farther away from the discharge region (axial distances greater than z ~ 10 cm). Also, the potentials decreased as the probe was moved close to the cathode, to within a couple of cm radius from the cathode/keeper orifice. The contour plots show the time averaged potential of the emissive probe.

At the 7.5 A discharge condition, there was a potential rise, or potential hill, just downstream of the hollow cathode where the peak 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 and moved farther downstream of the cathode. Also, the peak potential magnitude decreased when the discharge current was increased from 7.5 A to 15.0 A.

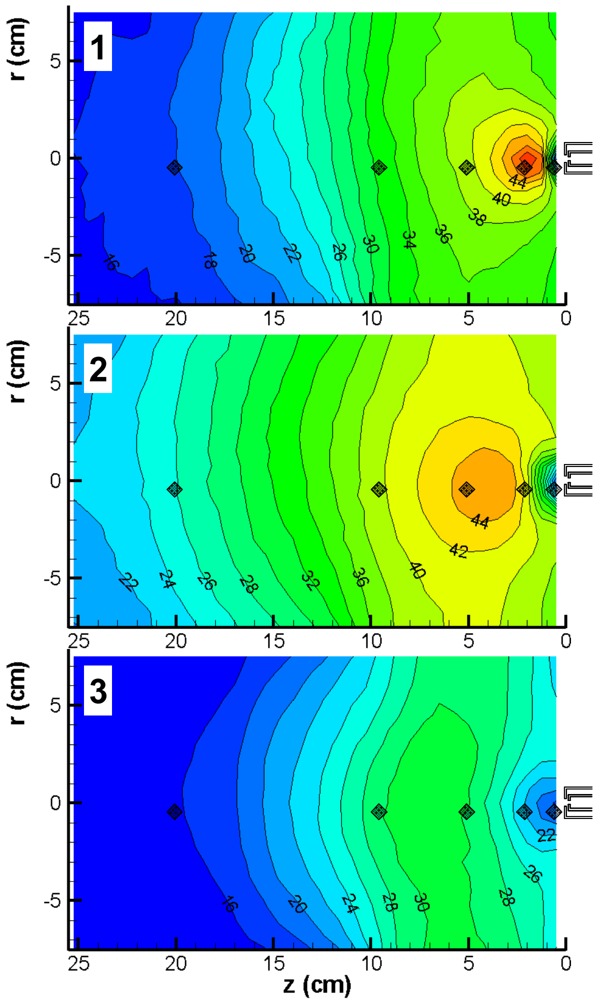

Figure 4. Emissive probe potential measurements at condition 1 (J_D = 7.5 A, V_D = 33.0 V). condition 2 (J_D = 11.25 A, V_D = 34.0 V), and condition 3 (J_D = 15.0 A, V_D = 33.5 V).

B. Triple Langmuir Probe Profiles (Steady State)

Figure 5 shows potential profile plots taken with the triple Langmuir probe. Similar to the emissive probe measurements, the potentials dropped off as the emissive probe was moved farther away from the discharge region (axial distances greater than z ~ 10 cm). The same potential well was observed when the triple probe was moved to within a couple of centimeters of the cathode/keeper orifice.

The triple probe results also show 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. One possible cause of error with the triple Langmuir probe is when significant numbers of primary electrons are present, as could be the case near the cathode and within the potential hill region. Another factor in triple probe error could be caused by the presence of intense plasma oscillation.

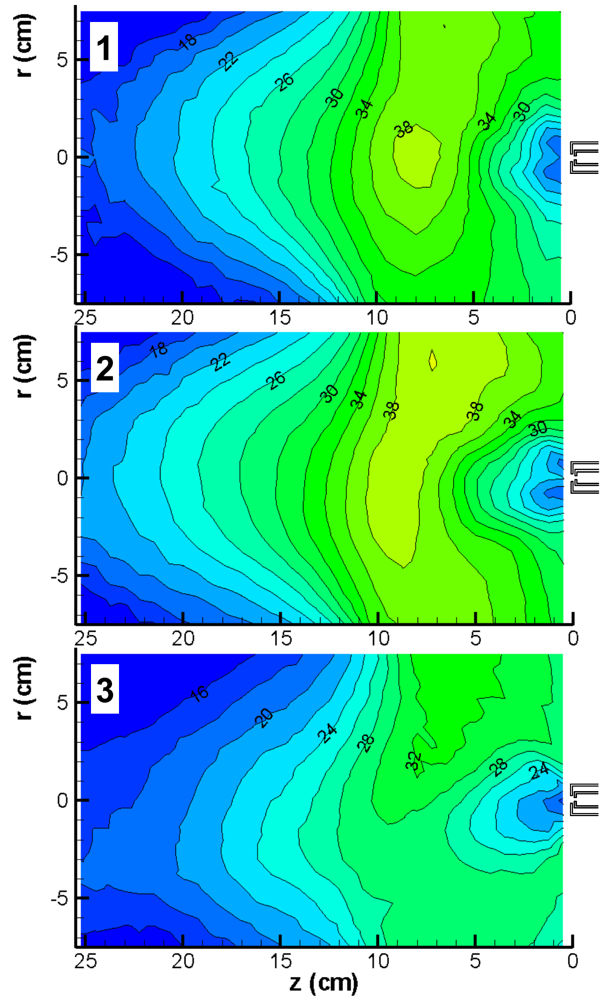

Figure 5. Triple Langmuir probe potential measurements at condition 1, 2, and 3.

C. Emissive Probe Potentials (Time Varying)

The emissive probe was also used to characterize the time-varying potentials (plasma potential fluctuations). Voltages were sampled at a rate of 1 Mhz using a high speed data acquisition system. The selected positions for the oscillation measurements are shown in Fig. 4 (r = 0.5 cm, z = 0.5, 2.0, 5.0, 9.5, and 20.0 cm).

Figure 6 shows the potential waveforms at each location. The largest potential oscillations were observed near the cathode centerline from about z = 1 cm to z = 6 cm from the cathode. At some locations, the potentials varied from about 20 V to over 85 V, which is the maximum potential that the emissive probe circuit is capable of measuring. We consider it likely that the plasma potential could have been fluctuating to potentials higher than 85 V. Like 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).

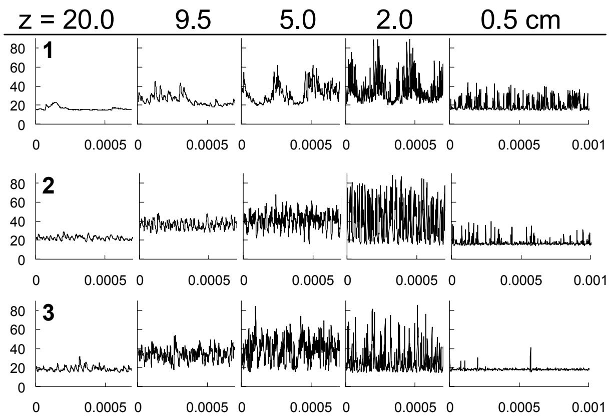

Figure 6. Potential oscillations for conditions 1, 2, and 3 (at r = 0.5 cm, z from keeper). The y-axis is plasma potential (0 V to 90 V scale) and the x-axis is time (s).

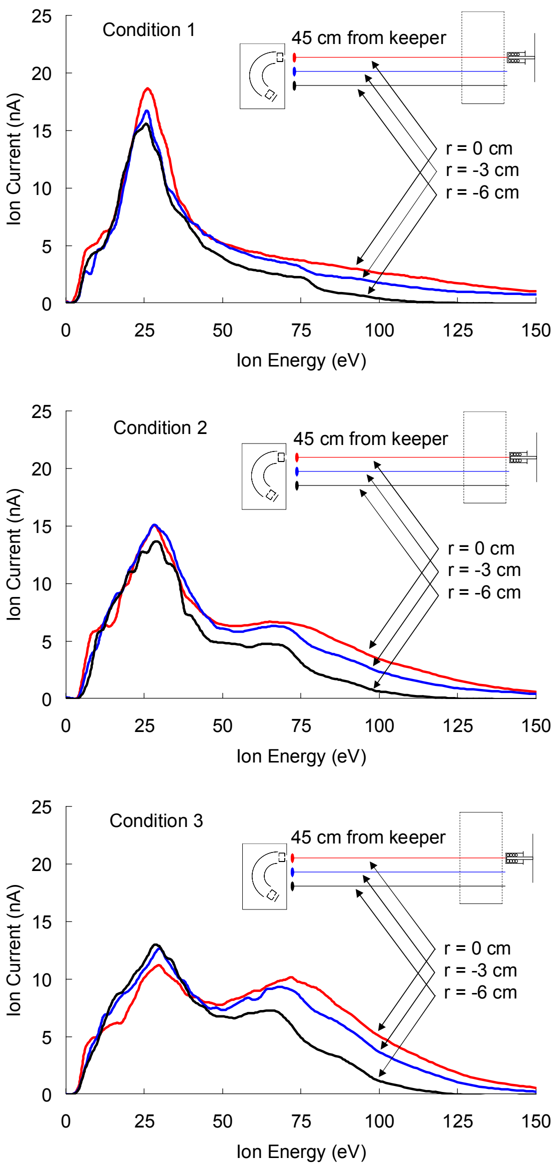

Figure 7. IEDF's measured with the ESA.

D. Electrostatic Analyzer (ESA) Data

The ESA was used to look at the discharge plasma. Figure 7 shows the measured IEDF's at the three operating conditions. The entrance to the ESA was located about 45 cm downstream of the keeper plate. Each of the three IEDF's corresponds to a radial location of the ESA relative to the cathode (r = 0 cm, -3 cm, and -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 a high energy ion signal present that had energies above 100 eV. As the discharge current was varied from 7.5 A to 15 A, the amount 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 is somewhat expected since the largest potentials and oscillations were seen closer to the cathode centerline axis.

IV. SUMMARY

A combination of direct (emissive, triple Langmuir) and remotely located (ESA) probes were used to study a plasma discharge that was driven by a hollow cathode. Using a floating emissive probe, large amplitude plasma potential oscillations were seen having potentials ranging from 20 V to 85 V when the discharge voltage was near 34 V. Remotely located ESA measurements showed a group of ions with energies near the discharge voltage as well as higher energy ions with energies over 100 eV.

V. REFERENCES

[1] M. T. Domonkos and G. J. Williams, Jr., "Investigation of Keeper Erosion in the NSTAR Ion Thruster," IEPC Paper 01-308, 27th International Electric Propulsion Conference, Pasadena, CA, October 2001.

[2] D. A. Herman and A. D. Gallimore, "Discharge Chamber Plasma Potential Mapping of a 40-cm NEXT-type Ion Engine," AIAA-2005-4251, 41st Joint Propulsion Conference and Exhibit, Tuscon, AZ, July 2005.

[3] B. E. Beal, A. D. Gallimore, and W. A. Hargus, Jr., "Plasma properties downstream of a low-power Hall thruster," Physics of Plasmas, 123503, December 2005.

[4] D. M. Goebel, K. Jameson, I. Katz, and I. G. Mikellides, "Energetic Ion Production and Keeper Erosion in Hollow Cathode Discharges," IEPC Paper 2005-266, 29th IEPC, Princeton, NJ, Oct. 31-Nov. 4, 2005.

[5] B. E. Beal, "Clustering of Hall Effect Thrusters for High-Power Electric Propulsion Applications," Thesis, University of Michigan, 2004.

[6] ESA Operating Manual, Model AC-901, Double Focusing Electrostatic Energy Analyzer, Comstock Inc., Oak Ridge, TN, 37830.