Direct and Remote Measurements of Plasma Properties nearby Hollow Cathodes

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Abstract: Measurements are presented of plasma properties near a hollow cathode made using a rapidly actuating Langmuir probe. The probe’s x-y positioning system is designed to allow characterization of the intense plasma region commonly present within a few millimeters of a hollow cathode orifice. Of major concern for the Langmuir probe is the probe surface temperature, which should remain below ~1500 K during use to avoid electron emission and possible corruption of the current/voltage characteristics it is intended to measure. To avoid excessive temperatures, the probe is afforded minimum time in intense plasma regions via use of a motion system traveling at an average speed of ~1 m/s. The system is used to execute a complete Langmuir trace every 0.5 mm over ~6 cm of travel. A combined electrostatic analyzer (ESA) and Wein Filter (ExB) probe is also described. The ESA/ExB system is used to remotely measure the energy and charge state of ions produced within a prototype NSTAR discharge chamber. The ESA portion of the probe is employed to measure the ion distribution as a function of energy per charge state (E/z). The ExB probe section is then used to measure the charge state (z) of the ions with the ESA portion set to an E/z of interest. Detailed measurements are reported along various lines-of-sight where the remotely located probe is aimed (relative to the axis of the discharge chamber). Plans are described where future correlations between direct and remote measurements will be performed.

Nomenclature

\[
\begin{align*}
A_p &= \text{probe surface area (cm}^2) \\
B &= \text{magnetic field (Tesla)} \\
c_p &= \text{tungsten probe specific heat (J/kgK)} \\
E &= \text{electric field (V/m)} \\
F &= \text{Lorentz force (N)} \\
I_e &= \text{electron collection current (A)} \\
I_{sat,e} &= \text{electron saturation current (A)} \\
k &= \text{Boltzman constant (J/K)} \\
m &= \text{probe mass (kg)} \\
\dot{m} &= \text{mass flow rate (kg/s)} \\
m_e &= \text{electron mass (kg)} \\
n_e &= \text{electron number density (cm}^{-3}) \\
\sigma &= \text{Stefan-Boltzmann constant (W/m}^2\text{K}^4) \\
P_{\text{probe}} &= \text{heating due to electron collection (J/s)} \\
q_e &= \text{elementary charge (C)} \\
Q_{\text{cond}} &= \text{cooling effect due to conduction (J/s)}
\end{align*}
\]

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\[ \dot{Q}_{rad} = \text{radiation heating component (J/s)} \]
\[ \dot{Q}_{re-rad} = \text{cooling effect due to re-radiating the heat to the surroundings (J/s)} \]
\[ \Delta t = \text{incremental time step (s)} \]
\[ T_e = \text{electron temperature (eV)} \]
\[ T_\infty = \text{temperature of the surroundings (K)} \]
\[ T_{p,i} = \text{probe temperature at the current time step (K)} \]
\[ T_{p,i-1} = \text{probe temperature from the previous step (K)} \]
\[ R_{tot} = \text{thermal network resistance} \]
\[ V_B = \text{probe bias potential (V)} \]
\[ V_p = \text{plasma potential (V)} \]
\[ W = \text{ohmic heating effect (J/s)} \]
\[ v_e = \text{electron velocity (m/s)} \]
\[ v_i = \text{ion velocity (m/s)} \]

I. Introduction

Life tests performed on both an engineering model NSTAR thruster and an NSTAR flight spare thruster conducted at the NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL) have revealed extensive erosion on both the discharge keeper and hollow cathode electrodes.\(^1,2\) The reason for this erosion has not been fully explained. Mapping of the plasma parameters directly downstream of a cathode assembly may assist in developing an understanding of the erosion processes by correlating cathode operating conditions to discharge plasma characteristics and providing data for model validation. Several research groups have successfully mapped the internal plasma of an ion engine nearby\(^3,4,5\) and within\(^6\) the hollow cathode and keeper structures.

One possible reason for increased erosion rates of keeper and cathode structures is bombardment by energetic or multi-charged ions. Energetic ions are inferred to be ions produced in the discharge plasma with energies exceeding the cathode-to-anode potential difference and can cause significant sputter erosion when striking the keeper or cathode. Multi-charged ions produced near the keeper and cathode can cause significantly more sputter erosion, because the energy they obtain is a multiple of both their charge state and the potential difference they fall through when striking the keeper or cathode surfaces. The energy gained by a multiply charged ion falling through a small potential difference can be sufficient enough to cause sputter erosion, whereas a singly charged ion falling through the same potential would not.

The work presented herein was focused on the near-field study of a simple hollow cathode configuration operated without a keeper electrode or any applied magnetic fields. This was done to provide data, from a very simple system, that is beneficial to model application and validation. Future work will focus on (1) documenting the effects an enclosed keeper and applied magnetic fields have on plasma flow field parameters, (2) correlation of direct plasma property measurements to remote diagnostics that monitor ion energy and charge state distribution, and (3) investigations of techniques for mitigating the causes of keeper and cathode erosion.

The main objective of the research presented in this paper is to demonstrate a method for obtaining high spatial resolution maps of plasma parameters near a hollow cathode. A fast actuating motion system for Langmuir probe placement, described in Section II, was used to accomplish this task. Section II also contains a description of a unique ion energy and charge state detector capable of characterizing the expanding plasma region surrounding plasma discharges created by hollow cathode devices. The detector was comprised of an electrostatic energy analyzer (ESA) stage and an ExB (or Wein filter) stage. In Sections II.D and II.E, a summary of the techniques used to analyze Langmuir probe traces and ESA/ExB data is presented. Section III contains results collected over wide ranges of flow rate and emission current, and Section IV contain conclusions and a discussion of recommendations for future work.
II. Experimental Apparatus

A description of the Langmuir probe positioning apparatus and related details are contained in Section A through D below. The combined ESA and ExB probe, for measurement of ion energy and charge state distributions, is described in Section E. Finally, a brief description of the vacuum test facilities is provided in Section F.

A. Rapidly Actuating Probe of Ion Diagnostics (RAPID) System

One of the key components for this study was a fast positioning system for Langmuir probe placement that was designed and constructed by a team of undergraduate and graduate students at Colorado State University. This positioning system was designed to travel into and out of intense plasma regions quickly while taking Langmuir probe traces over small increments of distance during the entire extent of its motion. Several important design details are included in Sections 1, 2, and 3 below.

1. Probe Thermal Analysis

When probing the plasma near a hollow cathode it is important that the residence time of the probe within intense plasma regions be held to a sufficiently short period. The following describes a simple thermal model used to determine temperature and time constraints for the heating and cooling of the Langmuir probe subjected to immersion within intense plasma.

Thermal analysis consisted of models describing the heat transfer to and from the probe tip. The Langmuir probe bias scheme, which will be explained later, consists of a saw-tooth type waveform with a maximum peak-to-peak amplitude of ~100 V. Due to this waveform, the probe was periodically heated from plasma electrons that were collected during times when the probe was held positive of the local plasma potential. This time interval was relatively short compared to the total immersion period in the plasma because of the waveform’s duty cycle (typically set to ~15% ±5% at a repetition rate of 1 to 10 kHz). Consequently, two models were developed: one for modeling the temperature rise during a probe operational sequence and one for determining the cooling time required before performing a subsequent scan. The heat addition model takes into account three methods of heat transfer (radiation from the hollow cathode components, electron collection, and ohmic heating) and two methods of heat rejection (radiation and conduction). The conduction cooling was neglected in some calculations to obtain worst-case probe temperature predictions. Through the use of this heat addition model, it was possible to determine the maximum exposure time of a probe to a given plasma environment, and particular probe waveform bias. A cool-down section of the model was developed to evaluate the required time for the probe to reach near ambient conditions after exposure to a plasma environment. As mentioned above, cooling processes included radiation to the surroundings and conduction down the probe lead and support structure. Typical plasma environments were assumed to be represented by a 30 V plasma potential, 6.5 eV electron temperature, and 10^{13} cm^{-3} plasma density. A lumped mass, discretized approach was used to develop thermal networks, and, from these networks, the following equations were constructed:

![Diagram of Langmuir probe heating model](image-url)

Figure 1. Langmuir probe heating model showing the contributions of different effects on temperature over time.
To validate the thermal model, a thermal-couple of similar dimensions to our Langmuir probe was used as a mock probe and placed in vacuum near a plasma source. Results indicated that in order for the probe tip temperature not to exceed 1500 K and become emissive, it must not be in the most intense plasma region for more then ~55 ms (assuming 1 m/s travel, 50 V waveform amplitude, 20% duty cycle, and 10 kHz repetition rate). A graph of these results can be seen in Figure 1. Once out of the plasma, the model predicts that the probe should be below 400 K and ready for another scan in less than 5 seconds, as shown in Figure 2. For the speed and waveform used in this study, probe maximum temperature was determined to be 1123 K.

2. Segmented Langmuir Probe Design

The presence of a Langmuir probe within a plasma has a perturbing effect, which is especially true of plasmas possessing large property gradients. Another part of the perturbation effect comes from the probe biasing scheme, especially when excessively positive voltage biases cause large currents to flow to the probe. This is both expected and more or less unavoidable. However, Staack et al. have found secondary electron emission from the insulated ceramic tubes surrounding and supporting most Langmuir probes can induce significant plasma perturbations. These perturbations were noted to be large enough to change plasma parameters on the order of their steady state values. In order to find a solution to this problem, the team at Staack et al. researched several low secondary electron emissive materials to shield the ceramic tubing from the plasma. Their research showed that a ceramic tube coated with tungsten did indeed reduce these perturbations. As a further step, to eliminate shorting of the plasma through this new conductive shielding, the tungsten was segmented in small sections. This idea is demonstrated in Figure 3.
Segmentation of the ceramic tubing used to create Langmuir probes for the RAPID system was accomplished by using a sputter deposition process. Individual ceramic tubes were placed behind a thin mask with a series of holes cut through it (0.6-mm wide, 1.2-mm spacing). The ceramic tubes were rotated behind the mask during the deposition process to form segments of even thickness. One of the segmented probes used in this study is shown in Figure 4.

The complete Langmuir probe design is shown in Figure 5. It consists of a short section of 1.27-mm O.D. x 0.508-mm I.D segmented alumina tubing attached to a larger diameter alumina tube (2.39 mm). About 10 cm of the segmented alumina tube is left exposed to plasma. A 10-cm long piece of 0.127-mm diameter tungsten wire was threaded inside the segmented section of the probe leaving 0.127 mm of wire extending from the end. The other end of the tungsten wire was crimped within a nickel tube, which was in turn connected to standard Teflon insulated copper wire.

3. RAPID System Stage

The RAPID system uses a H2W SR linear motor consisting of a “U” shaped magnetic track and a “T” shaped coil. The coil was mounted beneath a platform/stage riding on a ball-bearing supported rail. The H2W motor is capable of traveling up to 36 cm and includes an optical encoder with a resolution of 5 μm. The stage is capable of moving at velocities up to 6 m/s with a maximum acceleration of 12 g.

The H2W motor was mounted to an aluminum table, and the entire system was surrounded by a stainless steel shroud. A small hole placed at one end of the shroud (1 cm diameter) was used to allow probe passage during testing. The system is shown in Figure 6 without the stainless steel shroud installed. The linear motor was driven by an ELMO Harmonica digital servo drive controller. An interface between the driver and a computer-based data acquisition and control system was achieved via RS-232 and LabVIEW.

Since the system experiences large accelerations and high speeds of travel, it was important to ensure the Langmuir probe did not exhibit large vibrations, specifically perpendicular to its travel, which would decrease positional accuracy. Both model
and experimental vibration results were obtained via MathCAD, Pro/Engineer Mechanica and accelerometer testing, which revealed the vibration magnitude at the tip of the probe during measurement to be \(<10^{-3}\) mm, and was small enough to be ignored.

**B. Hollow Cathode Measurement Setup**

A 6.4 mm diameter hollow cathode was utilized for all testing described in this paper. The hollow cathode was equipped with an orifice plate that had 0.64-mm diameter hole at its center. The hollow cathode was oriented 10 cm above a THK LM Guide Actuator KR ball-screw stage, and mounted on an aluminum base plate. A small keeper electrode was located off to the side of the hollow cathode to facilitate starting the plasma discharge. During operation, the keeper bias was set to 0 V relative to the cathode. A large anode ring (4-cm wide and 15-cm diameter) was placed approximately 13 cm downstream of the cathode. The cathode assembly was oriented in such a way that the centerline of the cathode was in plane with and perpendicular to the center line of the RAPID system. The THK stage was positioned by an Oriental Motors AS46MA stepping motor, which was in-turn driven by an Oriental Motors ASD10K-B driver and a Trio MC202 motion controller. A Trio BASIC program was written allowing computer monitored control of the stage over a 6.5 cm axial distance from the RAPID system centerline. Figures 7 and 8 show the setup and orientation of the cathode and RAPID system. The dotted path lines in these figures are actual measurement lines used during testing. These lines began 0.25 cm axially downstream of the hollow cathode and continued in 0.25 cm steps to 1.25 cm axially downstream. At this point it was found that the plasma properties were not changing significantly and, to save data acquisition and analysis time, only two final path lines at 2.25 cm and 3.25 cm were used. All path lines began 2 cm radially away from the cathode centerline and continued inward to the cathode centerline.
C. Langmuir Probe Circuitry and Measurement Technique

In our experiments, the Langmuir probe was traversed through differing plasma properties starting from low density plasma regions at large radial positions and moving to the much higher density plasma regions near the cathode centerline. Throughout this trajectory, rapidly varying saw-tooth biases were applied to the probe and the resultant current-versus-voltage data were recorded. Other techniques have been used elsewhere, including one where a single voltage is applied to the electrode while the current to the electrode is monitored as it travels through the plasma. To obtain complete Langmuir probe traces this process must be done repeatedly at different voltages and then correlated back together by position. Although relatively straightforward to implement, this technique can be very time consuming to acquire sufficient data. Furthermore, this technique assumes that plasma properties and positions are constant throughout the lengthy measurement period. With the technique employed by CSU, complete Langmuir probe traces are acquired for each position throughout the same trajectory in one pass. This is accomplished by applying a waveform to the electrode at a rate far greater then the rate at which the probe travels through the plasma. For example, if a 1 kHz waveform is applied to an electrode that is moving at 1 m/s, a full waveform period will occur every 1 ms, which corresponds to a distance traveled of 1 mm. Because the Langmuir probe trace is acquired over a small fraction of the waveform period, sub-millimeter resolution is readily achievable. Most of the results reported in this paper were acquired using a 50 V amplitude, 1 kHz triangular waveform at a probe velocity of 0.5 m/s. Since the waveform is triangular, a full Langmuir sweep is present on either side of the triangle. In an attempt to limit disturbances from both capacitance, witnessed in measurement lines (which was subtracted out of final data), and the perturbation of the plasma at high positive biases, data was only taken on the upslope portion of each waveform well away from saw-tooth waveform slope transitions. These parameters resulted in acquisition of an individual Langmuir trace over a spatial extent of 0.25 mm. The distance between adjacent Langmuir probe traces was 0.5 mm apart. Notably, the data acquired from the optical encoder indicated that the Langmuir probe traces were being recorded over spatial distances of 0.25 mm ±10 μm, providing positive evidence in the accuracy of the data collection scheme. Also, with the use of the saw-tooth probe bias waveform the probe was not collecting large electron currents throughout its motion, and therefore \( \dot{p}_{\text{probe}} \) values in the thermal model were smaller. The lower heat load conditions allowed for longer exposure times before the probe became emissive when compared to the fixed-bias sweep techniques mentioned above.

As for the electrical circuitry of the RAPID system, the probe is biased by a Kepco BOP 400M power supply. This supply has an output range of ±100 V at 4 A with a frequency response from DC to 20 kHz. The output of the Kepco supply is controlled by a signal waveform generated by the computer control system. Current to the probe is sensed by measuring the voltage across a resister. This voltage is fed through an AD215 wide-bandwidth isolation amplifier and on to a PXI-based data acquisition (DAQ) system used to simultaneously record the probe bias voltage and the stage position. The AD215 amplifier has a unity gain bandwidth of 120 kHz. Probe bias voltage readings are first sent through a voltage divider to limit the maximum measured voltage to ±10 V, as are readings of current output from the AD215 amplifier. To avoid DAQ system damage, all signals are limited by Zener diodes and varistors. An electrical schematic of the

Figure 9. Langmuir probe circuit schematic including PXI and ELMO drive systems
system is shown in Figure 9. Data collected by the computer system are acquired and stored on a National Instruments 6133PXI S-series DAQ card. The signal waveform used to control the Kepco supply is produced on a National Instruments 6124PXI M-series DAQ card. The two cards have capabilities of 3 MS/s at 14-bits of resolution and 1 MS/s at 16 bits, respectively.

D. Langmuir Probe Data Analysis

The following is provided as analysis background information, advanced readers should skip ahead to Section E. A Langmuir probe is a relatively simple device for use in determining plasma properties. At its most basic level it consists of a small electrode immersed in a plasma. The net current collected by the probe consists of ion and electron currents that are functions of its potential, and the plot of net current versus probe potential is often referred to as the I-V curve\(^9,10,11\). Figure 10 represents an idealized Langmuir I-V curve. An I-V curve consists of three primary regions. The first of which, shown on the left in Figure 10, is the ion saturation region. In this region the probe potential is negative enough such that nearly all electrons are repelled and only ions are collected. Note the ion saturation current, which has been amplified in Figure 10 for illustration purposes. Region II, shown in the middle of Figure 10, is referred to as the electron retardation region and it consists of the potential range in which both electrons and ions are collected. In this transition region, two points are of notable significance, floating potential and plasma potential. In this region ions are attracted to the probe because it is biased negative of plasma potential and, while electrons are being repelled, some high energy electrons can still make it to the probe. The point where zero current is measured by the probe is called the floating potential. This is the voltage at which the ion current flowing to the probe exactly equals the electron current collected and thus they cancel. To the right of the floating potential the curve tends to grow steeply for most plasmas. If the electron population is Maxwellian, the current collected by the probe can be modeled by Eq. (3).

\[
I_e(V_B) = I_{\text{sat},e} e^{-\frac{(V_p-V_g)}{T_e}}
\]

\[
I_{\text{sat},e} = \frac{1}{4} q n_e \nu_e A_p = q n_e A_p \sqrt{\frac{qT_e}{2\pi m_e}}
\]

In region three, the probe potential is above plasma potential, and the electron current saturates. In the ideal case the transition is sharp between the electron retardation and electron saturation regions, thus making the determination of plasma potential straightforward. With cylindrical probes in actual plasma, the saturation current continues to grow slowly as the probe voltage is increased. Also, note the rounded area between region II and III. This area is referred to as the knee and the presence of a highly rounded knee makes calculating plasma parameters increasingly difficult and suggests plasma instability. A more in depth description of Langmuir probe analysis and physics can be found references 9, 10, and 11.

In order to obtain plasma parameters such as \(n_e\), \(T_e\), and \(V_p\) from I-V curves, the ion saturation current is first subtracted out. The resulting data is then plotted on a semi-log plot, \(\ln I vs. V\). From Eq. (3) one can see that the slope of this curve is proportional to \(1/T_e\). With \(T_e\) calculated from the slope of the electron retardation region, the next step is to determine the electron saturation current, which is the current where lines drawn through the electron...
retardation and electron saturation regions intersect. The voltage at the intersection is the plasma potential, and the electron current at the intersection is used in Eq. (4) to determine plasma density. A visual basic program was written to automatically analyze the Langmuir probe traces acquired with the RAPID system.

E. Combined Electrostatic Energy Analyzer and Wein Velocity Filter Diagnostics and Experimental Setup

A separate study from the rapidly actuated Langmuir probe work is also presented in this paper, and was conducted using different plasma source hardware and vacuum test facilities. This study focused on the measurement of ion energy and charge distribution functions made at locations immediately outside of an NSTAR ion thruster representative discharge chamber. The discharge chamber is equipped with a hollow cathode operated in the enclosed keeper configuration standard to an NSTAR thruster, in contrast to the open cathode configuration used in the fast probe study. The hollow cathode tube diameter was 6.4 mm and the orifice diameter was 0.55 mm. The keeper-to-cathode spacing was 0.5 mm, and the keeper orifice diameter was 2054 mm. Three magnet rings were used to produce the magnetic field. The first 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 a cylindrical sidewall section, the second was placed at the intersection of the cylindrical and conical anode sections, and the third on the back plate behind the cathode. The discharge chamber body was fabricated out of aluminum and the inside surface was covered with a stainless steel liner. Although no ion optics system was present, a pseudo-screen grid was placed where the ion optics would normally be located to enable operation at plasma and neutral densities similar to an NSTAR engine. To allow measurements using remotely located probes a slot, 7 mm in width, was cut along both the side of the anode and the pseudo-screen grid to allow the plasma to flow out of the discharge chamber. Additionally, the length of the 7 mm wide slot, cut into the discharge chamber wall, enabled attainment of neutral densities similar to an NSTAR thruster. Instead of having separate cathode and main flow as in a typical NSTAR discharge chamber, all of the xenon propellant in this experiment was sent through the cathode. A photograph of the discharge chamber is shown on the right hand side of Figure 11.

A combination of an electrostatic analyzer (ESA) and ExB probe was used to measure the energy \((E/z)\) and charge state \((z)\) distribution of the ions. The combined probe consists of a custom built ExB probe mounted onto the exit stage of a Comstock AC-901 ESA. This setup is shown in an inset photograph included in Figure 11, which also contains a photograph of the ESA/ExB probe and the NSTAR discharge chamber, as it appears when rotated into a position where ions flowing from zenith angles of 90 degrees would be characterized.

![Figure 11. Experimental setup showing the combined ESA and ExB probe pointed at the prototype NSTAR discharge chamber at a zenith angle of 90 degrees. Inset photo shows the probe with the ESA and ExB sections.](image)

With this probe setup, an ESA trace could be taken to obtain an ion energy distribution function \((E/z)\) by using the ExB probe structure as the ion collector plate of the ESA. In addition, with the ESA set to transmit ions at a given energy \((E/z)\), the ExB probe could be used to determine their charge state \((z)\). An actuator system was used to
position the probe radially (across a diameter of the chamber) and set the zenith angle of the probe collimator (relative to the discharge chamber axis). The combination of being able to rotate the discharge chamber, and translate and rotate the probe, allowed for investigations of ions expanding from different regions of the discharge chamber plasma.

1. **ESA Diagnostics**

An electrostatic analyzer (ESA) is a devise used to measure energy distribution (i.e., f(E/z)) of moving charged particles. The experiments conducted for this paper utilized a COMSTOCK AC-901 ESA. A sketch of an ESA is shown in Figure 12. Ions enter the ESA through a set of apertures (shown in lower left) and are deflected in a spherical electric field created by applying voltages to the two spherical plates that are a small distance apart. At the other end of the ESA is another aperture, through which ions are detected. Due to the geometry of the ESA only ions with energies resulting in flight paths along the curvature of the ESA are able to reach the final aperture. The energy at which ions enter the probe is selected by biasing the probe structure relative to the plasma being sampled. Ion energy distribution functions are obtained by scanning the bias of the probe structure over the range of interest.

2. **ExB Diagnostics**

The Wein velocity filter (or ExB) probe is made up of three sections including a collimator, an ExB-based separator structure, and a drift space. Figure 13 is a schematic of an ExB probe taken from Beattie.

![Figure 12. ESA Schematic [Ref. 12].](image)

![Figure 13. ExB Probe Schematic [Ref. 13].](image)

The collimator consists of a 5.1 cm stainless steel tube with stainless caps welded to either end. A small hole is located in the center of both caps that is typically 0.254 mm in diameter. These holes allow only ions with velocity vectors nearly parallel to the collimator centerline to enter and exit the collimator. Upon exiting the collimator, the ions enter the ExB separator, which is comprised of a pair of parallel electrode plates and a permanent magnet. The electric field between the plates (generated via an external voltage supply) and the magnetic field are oriented perpendicular to one another. As an ion enters the separator it is deflected by both the electric and magnetic fields according to

\[
F = q(E + v \times B)
\]  

(5)
In order for an ion to pass through the separator un-deflected, the electric field present must be such that its force component cancels the force component due to the magnetic field. Once through the separator, ions travel through a drift space where streams of deflected ions are allowed to separate from un-deflected ions. At the far end of the drift tube is an ion collector assembly, which is used to monitor the current of un-deflected ions transmitted under a given electric field condition. By controlling the electric field, one can select the charge stage of ions allowed to pass through the separator. Subsequent analysis of the ExB probe collector current versus plate voltage data allows one to determine the ratio of double-to-singles current.

F. Vacuum Chamber
Testing on the hollow cathode and RAPID system was conducted in a Varian 1.0-m long by 0.76-m diameter cylindrical vacuum chamber equipped with a CTI-8 Cryopump. Base pressures for this chamber are below 4x10^{-7} Torr. During operation of the cathode at Xe flow rates from 1.5 to 6 sccm, the chamber vacuum rose to pressures in the mid to upper 10^{-5} Torr range. Tests involving the ESA/ExB and NSTAR prototype apparatus were performed in a 1.2-m diameter, 4.6-m long stainless steel cylindrical vacuum chamber. This chamber is equipped with a 0.94-m diameter diffusion pump and a refrigeration-cooled baffle. Base pressure is in the low 10^{-7} Torr range, and typical operating pressures are in the mid 10^{-5} Torr range.

III. Results

A. Langmuir Probe Results
In order to obtain a more complete understanding of both the capabilities of the RAPID system and the discharge plasma nearby a hollow cathode, a wide range of Xe flow rates (1.5 sccm to 4.5 sccm) and discharge currents (2 A to 8 A) were investigated. Table 1 contains a list of these operating conditions, and the numbers contained in Column 1 will be used to specify the test conditions referred to in the following text.

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>J_d (A)</th>
<th>V_d (V)</th>
<th>( \dot{m} ) (sccm)</th>
<th>Pressure (x10^{-5} Torr)</th>
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<td>4</td>
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<td>57.6</td>
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</table>

Three typical Langmuir probe traces are shown in Figure 14, 15, and 16 that correspond to Operating Conditions #6, #10, and #12, respectively. Each I-V curve contains roughly 1300 data points. To obtain high quality traces in a wide variety of plasma conditions, adjustable amplification of the current signal was required. This was performed through selection of the current sense resistor shown in Figure 9. In addition, the amplitude of the saw-tooth biasing waveform was modified as needed to accommodate plasmas with different plasma potentials and densities. In general, a 100 \( \Omega \) current sense resistor and a +60 V to -30 V (100 V p-p), 1-kHz triangular waveform were used. Modifications to these values were made when measured signals from the probe exceeded the \pm 10 V limit of the DAQ system or when signal levels approached the noise floor of the 14-bit DAQ resolution.
From each trace, values for the electron density, electron temperature, and plasma potential were calculated using Eqs. (3) and (4). A brief error analysis summary for these measurements is discussed below. Figures 15 and 16 were both taken under modified conditions where the waveform maximum voltage was decreased to prevent excessive electron current. In addition, Figure 16 was obtained by replacing the 100 Ω resistor with a 33 Ω resistor, which was done to avoid saturating the DAQ. Because the maximum current in Figure 14 was low, it was possible to replace the 100 Ω resistor with a 1000 Ω one without exceeding the ±10 V DAQ input limit. When this was done, similar results were obtained, but with higher resolution, and adjustments to higher sense resistors were made whenever lower plasma density regions were to be characterized. In general, linear behavior over two to three orders of magnitude on log-linear plots like the ones shown in Figures 14, 15, and 16 was observed. This result suggests that the electron population is well thermalized. Although some evidence of primary or non-thermalized electrons was observed (e.g., see region between 0 V and 6 V in Figure 16), their presence was neglected in analysis of the Langmuir probe data. Finally, it is noted that rounding at the knee between the electron retardation and saturation regions was observed for some operating conditions. Excessive rounding is indicative of a noisy or turbulent plasma and excessive noise might be related to plasma conditions that result in heating of ions or formation of multiply charged ions that can cause sputter erosion of surfaces.

![Figure 14. Common individual Langmuir trace from Condition #6. 1000 Ω resistor, -32V to +37V waveform.](attachment:figure14.png)

Condition #6
1.0 cm axial
0.8mm radial
$n_e = 1.2 \times 10^{11}$ cm$^{-3}$
$V_p = 12.6$ V
$T_e = 1.89$ eV
Typically ~40 Langmuir traces were taken over a ~2 cm radial scan at a given axial distance downstream of the hollow cathode orifice. Figure 17 contains plots of electron density, electron temperature, and plasma density that were obtained from the analysis of a typical scan. The data shown in Figure 17 correspond to an axial position of 0.25 cm with the hollow cathode operating at Condition #3. Because of the close axial proximity to the cathode orifice plate plane, the electron density is only observed to increase quickly near the center line of the cathode (i.e., near \( r = 0 \) cm). Figure 18 contains similar data collected at an axial position of 1 cm for Condition #10. Here,
electron density is shown to start increasing at a larger radial position, but much more gradually as the centerline is approached compared to Figure 17. Radial scans performed at larger axial positions ($z = \sim 3$ to 4 cm) displayed nearly constant electron density curves over the entire radial range investigated. The radial profiles of electron temperature and plasma potential shown in Figures 17 and 18 do not display as much variation compared to plasma density profiles, regardless of what axial location was studied, and this was true of most data collected during this study.

Figure 17. Combined Langmuir traces for flow condition 3 at 0.25 cm axial position. Representative of common radial sweep at low axial positions.
After a set of combined Langmuir probe traces for each radial position had been analyzed, the plasma property data were curve-fitted to a 6th order polynomial prior to being pooled to create 2D contour plots. Three separate contours were formulated for each operating condition, one for each of the plasma parameters shown in Figures 17 and 18. Figures 19 through 25 show a variety of these contour plots taken during this study. Figures 19 and 20 contain electron number density and plasma potential contour plots for Condition #6. Figures 19 displays a monotonic expansion of plasma density starting from the cathode location at $z = 0$ and $r = 0$. From Figure 20, a slight rise in plasma potential is observed near the cathode orifice that is followed by a valley (or trench) structure developing along the centerline and extending downstream. In almost all of the other operating conditions, the plasma potential was noted to have a valley (or trench) that would form some distance in front of the cathode on the centerline, with most taking a similar form to the one shown in Figure 20. The electron temperature contour plot for Condition #6 is shown in Figure 21. The temperature was found to be relatively constant everywhere except for a slight increase near the cathode. Figure 22 is an extreme case of a plasma potential contour plot for Condition #4 where the valley subsided out in front of the cathode and formed a bowl. It is noted that this negative potential hill structure would tend to trap (or confine) low energy ions unless an ion heating mechanism is present to sweep them from the region. For this flow and discharge current condition it was noticed that relatively intense plasma was being formed throughout the entire chamber.

**Figure 18. Combined Langmuir traces for flow condition 10 at 1.0 cm axial position. Representative of common radial sweep at medium axial positions.**
Figures 23 and 24 are contours of electron number density and temperature for Condition #12. Here a decrease in electron temperature is seen as one approaches the cathode. This characteristic was noted in nearly all conditions except those possessing dense regions of plasma (plasmoids) that are separated from the cathode, which are discussed next. For a few of the electron temperature contours, the temperature fall near the cathode developed more structure and appeared as a valley leading into the cathode.
Figure 23. Electron number density contour plot for Condition #12.

Figure 24. Electron temperature plot for Condition #12.

Figure 25 contains a contour plot of electron number density at Condition #10. Note the ball-like peak structure representative of a plasmoid. This dense region corresponds visually to a region of brighter luminosity that was located downstream of the cathode. This structure was seen in density contour plots corresponding to discharge currents of 4 A and 6 A at 1.5 sccm Xe, and 2 A and 4 A at 4.5 sccm Xe. For these conditions, the electron temperature was found to be nearly constant and the plasma potential valleys were shallower compared to other conditions. No ball structures were observed for 3 sccm flow at the discharge currents that were investigated. Although some unusual plasma density contour plots were detected, most contours were monotonically decreasing in a standard plasma expansion manner.

Figure 25. Electron number density contour plot for Condition #10.
As reported in Ref. [3], traditional estimates for errors on electron number density and temperature are rather large and often are 50% and 20%, respectively. However, the relative error between individual measurements under similar operating conditions can be considerably smaller, which allows trends and relative comparisons to be made with high certainty. Regions where plasma densities were less then $1 \times 10^{9}$ cm$^{-3}$ resulted in low currents and, in the current study, low currents increased the signal-to-noise ratio and correspondingly decreased confidence in the results. On the other hand, regions of relatively high plasma densities (those greater then $1 \times 10^{11}$ cm$^{-3}$) often displayed a range of nearly four orders of magnitude in current on log-linear plots when going from the ion saturation to electron saturation regions. Very high levels of signal-to-noise were noted for these cases, which increased the confidence level of the plasma properties that were calculated. Rounding of the knee between electron retardation and saturation regions was also observed, and as noted above, this suggests that the plasma in most cases was unstable, which can also affect error levels in plasma density and potential calculations.

### B. ESA Results

Using the combined ESA and ExB probe, a study was performed with the NSTAR prototype discharge chamber to determine how the ion energy and charge state distributions changed as a function of plasma discharge current. Figures 26, 27, and 28 show the ion energy distribution function (taken with the ESA section only) when the probe was aimed at the cathode orifice along lines of sight at zenith angles of 0, 25, and 90 degrees relative to the cathode and discharge chamber axis. At each angle, distributions were measured at four discharge currents of 10, 15, 20, and 25 A. The Xe flow rate was set to a constant 4.6 sccm, and the discharge voltage varied from 24 to 28 V as the current was varied from 10A to 25A. The enclosed keeper was held at cathode potential during all of the tests described herein. The distributions are presented on a log-linear plot in order to view both the dominant main.

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**Table 2. Contour plot shape comparison table.**

<table>
<thead>
<tr>
<th>Oper. Cond.</th>
<th>$J_d$ (A)</th>
<th>$V_d$ (V)</th>
<th>$m$ (sccm)</th>
<th>Pressure ($\times 10^{-5}$ Torr)</th>
<th>$n_e$ Shape</th>
<th>$T_e$ Shape</th>
<th>$V_p$ Shape</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>37.4</td>
<td>1.5</td>
<td>3.5</td>
<td>Standard Expansion</td>
<td>Constant</td>
<td>Valley from Cath</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>48.7</td>
<td>1.5</td>
<td>3.5</td>
<td>Std Exp. w/ Plasmoid</td>
<td>Constant</td>
<td>Valley from Cath</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>56.7</td>
<td>1.5</td>
<td>3.5</td>
<td>Plasmoid</td>
<td>Valley to Cathode</td>
<td>Valley from Cath</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>86.4</td>
<td>1.5</td>
<td>3.5</td>
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<td>Valley to Cathode</td>
<td>Deep Valley</td>
</tr>
<tr>
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<td>36.4</td>
<td>3</td>
<td>6.4</td>
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<td>Valley to Cathode</td>
<td>Valley from Cath</td>
</tr>
<tr>
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<td>6.5</td>
<td>Standard Expansion</td>
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<td>Valley from Cath</td>
</tr>
<tr>
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<tr>
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<td>Constant</td>
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<tr>
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<td>4.5</td>
<td>8.6</td>
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<td>Fall to Cathode</td>
<td>Constant</td>
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<td>57.6</td>
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<td>8.6</td>
<td>Std Exp w/ Plasmoid</td>
<td>Fall to Cathode</td>
<td>Constant</td>
</tr>
</tbody>
</table>
discharge ions as well as higher energy ions in the tail of the distribution. The most probable energy of the ions was usually just above the discharge-to-cathode voltage difference, and all ion energies were referenced to the cathode potential. (The cathode was electrically tied to vacuum chamber ground.) At all zenith angles, some higher energy ions were measured in the tail of the distribution. Furthermore, the magnitude of the high energy ion signal increased as the discharge current was increased.

![Graph showing ion energy distribution](image)

**Figure 26.** Ion energy distribution function taken at zenith angle 0°.

![Graph showing ion energy distribution](image)

**Figure 27.** Ion energy distribution function taken at zenith angle 25°.
The charge state distribution of the ions was then measured using the ExB probe section of the probe with the ESA set to a constant transmission energy ($\Delta E = \pm 4$ eV). Transmission energy settings of 15, 25, 35, 50, and 75 eV were arbitrarily chosen to examine charge state information. Figure 289 shows an example of charge state data obtained with the ESA set to transmit 35 eV ($\pm 4$ eV) ions. The inset plot shows a single ESA trace (one of the distributions shown in Figure 27) with the selected transmission energies indicated by the vertical arrows. To obtain the doubly-to-singly charged ion ratio, the area under each charge state signal was found by integration and then the doubly charged value was divided by the singly charged value. For the trace shown in Figure 289, the doubles-to-singles ratio was about 12 \%.

![Figure 289](image_url)

**Figure 289.** Typical ExB probe trace used to determine the doubles to singles ratio. Data are for 35 eV ions.
Figures 30a, b, and c show how the doubles-to-singles ratio varies as a function of discharge current for zenith angles of 0°, 25°, and 90°. Looking first at Figure 30a each line corresponds to one of the selected ion energies listed above. At the lower discharge current of 10 A, the doubles-to-singles ratio varied from near 0% to about 25% as the ion energy of interest was varied from 15 eV to 75 eV. At 25 A of discharge current, the ratio varied from about 4 to 80%. In general, the 50 and 75 eV ions displayed higher doubles-to-singles ratios compared to the 25 and 35 eV ions. However, the 15 eV setting (black line in Figures 30a, b, and c) showed the largest variation in doubles-to-singles ratio as the discharge current was changed. It is believed that the ~15 eV ions may be created in the discharge chamber near the location of the pseudo-screen grid (in the 0° and 25° cases) or even outside of the discharge chamber wall (in the 90° case). The trends observed in the charge state distribution at the 25° and 90° zenith angles in Figures 30b and c are about the same as the 0o zenith angle case. Again, one main difference is in the 15 eV line. At these off-axis zenith angles, the doubles-to-singles ratio for the 15 eV ions was always much lower (i.e., below 8%). It is important to note that although the ratio of doubles to singles is high, the higher ratios usually occur at much lower ESA current signals, so there are actually a lot less doubly charged ions than might be expected by looking at the data contained in Figures 30a, b, and c.
A similar set of results are presented in a different form where more detailed measurements of the ion charge state were taken at discharge currents of 10 and 20 A and at zenith angles of 0 and 90 degrees. Figure 31 shows a plot of the ion energy distribution function measured with the ESA section of the probe (the red curve plotted against the y-axis on the right-hand side) at a discharge current of 10 A and a zenith angle of 0 degrees. The Xe flow rate was set to 6.6 sccm and the discharge voltage to about 24.7 V. The distribution had a most probable energy of 26 eV with a slight tail extending out to higher energies. Also plotted on Figure 31 (the blue curve and the y-axis on the left) are the values of the doubles-to-singles ratio measured at selected ion energies from 10 to 85 eV. At lower ion energies there was a rise in the doubles-to-singles ratio, which peaked near 22 % at an energy of 18 eV. At ion energies around the discharge voltage (~25 V) the doubles-to-singles ratio was lower, around 2 to 5 %. Finally, at ion energies well above the discharge voltage, the ratio increased to around 10 to 20 %.

Figure 31. Ion energy distribution function and doubles-to-singles ratio at 0 degrees and 10 A.
Figure 32 shows a plot of the ion energy distribution and doubles-to-singles ratio at a higher discharge current of 20 A. For these data, the zenith angle was also set to 0°, however, the Xe flow rate was slightly higher at 6.8 sccm. The most probable energy was 29 eV, near the higher discharge voltage of 27.8 V. At the higher discharge current, the doubles-to-singles ratio increased significantly. At low ion energies around 20 eV, the ratio was as high as 150%. At high ion energies above 45 eV, the ratio dropped to values around 15 to 30%.

The same measurements were done at a 90° zenith angle and the results are shown in Figure 33 for a discharge current of 10 A and Xe flow rate of 6.6 sccm. The discharge voltage was 24.7 V and the most probable energy measured from the ESA data was 24 eV. Unlike the 0° zenith angle, a peak was not seen in the doubles-to-singles ratio at low ion energies. Also, the doubles-to-singles ratio remained relatively low at 1 to 5% for ion energies near the discharge voltage. Then, at energies above 30 eV the ratio increased to about 8 to 15%. Comparing the distributions at the two zenith angles, there was a factor of 10 decrease in the ion current to the probe at the 90 degree angle, which supports the expectation that the magnetic field at the side wall location is filtering (reducing) the amount of plasma that flows in this direction. It is interesting to note that the most probable energy of the distribution decreased from 26 to 24 eV when going from zenith angles of 0° to 90°. It was expected that electrostatic confinement of the plasma by the magnetic field would have driven the most probable energy higher rather than lower.

Measurements were also made at the 20 A discharge current at the 90° zenith angle. The results for the distribution and doubles-to-singles ratio are shown in Figure 34. For this test, the Xe flow rate was 6.9 sccm and the discharge voltage was 27.7 V. Like the 10 A case, the doubles-to-singles ratio was low at energies near the most probable energy of 24.5 eV. Then, the doubles-to-singles ratio increased to 20 to 75% for ions with energies above 30 eV. These doubles-to-singles values were much higher than those measured at the 10 A operating condition.
Figure 33. Ion energy distribution function and doubles-to-singles ratio at 90 degrees and 10 A.

Figure 34. Ion energy distribution function and doubles-to-singles ratio at 90 degrees and 20 A.
Electron number density, electron temperature, and plasma potential measurements were made in the near field plume of a hollow cathode by a newly developed, fast-actuating Langmuir probe system. Contour plots of these plasma properties display a wide variety of trends as the hollow cathode operating conditions were changed. Specifically, evidence of plasmoids (localized dense plasma regions) were observed at a few operating conditions. For most operating conditions, however, straightforward plasma density expansion was observed from the hollow cathode that corresponded to valley or trench shaped plasma potential structures leading away from the cathode. Electron temperature contours often displayed the opposite trend, where valleys and trenches in temperature came and/or discharge current were increased, (2) plasma potential decreased everywhere when flow rate was increased or cathode that corresponded to valley or trench shaped plasma potential structures leading away from the cathode. Macroscopic trends showed that (1) plasma density increased everywhere when flow rate and/or discharge current were increased, (2) plasma potential decreased everywhere when flow rate was increased or discharge current decreased, and (3) electron temperature decreased everywhere when the flow rate was increased and was in-sensitive to discharge current variations. Ion energy and charge state measurements were also made on a prototype NSTAR discharge chamber using a remotely located ESA and ExB probe. Results from the ESA stage showed that the high energy content of the ion distribution function increased significantly when the discharge current was increased from 10 to 25 A. Charge state data measured with the ExB probe showed that the ratio of doubly charged ions to singly charged ions varied as a function of ion energy, discharge current, and viewing (or zenith) angles. When examining ion energies near the bulk of the distribution (i.e., near the discharge voltage), the doubles-to-singles ratio was low at around 0 to 10 %. More interesting results were found when looking at ions with energies above and below the discharge voltage. At low zenith angles (looking at the cathode along the discharge chamber centerline), large doubles-to-singles ratios were measured for ion energies below the discharge voltage. It is speculated that doubly charged ions are being created within a plasma potential trench region extending from the cathode to the pseudo-screen grid location. In contrast, at off-axis zenith angles (i.e., looking at the cathode along lines of sight that are not aligned with the discharge chamber centerline) the doubles-to-singles ratio remained low throughout most ion energy values until ions with energies significantly above the discharge voltage were measured. In general for high ion energies, the doubles-to-singles ratio increased when the discharge current was increased.

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