An Analysis of Energy Balance in a Helicon Plasma Source for Space Propulsion

by

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Abstract

This thesis covers work done on the mHTX@MIT helicon source as it relates to the analysis of power losses. A helicon plasma is a rather complex system with many potential loss mechanisms. Among the most dominant are optical radiation emission, wall losses due to poor magnetic confinement, and poor antenna-plasma coupling. This work sought to establish a first-order breakdown of the loss mechanisms in the mHTX@MIT helicon source so as to allow for a better understanding of the issues effecting efficiency. This thesis proposes the use of a novel thermocouple array, standard plasma diagnostics, and a simple global energy balance model of the system to determine greater details regarding the losses incurred during regular operation. From this it may be possible, by comparing the heat flux on the tube to the applied magnetic field profile, to gain some insight into the effects of magnetic field geometry on the character of the helicon discharge.

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Chapter 1

Introduction

Space propulsion is a mature, but dynamic field where the state-of-the-art is always being redefined. The complexity of a typical space propulsion system requires interdisciplinary studies and relies on a number of experts in different areas to fully understand and synthesize new technology. While many concepts have been studied rigorously and have been used in space applications for many years, there still exist some newer, less-understood technologies.

1.1 Space Propulsion

Space propulsion can be separated into two main categories: chemical systems and electric systems. Chemical systems utilize the energy stored in the bonds of the propellant to produce a high temperature, high pressure working fluid that can then be expelled from a conventional, converging-diverging nozzle to produce thrust. The major concepts within this area are solid propellants, liquid-bipropellants, monopropellants, and cold-gas thrusters. All of these engines have been successfully implemented on many missions ranging from on-orbit trajectory corrections and drag make-up of satellites to interplanetary science probes. These technologies have been developed very thoroughly in the past half century and benefit from that heritage in the consideration for placement on current and future missions.
The second category, electric propulsion, uses electrical energy to produce an ionized gas or plasma, which then can be accelerated from the engine using a variety of electrothermal, electrostatic, or electromagnetic mechanisms. The most well-understood and best implemented of these concepts is the ion thruster. This thruster relies on a conventional ionization source such as a direct current (DC) arc discharge to ionize the propellant gas, which is then accelerated electrostatically via an array of grids at varying potentials. This is an example of an electrostatic concept because it uses a static electric field to accelerate the working fluid. There are also electrothermal thrusters, which use a DC arc discharge or heating coil to super-heat the gas in preparation for expulsion through a conventional nozzle. Finally, there are electromagnetic thrusters, which ionize the propellant gas in much the same way as the electrostatic concepts, but utilize magnetic fields as part of the acceleration mechanism.

At this point, the reader should have a better appreciation for the difficulty in choosing from one of the many propulsion concepts to service a given mission. This is why a space propulsion engineer must have an intimate understanding of the advantages and disadvantages of each of these technologies. As was previously mentioned, chemical systems have the advantage of being well tested and characterized in the laboratory and in space. However, one of the main disadvantages of chemical propulsion systems is that there is a upper limit on the maximum specific impulse that can be achieved. The specific impulse of a propulsion system can be expressed as the thrust produced per unit mass flow rate of propellant:

\[ I_{sp} = \frac{T}{\dot{m}g_0} \]  

Where \( T \) is the thrust produced at a given mass flow rate \( \dot{m} \) and \( g_0 \), the gravitational acceleration of Earth, is used to make specific impulse have units of seconds. Specific impulse is one of the main performance parameters used by engineers to compare propulsion concepts and can be thought of as a measure of efficiency of a particular
<table>
<thead>
<tr>
<th>Concept</th>
<th>$I_{sp}(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>cold gas</td>
<td>50 - 250</td>
</tr>
<tr>
<td>monopropellant</td>
<td>125 - 250</td>
</tr>
<tr>
<td>solid propellant</td>
<td>250 - 300</td>
</tr>
<tr>
<td>bipropellant</td>
<td>200 - 450</td>
</tr>
<tr>
<td>electrothermal</td>
<td>500 - 1000</td>
</tr>
<tr>
<td>electromagnetic</td>
<td>1000 - 5000</td>
</tr>
<tr>
<td>electrostatic</td>
<td>2000 - 20000</td>
</tr>
</tbody>
</table>

Table 1.1: Typical values of specific impulse for various chemical and electric propulsion concepts.

propellant. Table 1.1 shows the ranges of specific impulse of the abovementioned concepts. Notice that these propulsion systems span four orders of magnitude in specific impulse. This allows the propulsion engineer a great deal of flexibility in the choice of concept to be employed on a given mission; however, it also makes the design process a long and difficult one unless there are clear constraints or requirements.

Another, perhaps, more telling figure of merit used to evaluate the performance of a particular engine or thruster is that of the thrust or internal efficiency. This is a measure of the efficiency of a concept to convert the input energy, whether chemical or electrical, into useful, thrust-producing energy. This can be expressed as

$$\eta = \frac{T^2}{2\dot{m}}$$

(1.1.2)

Where, the term in the numerator is the exhaust or kinetic power and is the component that directly produces thrust and $\dot{m}$ is the propellant mass flow rate. Also, for chemical propulsion systems, $P_{input} = \dot{m}H_{reaction}$ and represents the total chemical power stored in the the bonds of the propellant mixture as the product of the propellant mass flow rate, $\dot{m}$ and the heat of reaction of the combustion process, $H_{reaction}$. Finally, for electric propulsion systems, $P_{input} = IV$ and represents the total electric power cast as the product of the current and voltage of the power supply [1].

The internal efficiency is a rather practical measure, as it includes all losses incurred from the point of initial energy input to the final expulsion of the working
fluid from the engine or thruster. This includes losses due to incomplete combustion or finite enthalpy in the exhaust stream in the case of chemical systems or wall losses, excitation collisions, and multiple ions in electric thrusters. While, from a practical standpoint, what happens in between is of little or no interest to the end-user, it is of utmost importance to propulsion researchers. If the nature of the loss mechanisms can be resolved, then there is a possibility that certain measures can be taken to reduce or eliminate them, thus increasing the efficiency of the system. To that end, many aspects of a given propulsion system can be examined in an attempt to resolve and subsequently eliminate specific loss mechanisms; however, a simple model is always the best place to begin.

1.2 Helicon Plasma Sources

Helicon waves are a special case of the right-hand circularly polarized (RCP) electromagnetic wave in that they propagate only in bounded magnetized media. The helicon wave was found in 1960 by Aigrain during his study of waves in solid metals [3]. He observed waves in slabs of super low-temperature sodium that propagated in the range of frequencies $\omega_{ci} \ll \omega \ll \omega_{ce}$, where $\omega_{ci}$ is the ion cyclotron frequency and $\omega_{ce}$ is the electron cyclotron frequency. Upon further study, he determined that the wave magnetic field vector traced a helix at a fixed time, hence the name "helicon."

Modern helicon plasmas are produced in cylindrical geometries with a DC magnetic field applied along the longitudinal axis [3, 4]. The gas is first weakly ionized by the electrostatic fields in the antenna region as in a typical capacitively- (CCP) or inductively-coupled plasma (ICP). However, upon application of the external magnetic field, the plasma discharge changes character in that it is no longer subject to the skin depth constraint to which the aforementioned CCP and ICP are. This allows the helicon wave to penetrate into the core of the plasma column. The plasma is then further ionized due to a wave-particle interaction and is thought to be aided by a mode conversion at the wall boundary.
Today, helicon wave sources are being used for a variety of applications due to their ability to efficiently produce a uniform, high density plasma. For example, Chen et. al. [5] have produced helicon plasmas with densities up to $10^{18}$ m$^{-3}$ with uniformities of $\pm 3\%$ for use in materials processing devices. A helicon source is being used as the primary ionization source in the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) concept currently being developed at NASA Johnson Space Center [6, 7, 8]. Jacobson et. al. [9] have been able to routinely produce hydrogen, deuterium, and helium plasmas with peak densities of $10^{19}$ m$^{-3}$ with the VASIMR helicon source.

Helicon sources have many advantages over conventional plasma sources. First and foremost, they are the most efficient laboratory sources of plasma currently known. The reason for their high efficiency is still a much debated topic; however, it seems to be related to the mechanism by which the wave energy is transferred to the plasma. They also have the ability to produce relatively dense plasmas in the range of $10^{18}$ m$^{-3}$ to $10^{21}$ m$^{-3}$. Another very important advantage, particularly in materials processing applications, is the fact that there are no electrodes in contact with the plasma, thus eliminating the possibility of contamination via sputtering. This, of course, is common to all RF plasma sources.

1.3 Overview of Research

The work presented in this thesis seeks to determine the internal efficiency of the mHTX@MIT helicon plasma source as a precursor for propulsion concept studies. That is to say, that a global energy balance will be performed in an effort to quantify the losses present in the system and their relative proportions. This includes losses incurred due to antenna-plasma coupling inefficiencies, radiation, and magnetic confinement as well as the energy lost to the plume.

This is done by using a simplified model of the system whereby the energy balance is made between the RF power input, the radiation and confinement losses, and the plume losses. It will be shown that for purposes of experimental determination of both
the radiation and confinement losses, it is a reasonable approximation to assume that both losses are sufficiently absorbed by the plasma source tube material to simply diagnose the energy incident on the inner surface of the tube without differentiation between mechanisms.

Chapter 2 gives a brief overview of the experimental facilities that were to be used in conducting this research including the vacuum system, control system, and the radio frequency (RF) power system as well as a brief discussion of the source operation and corresponding observations. Chapter 3 discusses plume diagnostics fundamentals including the general operation and theory governing Langmuir probes, Faraday probes, and Retarding Potential Analyzers (RPA). Chapter 4 reviews heat conduction theory with an extension to the simple method used to determine losses to the plasma source tube. Chapter 5 develops the model used to build the energy balance of the mHTX@MIT helicon system. Finally, Chapter 6 covers recommendations for future work.

Appendix A is a rather detailed overview of helicon wave theory as it is currently understood and covers a full derivation of the helicon wave equation including the various modes and the effects of boundary conditions. This should serve as a basis upon which future theoretical and computational work can be launched as well as a primer for those new to helicon plasma physics. Appendix B discusses a simple helicon fluid model that was developed at the beginning of this work, when computation was still a priority. It is complete insofar as it presents a simple drift-diffusion model that matches those used by other researchers as a starting point for helicon simulation. It includes a description of both the ion and electron fluid equations as well as the antenna current model and simple boundary conditions that provide closure of the system. It is meant to orient the reader towards thinking in terms of helicon plasma simulation, although it should not be taken as a complete or valid model without further study. The author leaves further computational development to those who will take up the responsibility of helicon simulations in the future of the mHTX@MIT program. Appendix C describes the process by which a helicon source and antenna
can be designed using a simple extension of the helicon dispersion relation derived in Appendix A. This method is based largely on theory given by Chen et. al. [3, 4, 5, 10, 15] and has been employed in the design of the mHTX@MIT helicon source. The author cautions the reader that it is merely a proposed method and has not been validated in any broad way; however, it may be used as a baseline for source and antenna design, whilst keeping in mind the controversial nature of current helicon theory and the tenuous understanding of the physical mechanisms governing helicon plasma source operation. Finally, Appendix D gives a brief overview of the methods used to bond the surface-mounted thermocouples to the source tube including details epoxy preparation and curing.
Chapter 2

The mHTX@MIT Facility

The Mini-Helicon Thruster Experiment (mHTX) at MIT’s Space Propulsion Laboratory (SPL) is a new program that seeks to establish a firm understanding of the theory and applications of the helicon plasma source as a competitive space propulsion concept. The helicon plasma source, used as an electrothermal thruster, is believed to have the ability to produce moderate thrust levels at moderate to high specific impulses using a variety of different gases [14]. Thrust can also be varied easily by adjusting the mass flow rate of the propellant gas. The helicon source is used because it offers high plasma densities ($10^{13} - 10^{14}$ cm$^{-3}$) and efficiencies at relatively low powers ($\sim 1$ kW).

The system consists of a pair of electromagnets surrounding a quartz tube, in which the plasma is confined. Around this quartz tube and between the two electromagnets, there is a helical antenna that is powered by a radio frequency (RF) power supply. This entire setup is enclosed within a vacuum chamber. The propellant gas is fed to a 2-cm diameter quartz tube through the vacuum chamber wall via a digitally-controlled flow meter. Optical and electrical ports on the chamber walls provide access to the experiment for various diagnostics. The details of each of the above-mentioned systems will be discussed in the sections that follow.
2.1 Vacuum Chamber

The SPL vacuum chamber, affectionately known as AstroVac, is a cylindrical system measuring 1.5 m in diameter and 1.6 m in length. It has six 8 inch ports, four 2-3/4 inch ports, and eight 1-1/4 inch ports, providing maximum flexibility in terms of number and placement of vacuum feedthroughs and optical viewing ports. The chamber is bakeable and is equipped with a mechanical roughing pump and two cryopumps capable of a maximum throughput of 7000 L/s Xenon, which makes possible an ultimate pressure of below $10^{-8}$ Torr. The entire mHTX experimental setup is contained within AstroVac so that all components are under vacuum while running tests. This provides the ability to measure thrust in the future.

2.2 Magnet System

The magnets used to produce the external magnetic field in a helicon discharge are of utmost importance in determining the behavior of a particular design and, as such, need to be designed in such a way that a wide range of field intensities and shapes can be achieved. The mHTX magnet system is composed of two to three electromagnets wound from 10 AWG square, insulated magnet wire. The magnets are powered by two to three, 35-A, 350-V power supplies and are controlled via the main SPL computer system. These magnets are held in place via four tie rods which have removable spacers, allowing the spacing between the magnets to be varied if field shaping is desired. The default spacing is that necessary to produce a Helmholtz array, thus ensuring a uniform field in the antenna region of the helicon source.

The magnet system is capable of producing a continuous field intensity of approximately 1800 G at a current of 35 A per coil and can be precisely controlled between zero and 1800 G. Due to the high power of these magnets and the fact that they are designed to operate at high vacuum, they have been instrumented with two thermocouples per coil so that their internal temperatures can be monitored. This gives the user a measure of how much longer the system can be run before needing to be cooled.
Figure 2-1: Two of the three electromagnets are mounted in a Helmholtz pair configuration. Notice the four tie rods with spacers in between the coils. Also, the shielded, orange thermocouple leads are clearly visible on the right magnet coil. As can be seen, the quartz tube is suspended inside the magnet cores and is attached to the gas feed system at the upstream (right) end.

by way of venting the chamber to atmosphere. Figure 2-1 shows the magnet system with two of the three magnets set up in a Helmholtz pair configuration.

2.3 RF Power System

The RF power system consists of an Advanced Energy RFPP-10 1.2 kW power supply operating at 13.56 MHz, an impedance-matching network, a 13.56 MHz vacuum power feedthrough, a vacuum transmission line, and finally the helicon antenna. This system is rather complex and requires a fair amount of care and attention on a regular basis to ensure that all conductors are making proper contact and that continuity is maintained. Since the power supply, vacuum feedthrough, and transmission line are standard equipment, the details of their design and operation will not be mentioned.
2.3.1 Impedance Matching Network

The impedance-matching network is the most important component in the RF power system. It was designed based on the classic L-network circuit structure and employs two tuneable, vacuum capacitors: one in series and one in parallel with the load (in this case, the antenna and plasma). The need for such a device comes from the fact that the plasma load is dynamic in nature and, as a result, it is necessary to be able to tune the impedance "seen" by the RF power supply to minimize reflected power, thus maximizing the power transmitted to the load. This tuning is done in realtime due to the fact that, during any given test run, parameters such as flow rate, power, or magnetic field intensity may be varied, thus changing the impedance of the discharge. This tuning is performed manually using an oscilloscope, which allows the voltage waveform in the circuit to be measured. The tuner makes adjustments to the capacitance values such that the amplitude of the measured waveform is maximized for a given set of experimental parameters.

2.3.2 Antenna Design

A variety of antenna designs have been employed over the many years of helicon research with varying results [10, 15]. The classic, helical antenna is among the most well characterized and widely used designs [20]. The reader is referred to Figure 2 for details of the physical geometry of a typical helical antenna as it is used in mHTX. Helical antennas come in two varieties: left-handed and right-handed. This nomenclature refers to the direction of rotation of the antenna legs as seen with respect to the wavevector, $\mathbf{k}$. These directionalities also specify the wave mode, where the left-handed and right-handed preferentially excite $m = -1$ and $m = +1$ azimuthal modes, respectively.

To avoid confusion, the reader should note that the twist direction of the antenna and the direction of rotation of the waves are not the same. The left-handed and right-handed helicon waves are based on the direction of rotation of the wave magnetic field
vector with respect to the externally applied magnetic field. As such, the direction of the external magnetic field need only be reversed for a given helical antenna design to change the mode that is excited. While either antenna will excite both modes, the $m = +1$ mode has been found to propagate with a greater intensity than the $m = -1$ mode [15].

The antenna used in the mHTX thus far, was designed as a right-handed ($m = +1$), helical antenna with a radius of 1 cm, per the quartz tube size. It is thought that Landau damping is the primary mode of energy transfer between the wave and plasma. It is possible to design the antenna based on this concept. Since, in the case of Landau damping, wave energy is transferred to particles that are near the phase velocity, an antenna can be designed to launch waves of a desired axial phase velocity, $v_p = \omega/k_z$, which is related to the resonant energy, $E_r$ by $E_r = 1/2mv_p^2$. By choosing this energy to be on the order of the peak ionization cross-section energy, the resonant electrons will absorb sufficient energy from the wave to produce ionization
events [10]. Following this line of reasoning, the mHTX antenna has been designed by setting the RF power frequency, $\omega$ and choosing an antenna length, $L$ ($k = \pi/L$ for a half-wavelength antenna) equal to that which is necessary to produce a resonant energy on the order of that of the propellant gas. In the case of Argon, resonant energies of 20 eV and 40 eV were selected.

### 2.4 Operation

Experimental results with argon (Ar) gas operation have been truly encouraging. An RF power of 400 - 1200 W was able to be delivered to the antenna with minimal reflected power. The flow rate was varied between 10 - 100 sccm. In figure 2-3,
three distinct modes of operation are visible. An ICP discharge was observed for a magnetic field intensity below 800 G, an intermediate mode was observed for magnetic field intensities in the range of 800 - 1300 G, and the blue helicon mode was excited above 1300 G. It can be seen that there is a collimated ion beam (blue color from 430 - 480 nm ion emission) ejected axially from the discharge [11, 12, 13].

In addition to Ar, which was the primary propellant during initial testing, the behavior of the discharge in molecular nitrogen (N$_2$) was studied extensively. Both ICP and helicon modes have been achieved as shown in figure 2-4. A narrow plasma beam can be seen to be formed in the photo on the right. Operating the source using N$_2$ showed distinct differences from Ar operation. For example, higher flow rates (~40 sccm) and lower magnetic field intensities (below 1200 G) were required for best antenna-to-plasma coupling and discharge stabilization. Under these conditions, a full 1.2 kW of RF power was able to be delivered to the antenna.

Plasma source operation was also attempted with air, an N$_2$/Ar mixture, and xenon (Xe). A stable discharge was achieved in each case. Running the experiment during a continuous transition from pure N$_2$ to pure Ar with fixed magnetic field intensity and sporadic tuning of the RF impedance-matching circuit demonstrated the ability to deliver ~800 W for any N$_2$/Ar proportion [11, 13]. An example of operation using the mixture of the gases is presented in figure 2-5. The photograph...
Figure 2-6: Operation at 20 sccm Ar gas flow with a permanent ceramic magnet in view at the end of the source tube. Note the constriction of the plasma column followed by an abrupt expansion to what appears to be a planar structure in the upstream region. Also note the semi-spherical structure in the downstream, plume region.

on the right shows the operation of the system with air taken directly from the lab atmosphere.

As a part of initial testing, permanent Neodymium and ceramic magnets have been used in addition to the aforementioned electromagnets [11]. A stable helicon discharge was obtained in all of these cases, as well. For a certain configuration, double-layer-like structures have been observed in the flow as shown in figure 2-6. An attempt is being made to characterize this observation more deeply using lab diagnostics and adaptive kinetic modeling [14, 23, 24, 25, 26, 27].
Chapter 3

Plume Diagnostics

There are a variety of diagnostic techniques for characterizing a plasma depending on the target parameter to be studied. These techniques can be separated into two main categories: intrusive and non-intrusive. An intrusive technique is characterized as one in which a physical probe is placed in the plasma and, thus, perturbs the plasma. This perturbation can be minimal or significant depending on the dimensions of the probe as compared to the characteristic dimension of the plasma. As a result, there are situations in which intrusive diagnostics fall second to non-intrusive methods. Non-intrusive methods include a variety of optical techniques such as emission spectroscopy and microwave interferometry; however, these techniques typically suffer from the need for a sizable financial investment and a rather complex experimental setup. Typical intrusive techniques include Langmuir probes, Faraday probes, and Retarding Potential Analyzers (RPA). These probes are usually simple in construction and, as such, are rather economical. While both categories can accomplish similar goals, the scope and budget of this research specified the use of intrusive diagnostics in order to diagnose the plume region of the helicon plasma source.
3.1 The Langmuir Probe

The Langmuir probe is the simplest of the intrusive instruments. In its most basic form, it consists of a rod of tungsten, which serves as a single electrode. The rod is typically insulated with a sheath of ceramic material along its entire length save a small tip that is left exposed. In practice, any refractory metal can be used; however, tungsten seems to be the most popular due to its relatively low cost and high availability. The rod itself may range in size from sub-millimeter to several millimeters in diameter, although, the perturbation caused by the probe is proportional to the characteristic dimension of the probe tip as compared to the characteristic dimension of the plasma to be diagnosed, so its diameter is a practical consideration to be made by the experimentalist. See Figure 3-1 for a simple representation of a Langmuir probe.
probe.

The Langmuir probe can be used to determine the plasma and floating potential and the electron temperature and density by way of sweeping the potential applied to the electrode over a range of negative and positive voltages while immersed in the plasma. While doing so, an instantaneous current is measured corresponding to the instantaneous applied potential and a current-voltage (I-V) characteristic curve is constructed. From this I-V curve, the plasma parameters can be determined with appropriate application of the Langmuir probe theory.

### 3.1.1 The Electrostatic Sheath

The classical Langmuir probe theory is based upon the concept of the plasma or electrostatic sheath, which is a structure formed on any solid surface in contact with a plasma. The existence of the sheath arises as a result of the disparity in electron and ion fluxes to the collecting surface. The pre-sheath and sheath fluxes are a function of the electron and ion densities as well as the temperatures and masses of the particles and can be expressed as follows:

Pre-sheath:

\[
\Gamma_e = n_e \sqrt{\frac{kT_e}{2\pi m_e}} \\
\Gamma_i = n_i \sqrt{\frac{k(T_e + ZT_i)}{m_i}}
\]

Sheath:

\[
\Gamma_e = n_e \sqrt{\frac{kT_e e^{-\frac{\Delta \phi_s}{T_e}}}{2\pi m_e}} \\
\Gamma_i = n_i \sqrt{\frac{k(T_e + ZT_i)}{m_i}} e^{-\frac{1}{2}}
\]
Where \( n_e \) and \( n_i \) are the electron and ion densities, respectively and are assumed to be approximately equal due to the assumption of quasi-neutrality, \( k \) is Boltzmann’s constant, \( T_e, T_i, m_e, m_i \) are the electron and ion temperatures and masses, respectively, \( Z \) is the charge state of the ion species, and \( \Delta \phi_s \) is the sheath potential [2].

Now, since the plasma is assumed to be quasi-neutral, the densities will be unified and expressed as \( n_e \approx n_i = n \). Also, most laboratory plasmas are considered to have cold ions, which means that the ion temperature is significantly lower than the electron temperature so as to be able to safely neglect that term in the above equations. That is, \( T_e \gg T_i \). Applying these changes to equations (3.1.1), and taking the ratio of electron to ion fluxes in the pre-sheath, it is found that

\[
\frac{\Gamma_e}{\Gamma_i} \approx \sqrt{\frac{m_i}{2\pi m_e}}
\]

(3.1.3)

This value can be many times greater than unity and, in fact, in the case of Argon \((m_i = 39.95m_{proton})\) as the working fluid, it is approximately 108. Because of the fact that electrons stream to the surface in contact with the plasma at a rate much greater than that of the ions, the surface accumulates a net negative charge. The accumulation of this negative charge value grows until a balance between electron and ion fluxes is met, thus creating a "potential sheath.” That is to say that the electron flux is retarded and the ion flux is accelerated by negative surface potential until an exact equilibrium is reach and there is no net charge exchanged across the boundary of the sheath. The potential at which the sheath is located is referred to as the floating potential and can be found by equating equations (3.1.2) and solving for \( \Delta \phi_s \) as follows:

\[
|\Delta \phi_s| = \frac{kT_e}{e} \ln \sqrt{\frac{m_i}{2\pi m_e}}
\]

(3.1.4)

The exact location of the sheath boundary is a more complex topic and requires the satisfaction of what is referred to as the Bohm Sheath Criterion; however, for the purposes of this discussion, it is sufficient to mention that this is met when the ion
Figure 3-2: A plot showing the important aspects and regions of a typical Langmuir probe I-V curve. Notice that the floating potential is negative with respect to the plasma potential.

velocity becomes sonic:

\[ u_i \geq c_s \approx \sqrt{\frac{kT_e}{m_i}} \]  \hspace{1cm} (3.1.5)

Where \( u_i \) is the ion velocity and the same assumptions of cold ions has been applied to simplify the temperature term in the numerator. Also, the reader should note that, in the most strict sense, the Bohm Sheath Criterion is an inequality as shown in equation (3.1.5).
3.1.2 Langmuir Probe Theory

Now that a basis has been formed for an understanding of the electrostatic sheath, the specifics of its role in Langmuir probe theory can be discussed. There are several regions of interest in a typical Langmuir probe I-V curve as shown in Figure 3-2. Referring to Figure 3-2 for the remainder of this discussion and going from left to right, the first region of interest is the ion saturation region. This is the region in which the probe has been biased sufficiently negative so as to repel all but the most high-energy electrons, thus preventing any greater negative charge build-up. This is characterized by a rapid leveling of the I-V curve to a negative current value [22, 34].

Following the ion saturation region is a brief but intense decrease in current. This occurs as a result of decreasing probe potential, thus permitting a increasingly greater number of electrons to reach the surface and culminates in a zero-current, potential value known as the floating potential, denoted as $V_F$. This is when the applied voltage on the probe produces an equilibrium in the electron and ion fluxes as discussed in the above section and is exactly synonymous with the equilibrium sheath potential case on a non-biased or floating-potential surface in the plasma.

The next region of interest is the electron retardation region. This lies between the floating potential and the plasma potential values and is characterized by a rapid increase in positive current due to the increasingly more positive probe bias. This causes a larger portion of the electron distribution to reach the probe surface and eventually leads to the electron saturation region. The plasma potential, $V_P$ is the voltage value characterized by the rapid decrease in current from the electron retardation region to the electron saturation region. For voltages below $V_P$ an electron sheath exists; however, when the probe bias potential is increased beyond $V_P$, the sheath shrinks until all electrons are permitted to reach the probe surface. This is now the electron saturation region and, of course, occurs as a result of a physical inability of a bulk of the ion distribution to reach the probe [22, 34].
3.1.3 Determination of Plasma Parameters

Floating and Plasma Potentials

With a basic understanding of Langmuir probe theory it is now possible to calculate the plasma parameters of interest from the information provided in the Langmuir probe I-V curve. First, the most simple values to determine are the floating and plasma potentials. The floating potential, \( V_F \) is simply the x-intercept value of probe potential. The plasma potential, \( V_P \) can be found by drawing tangents to the electron retardation and electron saturation regions and is the voltage value corresponding to the intersection point of the two tangents. The value can also be found more rigorously by taking the maximum of the first derivative of current with respect to voltage, namely \( I' (V) \) [22, 34].

Electron Temperature

In order to determine the electron temperature, it must be assumed that the electron energy distribution function is purely Maxwellian. If this is the case, then the electron current in the retardation region can be written as an exponential function of the potential and temperature as follows:

\[
I_e^r = e n_e A_p \sqrt{\frac{k T_e}{2 \pi m_e}} e^{\frac{U}{k T_e}}
\]  

(3.1.6)

Where \( e \) is the fundamental charge, \( A_p \) represents the probe collection area, and \( U = V - V_P \) has been introduced to denote the value of potential with respect to the plasma potential, the utility of which will become apparent in the electron density discussion. Now, upon taking the logarithm of equation (3.1.6) and differentiating with respect to potential, the final result is found to be

\[
\frac{d \ln I_e^r}{dV} = \frac{e}{k T_e}
\]

(3.1.7)

It should be noted that if the logarithm of equation (3.1.6), namely in the form
$\ln I_e = eV/kT_e + C$, is plotted on a log-linear scale, the relationship between $\ln I_e$ and $V$ should be a linear one, whose slope is proportional to the electron temperature by equation (3.1.7); however, deviations from a linear relationship will indicate a non-Maxwellian electron energy distribution function [22].

**Electron Density**

To determine electron density, it is necessary to know electron temperature a priori using the above-mentioned method. Now, by taking equation (3.1.6) and considering the situation where $V = V_P$, it is found that $U = 0$ and the exponential term vanishes, leaving

$$I_e^r (V = V_P) = e n_e A_p \sqrt{\frac{kT_e}{2\pi m_e}}$$

(3.1.8)

Further assumption that the characteristic dimension of the sheath is negligible compared to the dimensions of the actual probe tip itself allows the physically measurable area to be used for the probe area value. Of course an explicit equation for electron density only requires a trivial reorganization of equation (3.1.8).

### 3.2 Faraday Probe

The Faraday probe is a simple instrument that is used to measure the current density of the target plasma and ultimately, in combination with simultaneous electron density measurements from a Langmuir probe, can provide an estimate of the speed at which the bulk plasma is traveling. Another use is the opposite situation where the birth potential of the ions is known and hence, a value of ion velocity is able to be computed. In this case, the Faraday probe can then be used to determine electron density, which is often more accurate than Langmuir probe measurements.

The probe itself is not unlike a Langmuir probe in that it utilizes an electrode immersed in the target plasma; however, the main difference is that, rather than having a small tip, the Faraday probe has a plate-like electrode whose exposed area is
Figure 3-3: A pictorial representation of a Faraday probe in contact with the target plasma. Notice that the guard ring successfully attracts ions from the sides of the probe so as to collimate the field of view of the probe surface.

known precisely. Surrounding this flat-plate electrode is an electrically isolated ring known as a guard ring. In general operation, both the electrode and guard ring are independently biased at a sufficiently negative, but equal potential as to place the probe in the ion saturation region. In doing this, the guard ring collects a fair amount of current and "fools" the plasma, thus canceling geometrical fringe-field effects [34].

Figure 3-3 shows a diagram of a Faraday probe during operation. Notice that the guard ring is electrically isolated from the collector plate via the ceramic sheath surrounding the stem of the collector plate electrode; however, as mentioned above, it is not floating. Figure 3-4 shows the actual Faraday probe to be used. This particular design was originally developed by Azziz et. al. [34] at the MIT Space Propulsion Laboratory for use in Hall thruster plume diagnostics and has been reconstructed.
and adapted for diagnosing the mHTX@MIT helicon plume. For practical purposes, both the guard ring and the collector plate should be biased at the same negative potential in the range of -8V to -20V, based on experiments performed by Azziz et al. [34]. These voltages were found to place the probe well within the ion saturation region, while the fact that both were biased to the same potential produced a uniform sheath around both the collector plate and guard ring. For a fully detailed discussion of probe design considerations, the reader is referred to [34].

In practice, the Faraday probe measures a current that is induced by the ions incident on the collector plate. This current is then simply divided by the known area of the collector plate to determine the current density. The probe is typically swept in angle at some fixed radius from the plasma source exit to build a profile of current density as a function of angle. This, in turn, can be used to determine total plume current and plume divergence, which is a useful measure of the extent to which a plasma beam is collimated. Plume divergence is an important aspect of thruster performance when considering the possibility of plume impingement on nearby spacecraft surfaces and also specifies, to some extent, the proportion of the
ejected bulk plasma that is actually used to produce an on-axis thrust force. Equation (3.2.1) shows the relationship between current density, $j$, collected current, $J_c$, collector plate area, $A_c$, and ion velocity, $v_i$ as follows:

$$j = \frac{J_c}{A_c} = e n_e v_i \quad (3.2.1)$$

The plume can be considered a cone with a a spherical cap whose apex is centered at the origin of a spherical coordinate system $(r, \phi, \theta)$, which is located at the center of the plasma source exit plane. The longitudinal axis of the plasma source is the z-axis and points in the positive direction. The location of the Faraday probe is then given by the radius, $r$ specifying its distance from the origin and its angular location is fixed in zenith ($\theta = 0$) but is free to rotate in azimuth ($-\pi/2 \leq \phi \leq \pi/2$). Furthermore, it is assumed that the face of the Faraday probe is always facing the origin, that is to say that the longitudinal axis of the probe is collinear with a vector extending from the origin to the face of the Faraday probe with a magnitude of $r$ and an azimuth of $\phi$. Thus, the path of the Faraday probe describes the projection of a cone onto the x-z axis. In this system, assuming that the angular current distribution is axisymmetric, it is simple to see that to determine the total current contained in the plume, the following equation for the solid angle that is subtended by a half-cone of the type describe above is:

$$I_p = 2 \pi r^2 \int_{0}^{\pi/2} j(\phi) \sin(\phi) \, d\phi \quad (3.2.2)$$

Equation (3.2.2) can then be augmented slightly in order to determine the plume divergence half angle by specifying a reasonable value of the beam current that should be contained within the plume and finding the half-angle at which this value is satisfied. In the past, researchers have used values in the range of 95 - 98% of the beam current. Based on the work of Azziz et. al. [34], the author suggests the use of 95% as a starting value. Equation (3.2.2) can be recast as a condition to be satisfied as follows:
Finally, the most important calculation to be made for purposes of this work is that of the total plume energy or power. This can be done by way of capturing angular distributions of plasma potential and current simultaneously using a Langmuir probe and Faraday probe. The product of plasma potential and current at a given azimuth and radius is then the power and can be expressed as follows:

\[ P(\phi) = J_c(\phi)(V_0 - V_P(\phi)) \]  

(3.2.4)

Where \( V_0 \) is the ion birth potential and is determined from ion energy distribution data. The integral of equation (3.2.4) in the range \( 0 \leq \phi \leq \phi_{1/2} \) will then give the plume power

\[ P_p = 2\pi r^2 \int_0^{\phi_{1/2}} P(\phi) \sin(\phi) \, d\phi \]  

(3.2.5)

This result will then be used in the global power balance model of the mHTX@MIT helicon source and will specify the value of the numerator in equation (5.3.3) for purposes of determination of the internal efficiency of the system.

### 3.3 Retarding Potential Analyzer

The final instrument to be discussed is what is typically referred to as a Retarding Potential Analyzer (RPA). The RPA is basically a collimated Faraday probe with the addition of a number of grids spanning the length of the instrument. Each grid is responsible for shielding the collector plate from a different class of particles by way of an applied potential. The first grid is typically left floating to shield the instrument from the bulk of the plasma. The second grid is referred to as the electron-repelling grid and is biased to a sufficiently negative voltage so as to repel electrons from further penetration into the probe body. The third and final grid is the ion-retarding grid.
and is swept thru a range of voltages from zero to sometimes as high as 500V. As the potential of the ion-retarding grid increases, an increasingly greater number of ions are unable to travel up the potential to pass the grid and be collected. This effectively gives the experimentalist an I-V characteristic curve that describes the quantity of ions whose energies are those swept through by the RPA. This I-V curve is then used to determine the energy distribution of the ions in the target plasma, since the ion energy distribution is proportional to $I'(V)$.

It should be mentioned that in some RPA designs, a fourth grid is included just upstream of the collector plate. This is called the secondary-electron repelling grid and is positively-biased to prevent the measurement of an erroneously high current due to secondary-electron emission. Secondary-electron emission is caused by very
high energy ions as they impact the collector-plate surface and can be dealt with by the addition of a fourth, positively-biased grid or by constructing the collector plate of a material with a higher work function, such as tungsten or another refractory metal. It should be noted; however, that at plume potentials lower than about 1 kV, this effect is small and can be corrected for from secondary-electron emission data [22, 34].

Figure 3-5 shows a picture of an RPA during operation. As with the Faraday probe, the particular RPA used for the mHTX@MIT diagnostics was developed by Azziz et. al. at the MIT Space Propulsion Laboratory. The original design has been reproduced for the purposes of this work and a photograph of the probe deconstructed to show the details of the grid arrangement is shown in Figure 3-6. Again, the reader is referred to [34] for details of the design of the RPA used in this work.