The use of electric probe techniques for electric potential measurements in plasma thrusters

IEPC-2011-174

Presented at the 32nd International Electric Propulsion Conference, Wiesbaden, Germany
September 11–15, 2011

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Accurate measurements of the plasma potential are critically important for understanding plasma production, acceleration, and plasma-wall interactions in plasma thrusters. Such measurements are also a critical challenge, especially for complex, flowing, and magnetized plasmas, such as produced in plasma thrusters. Because of its convenience and simplicity, the floating emissive probe technique has been widely employed for potential measurements in plasma thrusters, especially for Hall thrusters. However, this technique is expected to give a value of $T_e/e$ below the plasma potential ($\phi$) due to space charge effects. For plasmas with $T_e/e\phi$ this may lead to large errors in the determination of the plasma potential distribution. In this paper, we summarize the experimental validation of the predicted space charge effects for the emissive probe, detailed elsewhere.¹ We compared various emissive and non-emissive probe techniques for measuring the plasma potential. The measurements were conducted for a 2kW, 12 cm diameter Hall thruster operated in the Large Thruster Facility at the Princeton Plasma Physics Laboratory (PPPL). The thruster was operated with xenon gas in subkilowatt power range and the discharge voltage range of 200 to 450V. The probe was placed at the channel exit where the electron temperature is in the range of 10 to 60eV and the plasma potential is in the range of 50 to 250V. The experimental results generally support theoretical predictions and results of numerical simulations for the potential near the floating electron emitting surface. Specifically, it is shown that the floating potential of the emissive probe is $\sim 2T_e/e$ below the plasma potential. It is observed that the separation technique, which involved measurements of the probe I-V characteristics for cold and hot probes varies wildly and does not give a good measure of the plasma potential.

I. Introduction

Emissive probes have been effective in measuring the plasma potential in a wide variety of plasmas from RF discharges to tokamaks.²³ There are, however, different techniques for using emissive probes which can give different results, so this experiment has compared the various techniques and evaluated them. From this, conclusions can be drawn concerning the floating potential of a highly emissive surface. This paper highlights the experiment described in a recently published article (Ref. 1).

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II. Overview of techniques that were compared

Three emissive probe techniques and one Langmuir probe technique were compared in this experiment. The separation point is an emissive probe technique that takes the plasma potential to be the voltage on the probe above which the emitted electron current is zero and below which the emitted electron current is greater than zero. The most popular emissive probe technique is the floating point method which measures the floating potential of an emissive probe when it is heated to the point of saturated emission. The inflection point in the limit of zero emission technique is performed by measuring the inflection point of emissive probe current-voltage (I-V) traces for multiple small levels of emission and extrapolating to the point of zero emission. Finally, the inflection point of a Langmuir probe technique was used, which takes the plasma potential to be the inflection point of an non-emitting Langmuir probe I-V trace. These techniques have been summarized in detail elsewhere.

III. Experimental setup

A. Hall thruster

The various methods for measuring the plasma potential were tested in a 2kW cylindrical Hall thruster (see the original article for greater detail). The Hall thruster has an outer diameter of 12.3 cm, an inner diameter of 7.3 cm, and a channel depth of 4.6 cm with two electromagnetic coils that produce a magnetic field. The working gas, xenon, was flowed from the anode, which was biased between 250 and 450 V with respect to the cathode. The cathode was biased at −15 V with respect to ground. These discharge parameters created a plasma with \( n_e \sim 10^9 - 10^{10} \text{cm}^{-3} \) and \( T_e \approx 10 - 50 \text{eV} \) (the plasma parameters varied across this range spatially within a single discharge). The plasmas examined in this region had a wide variety of temperatures and potentials, magnetic field, secondary electron emission effects, and ion drift. In order for an emissive probe technique to be robust, it must be able to make measurements with all of these non-ideal conditions affecting the probe.

B. Emissive probe construction

A diagram of the emissive probe used is shown in Fig. 1. The alumina (Al\(_2\)O\(_3\)) tube was double bored to accommodate the two separate sets of wires leading to the probe. The probe was constructed by first inserting the probe filament made of 0.005 cm diameter thoriated tungsten so the wire stuck out the opposite end of the tube through both bores. The emissive probe wire was secured by inserting seven pieces of tungsten (not thoriated) wire of the same diameter into the bores, but leaving the two tubes electrically connected only by the filament wire. By inserting seven additional wires into each bore the electrical contact and mechanical security was maintained. The boron nitride tube covered the 0.5 cm of alumina closest to the emitting wire which served to reduce secondary electron emission.

C. Electronics

As mentioned before, one reason for the floating point method’s popularity is its ease of use, which can be seen in the electronics necessary to take measurements. A circuit diagram of the electronic system used to make measurements with the floating point method is shown in Fig. 2. The system consists of a power supply swept at a low frequency (\(~ 0.1 \text{Hz}\)) with a triangular waveform which heats the emissive probe.
Figure 2. The circuit diagram of the electronics used to measure the floating potential of an emissive probe at saturation.

The floating potential of the probe was measured using a high impedance operational amplifier to which was added one half of the heating voltage.

The three other methods were performed by taking one or more I-V traces at various emission levels. Figure 3 shows the circuit diagram used to take emissive probe I-V traces. The bias on the probe was swept by a function generator with a sinusoidal waveform at 30 Hz amplified by a bipolar amplifier. The probe was heated by a floating power supply that was manually controlled since the emission only needed to be changed between I-V traces, not during them. The probe current was determined by measuring the voltage across the 200Ω current shunt resistor. More details can be found in Ref. 3.

IV. Results

The difference between both inflection point methods and the floating point method and the difference between the separation point method and the floating point method are normalized to and plotted against effective electron temperature ($T_{e,\text{eff}}$) in Fig. 4. An effective electron temperature was used to account for the enhanced high energy tail of the Electron Energy Distribution Function (EEDF). Error bars were not included because the uncertainty was small (0.1 to 0.3$T_{e,\text{eff}}/e$). If the plasma was a pure Maxwellian, the normalized difference between the plasma potential and the floating potential is expected to be 1.8, as indicated by the dashed line. Notice that the inflection point in the limit of zero emission ($V_{\text{IP}}$) and the inflection point of a Langmuir probe ($V_{\text{LP}}$) agree quite closely with each other. Both measures of the plasma potential are consistently around 2$T_{e,\text{eff}}/e$ above the floating potential of a highly emissive probe. This is fairly consistent with analytic and simulation predictions if the inflection point methods accurately measure the plasma potential. The result of 2$T_{e,\text{eff}}/e$ rather than 1.8$T_{e,\text{eff}}/e$ may be explainable by the presence of beam electrons. Additionally, Fig. 4 shows the relationship between the separation point technique ($V_{\text{sep}}$) and the floating point technique. The normalized difference between these two techniques varies wildly, between 1 and 4. Because the floating point method is expected to have a consistent relationship to the plasma potential it is reasonable to conclude that the separation point technique does not give a good

Figure 3. The circuit diagram of the electronics used to take I-V traces.
Figure 4. The differences between the inflection point in the limit of zero emission method and the floating point method \((V_{LP} - V_F)\), the inflection point of a Langmuir probe method and the floating point method \((V_{IP} - V_F)\), the separation point method and the floating point method \((V_{sep} - V_F)\) versus electron temperature. The dashed line indicates the expected result of \(\varepsilon \Delta V_{measurements}/T_{e,eff} = 1.8\). This graph shows that a highly emitting surface floats \(\sim 2T_{e,eff}\) below the plasma potential as measured by the inflection point techniques.

V. Conclusions

Although the floating point technique is the most popular method for measuring the plasma potential, it is not the more accurate. This experiment has shown that a highly emissive probe floating \(\sim 2T_{e,eff}/e\) below the plasma potential as accurately measured by the inflection point techniques. The floating point technique is still very useful because of its easy construction and operation, but it must be tempered with the knowledge of its inaccuracies. See Ref. 1 for more information about this experiment and the results.

VI. Acknowledgments

Special thanks are due to Martin Griswold and Lee Ellison for all of their assistance. This work was supported by US Department of Energy grants No. DE-AC02-09CH11466, and No. DE-FG02-97ER54437, the DOE Office of Fusion Energy Science Contract DE-SC0001939, and the Fusion Energy Sciences Fellowship Program administered by Oak Ridge Institute for Science and Education under a contract between the U.S. Department of Energy and the Oak Ridge Associated Universities.

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