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DESIGN AND MANUFACTURING OF THE SINGLE LANGMUIR PROBE FOR PLASMA MEASUREMENTS IN HALL EFFECT THRUSTER EXPERIMENTS

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ABSTRACT

Electric propulsion is a technology which has been tested on ground and in space since 1960s. The goal of electric propulsion systems is to achieve thrust with high exhaust velocities using electricity. To date, more than 200 hundred electric thrusters have been flown and operated successfully onboard communication satellites and deep-space scientific missions for years with zero failure rate, making the technology more attractive in recent years. Thrust, specific impulse, total efficiency and plume divergence are some figures of merit for the performance of the thruster ([1,2]). Different probes are used in plasma measurements to evaluate and test the performance of the Hall Effect Thrusters. In this study, a Single Langmuir probe design is given for plasma measurements in low pressure. The basic working principle of Single Langmuir probe along with the criteria and measurement methodology applied in the design of the probe is also described. In addition, the technique that will be used in the analysis of the current-voltage characteristics to determine the local plasma potential, electron number density and temperature is discussed in detail.

INTRODUCTION

Electric propulsion is a cost effective solution for many space applications compared to other conventional propulsion methods, such as chemical propulsion, because it creates higher specific impulse and therefore reduces the amount of propellant required for a specific space mission. Less propellant allows for less launch mass of a spacecraft and it reduces the cost to send a desired mass into a given orbit or to a deep-space target. ([1,2]).

Firstly Robert Goddard conceived electric propulsion in 1906 and Tsiolkovskiy independently described it in Russia in 1911. Hermann Oberth in Germany in 1929 and Shepherd and Cleaver in Britain in 1949 provided several electric propulsion concepts for a variety of space applications. *Ion Propulsion for Space Flight*, written by Ernst Stuhlinger in 1964, included the first systematic analysis of electric propulsion systems and a book of Robert Jahn first described comprehensively the physics of electric propulsion thrusters in 1968. S.Grishin and L.Leskov wrote a book which includes an extensive presentation of the principles and working processes of several electric thrusters in 1989 [2]. Russia made the first extensive application of electric propulsion using Hall Thrusters for station keeping on communication satellites. Over 238 Hall thrusters have been operated on 48 spacecraft to date, since 1971 when the Soviets first sent a pair of SPT-60s on the Meteor satellite. In the past

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20 years, electric propulsion use in spacecraft has been preferred for scientific missions and as an attractive alternative to chemical thrusters for station-keeping applications in geosynchronous [2].

There is wide variety of electric propulsion types and for better understanding they are classified. Electrostatic, electro-thermal and electromagnetic thrusters are the three major categories of electric propulsion systems [1]. Hall thrusters which are electrostatic type have basic structures compared to other electric propulsion systems.

The ultimate goal of our study is to design, manufacture and use a single cylindrical Langmuir probe to measure the plasma characteristics in the plume of a HET in space simulator. This work is the first step taken to achieve this goal and includes a single Langmuir probe design proposed to be used in an RF and DC plasma. In the following paragraphs first the working principle of HETs and theory of Langmuir probes are briefly described. Then, measurement system, criteria applied in the probe design and the proposed probe is presented. Following this work, we are planning to manufacture and test the probe in low pressure plasma measurements in the vacuum chamber. Moreover, current-voltage characteristics of a standard commercial single probe obtained in the same measurement system will be analyzed and the results will be compared with our probe. In the future, we aim to apply our design in studying the plume and performance characteristics of a Hall Effect thruster.

METHOD

The Working Principle of a Hall Effect Thruster

A Hall Thruster basically consists of three components which are the cathode, the discharge region and the magnetic field generator. The discharge region is enclosed by a cylindrical insulating channel. A radial magnetic field is generated by magnetic coils. Gas is injected at the anode and dispersed into the channel. Hall current is created by the electrons which tend to spiral around the thruster axis in the ExB direction. The collisions between the electrons and neutral gas create the Xe ions. These ions are accelerated by the electric field between the anode and cathode. The accelerated ions produced the thrust at the exit of the thruster [2]. There are two types of Hall Effect Thruster in literature which are Stationary Plasma Thruster (SPT) and Thruster with Anode Layer (TAL) classified according to their material of the inner channel. In this study, we focus on the Stationary Plasma Thrusters, specifically SPT-100 types for our plasma measurements.

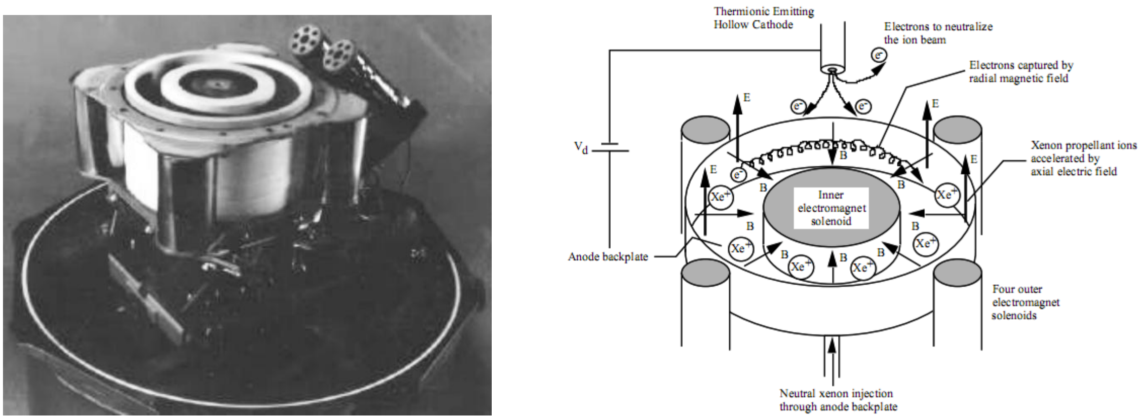

Figure 1: Photograph of SPT-100 and schematic of a basic SPT-100 operation [3]

The Working Principle of a Langmuir Probe

The Langmuir probe, which was first developed by Irving Langmuir in 1924, is an electrostatic diagnostic tool used in the evaluation of several plasma properties in Hall Effect Thrusters. Local plasma potential, electron number density and electron temperature can be discerned from the I-V characteristics based on the collected current response of a single electrode to an applied bias voltage [4]. Langmuir probe is basically just a wire placed into the plasma. As seen in figure 2, plasma sheath limits the electrical contact between the probe and plasma. The probe's voltage can be traced by an external power supply and the resulting current can be measured. From the careful analysis of I-V curve, local plasma potential, electron number density and electron temperature can be determined [5]

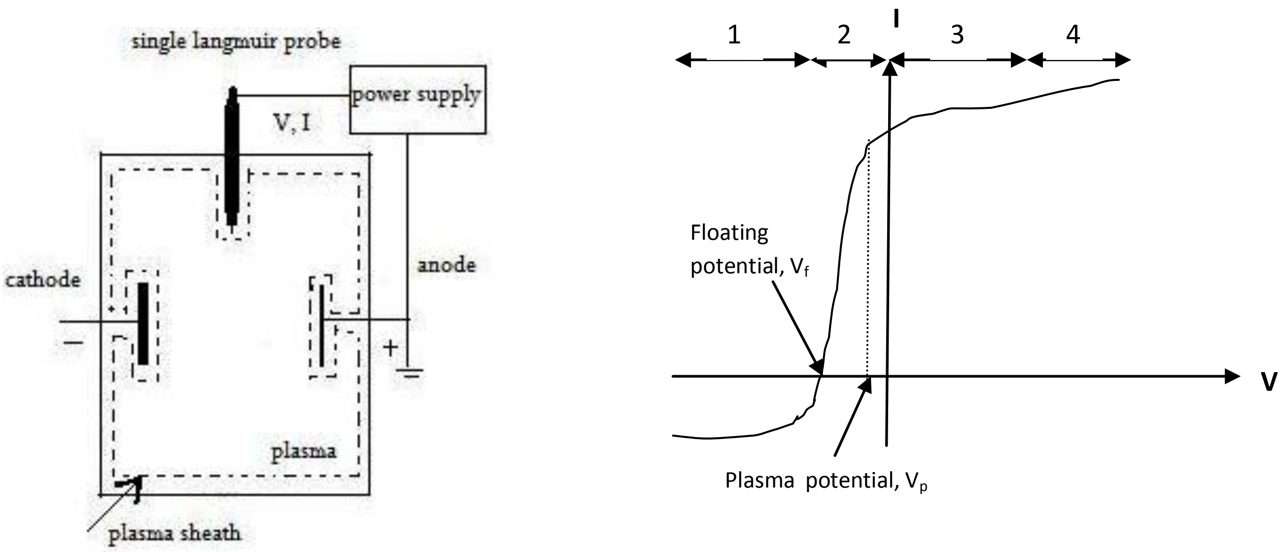

Figure 2: Single Langmuir probe placed into the plasma and I-V relationship [5]

<u>Langmuir Probe Theory</u>

Although Langmuir probe has a basic structure, the physics behind its working principle and reliable evaluation of measurements can be quite complicated. Therefore, in years the Langmuir probe theory was developed for the evaluation of the I-V characteristic and determination of the plasma parameters using these probes. As seen in figure 2, there are four regions in an I-V curve. In region 1, when a negative bias voltage is applied, electrons are repelled from the probe and collected current is dominated by ions. As the probe bias voltage is gradually increased, ion and electron currents reach a balance. At the point where a zero net current is collected, the measured potential is called "floating potential". In region 2, when the probe bias voltage is further increased, electrons continue to be pushed but only highly energetic electrons are able to pass the sheath and make contribution to the collected current. In this region, there is a positive current towards the electrode. When the probe bias voltage is further increased, local plasma potential bends over a knee-point in region 3. An increase in the bias voltage beyond this point results in, electron saturation in region 4 and almost all electrons are collected by probe. In this region the sheath becomes even thicker [4].

<u>Analyzing I-V Slope</u>

Using OML (Orbital Motion Limited) assumption, also called as thick sheath analysis, electron temperature is obtained easily from the transition region (region 2) using the following equation [6]

$$T_e = \left(\frac{d \ln I_e}{dV} \right)^{-1} \tag{1}$$

In order to measure plasma potential, the following equation is used [6]

$$V_s = (dI/dV)_{\max} \tag{2}$$

Electron number density can be derived from the following ion-saturation current [7]

$$I_i = A_p.n_e.\frac{\sqrt{2}}{\pi}\sqrt{\frac{e(V_{s1} - V_p)}{M_i}} \tag{3}$$

$$n_e = \frac{I_i}{A_p.\sqrt{\frac{e(V_{s1} - V_p)}{M_i}}}\frac{\pi}{\sqrt{2}} \tag{4}$$

In (4), A_p is the probe surface area, e the electron charge, V_p the probe potential and M_i the ion mass. Vs_1 is a temporary space potential used for fitting [7].

Measurement System

In general, plasma properties inside, near and far from the thruster vary in great respect. Therefore different measurement methodologies and different Langmuir probe designs are needed to be used in different regions. In the future, we are planning to study the *plasma* parameters in the *far-field* plume of a *Hall Effect thruster* to determine the performance characteristics.

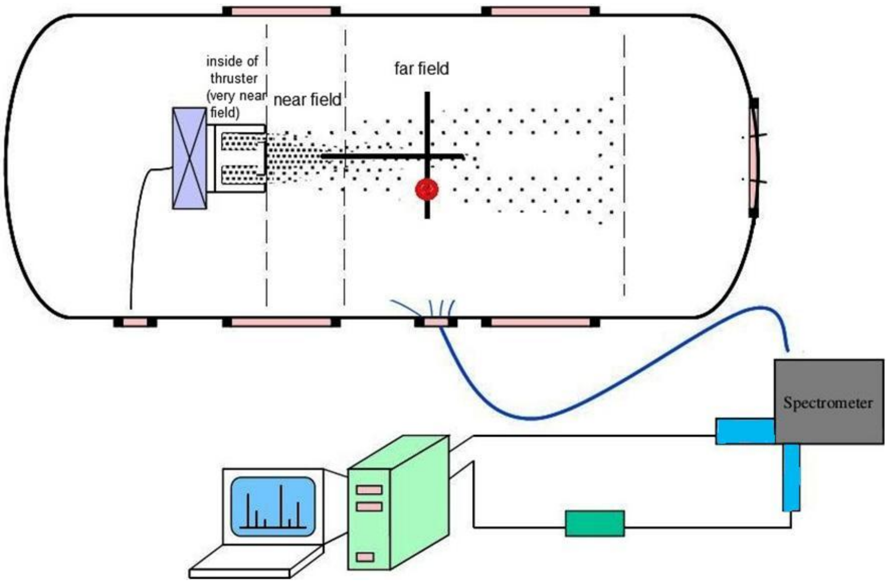

Figure 3: Schematic of Experimental Set-up of Hall Effect Thruster, showing different regions of plasma [8]

However, in this work we are working on the following system shown in figure 4. Langmuir Probe is inserted into a stainless steel cylindrical plasma chamber whose dimension is 500 x 400 mm^2. Inside the chamber, two identical electrodes are assembled with a 40 mm distance like a parallel plate capacitor. Diameter of these two-isolated identical aluminum electrodes is 200 mm. The plasma is generated by heating the gas between the electrodes under low pressure. In this system, both an RF and a DC generator can be used as a power source. Moreover, either Xenon or Argon can be chosen as the plasma source gas.

The ALP System electronics performs the data acquisition, control, analysis of the Langmuir Probe and transfers them to a computer.

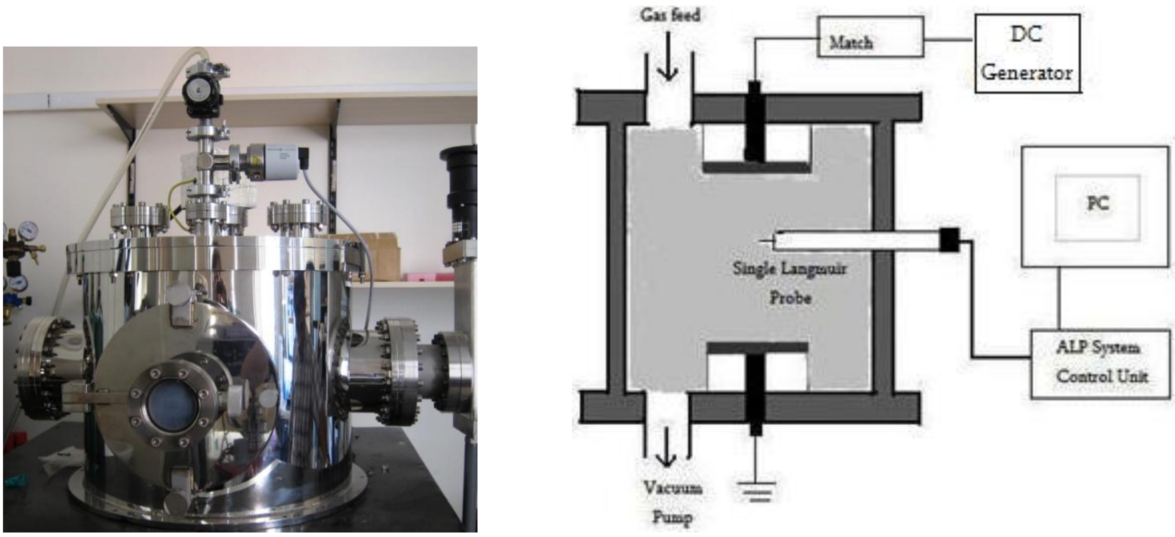

Figure 4: Photograph of cylindrical plasma chamber and schematic of experimental set-up

The Dimensions and Materials of the Probes

<u>Design Criteria</u>
One important parameter in probe design is that whether there are too many collisions in the probe sheath or they can be ignored [9]. Knudsen Number (K_n) is an unitless number which characterizes particle collisions in probe sheath [4].

$$K_n = \frac{\lambda_{mfp}}{r_p} \quad (5)$$

If electron-neutral mean free path is bigger than the probe radius, K_n is bigger than 1 and it is said that probe is in collisionless region [4].
The other important property to determine plasma parameters is the ratio of probe radius to Debye length [10].There is a direct relationship between plasma sheath thickness and Debye length. Debye length is given as

$$\lambda_D = 7430\left(KT/n\right)^{1/2} m \quad (6)$$

In (6), n is plasma density in m^{-3} and KT is electron temperature in terms of eV.

As mentioned, the relationship between probe radius and Debye length is important for probe design. Depending on this relationship, different theories such as *thin sheath analysis* and *OML* (*thick sheath) analysis* have been developed. If the ratio of probe radius to Debye length is smaller than ~3, the probe is in OML (thick sheath) region. If this ratio is bigger than ~10, thin sheath analysis can be applied [4].

In the following table, a number of probe dimensions are listed, which are designed taking into account the criteria mentioned above for plasma measurements in the SPT 100 HET performance tests.

Table 1: Different Langmuir Probe Examples from Literature

Field	Machine	Probe Material	Probe diameter	Probe Length	Cover type (length/diameter)
Very Near	SPT100 [3]	Tungsten wire	0.127 mm	0.88 mm	Alumina
Far	SPT 100 [4]	Tungsten wire	0.5 mm	10 mm	Alumina
Near-Far	SPT 100 [3]	Rhenium wire	0.42 cm	5.1 cm	Molybdenum
Far	PPS100-ML [6]	Tungsten wire	0.38 mm	100 mm	2mm diameter of alumina
Far	SPT 100 [11]	Stainless Steel	6.35 mm	40 cm	7.9 mm diameter of alumina

Probe Dimensions and Materials

In order to protect the probe from the plasma, a high-temperature material, usually a tungsten rod or wire with 0.1-1 mm in diameter and 2-10 mm in length are used for the probe tip. To avoid disturbing the plasma, a thin ceramic coating, preferably < 1 mm in diameter but usually several times this, is chosen for insulation [10].

In this work, a tungsten wire with a 0.375 mm diameter and 4 mm length is used. Total length of the probe is determined 30 cm. As seen in figure 5, for both probe protection and avoid of plasma disturbances, a ceramic coating is utilized. The physical dimensions of the probe summarized in Table 2.

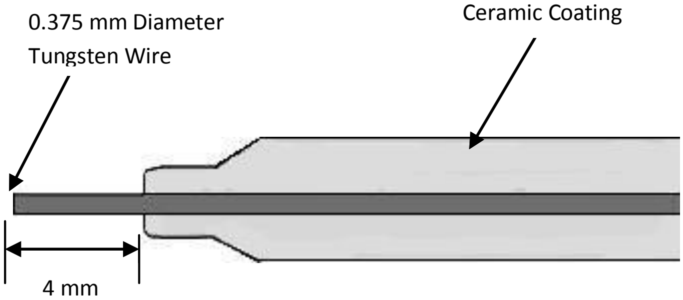

Figure 5: Schematic of single Langmuir probe

Table 2: The dimensions and materials of the probe

Tungsten wire diameter	0.375 mm
Tungsten wire length	4 mm
Ceramic coating diameter	4 mm
Total length of langmuir probe	30 cm

Calculations of Important Plasma Parameters

In order to determine the design criteria, whether OML (thick sheath) analysis or thin sheath analysis is applicable, we calculate some important plasma parameters using typical plasma values for low pressure discharges.

Calculation of Debye Length (λ_D)

$$\lambda_D = 7430\left(\frac{KT}{n}\right)^{1/2} m \qquad (7)$$

Range of typical parameters for low pressure discharges [12]:
Electron temperature T_e (V): 1-10
Pressure P (mTorr): 1-1000
Plasma density n (m^3): 10^{14}-10^{19}

For KT=1eV

$n_e = 10^{14}\ m^3$

$$\lambda_D = 7430\left(\frac{1}{10^{14}}\right)^{1/2} = 7.43x10^{-4}m = 0.743mm \quad (8)$$

The Langmuir probe radius: 0.188 mm
The ratio of probe radius to Debye length (p_r/λ_D): 0.252 < 3

For KT=10 eV

n_e= $10^{17}m^{-3}$

$$\lambda_D = 7430\left(\frac{10}{10^{17}}\right)^{1/2} = 7.43x10^{-5}m = 0.0743mm \quad (9)$$

The Langmuir probe radius: 0.188 mm
The ratio of probe radius to Debye length (p_r/λ_D): 2.52 < 3

Therefore, the probe works in OML regime.

Calculation of Mean Free Path (λ_{mfp})

$$\lambda_{mfp} = \frac{1}{n_n \sigma_n} \quad (10)$$

n_n is neutral gas density in m^{-3}, σ_n is collisional cross sectional area in m^2.

$$p = n_n kT \quad (11)$$

K is Boltzman constant ($1.38066x10^{-23}$N.m/K)
T is room temperature (298K)
p is pressure (0.1 torr)
0.1 torr= 13.33 N/m^2

$$n_n = \frac{p}{kT} \quad (12)$$

$$n_n = \frac{13.33\, N/m^2}{(1.38066x10^{-23}\, Nm/K)(298K)}$$

$$n_n = 3.24x10^{21}m^{-3}$$

$$\sigma_n = 8.8x10^{-19} m^2$$

$$\lambda_{mfp} = \frac{1}{(3.24x10^{21} m^{-3})(8.8x10^{-19} m^2)} = 3.51x10^{-4} m = 0.351 mm$$

$$K_n = \frac{0.351mm}{0.1875mm} = 1.87 > 1$$

Therefore, the probe is in collisionless region.

Table 3: Calculated Plasma Parameters

Parameters	For low n_e, KT	For high n_e, KT	Equations used
Debye Length (mm)	0.743	0.0743	$\lambda_D = 7430\left(\frac{KT}{n}\right)^{1/2} m$
Ratio of radius of probe to debye lenghth (rp/λ_D)	0.252	2.52	r_p/λ_D r_p=0.1875mm
Ratio of mean free path to probe radius ($K_n=\lambda_{mfp}/r_p$)	(0.351mm/0.1875mm)=1.87 1.87>1 so probe is collisionless region		$\lambda_{mfp} = \frac{1}{n_n \sigma_n}$

In the following figures, angular profiles of typical electron temperature and electron number density in the plume of a SPT-100 Hall Effect Thruster are presented [3]. These profiles show that in the plume of a SPT 100 electron temperature ranges from 0.5 to 1.6 eV and electron number density ranges from $10^{16}$to 10^{17} m^3. In other words, the properties of the plume plasma for a SPT-100 Type Hall Effect Thruster is approximately in the same range with the plasma generated in our measurement system. This allows us to utilize the probe designed in this paper for the study of the plume of Hall Effect Thrusters in the future.

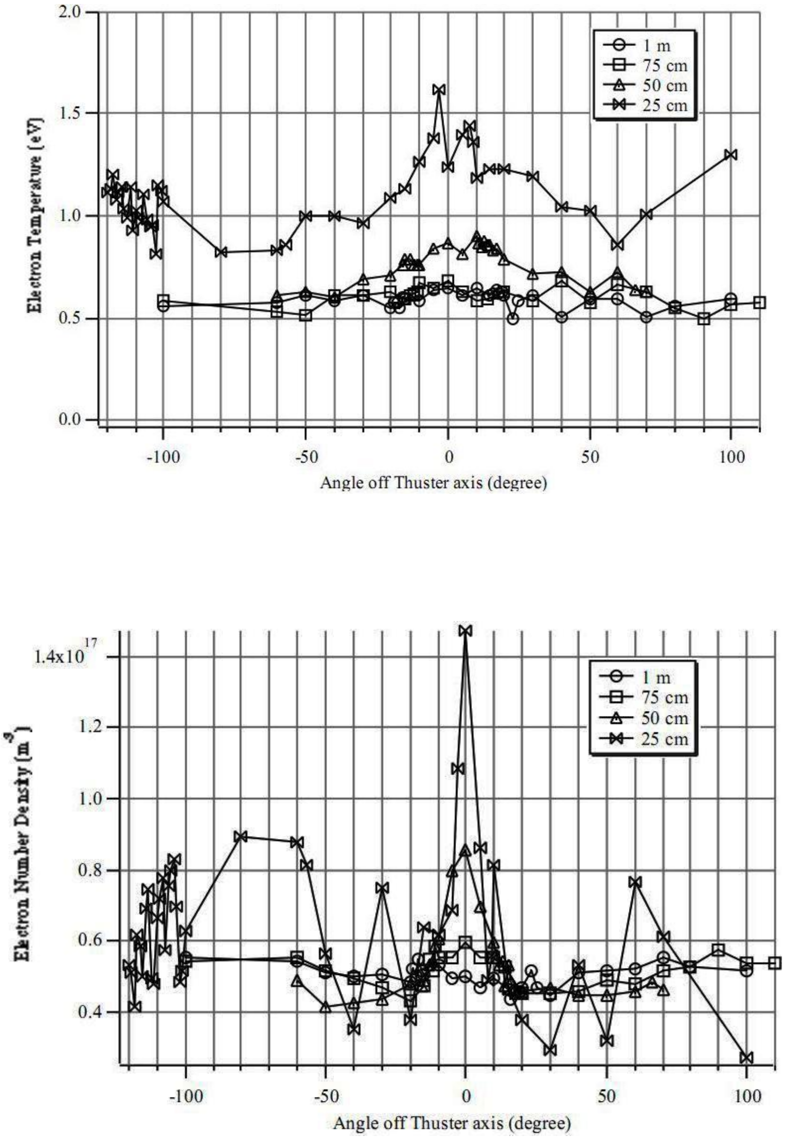

Figure 6: Angular profiles of electron temperature and electron number density from the SPT-100 exit plane [3]

CONCLUSION AND FUTURE WORK

In this work, we designed a single Langmuir probe for low pressure plasma measurements, which consists of a 0.375 mm diameter and 4mm length tungsten wire. The rest of the probe is coated by ceramic with total length of 30 cm. The ratio of the probe radius to Debye length is smaller than 3 and the ratio of mean free path to probe radius is bigger than 1. Taking into account these results and design criteria defined, the plasma is weakly ionized, the probe works in the collisionless regime and the OML (thick sheath) analysis is valid for the evaluation of the measurements under low pressure. Our future plan is to manufacture the probe and perform the plasma measurements to determine plasma characteristics, such as local plasma potential, electron number density and electron temperature. These works will also provide a foundation for studying the plume and performance characteristics of a Hall Effect thruster using a single cylindrical Langmuir probe.

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