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Comparing Langmuir Probe I-V Characteristics of Different Probe Radius in Maxwellian Ionospheric Plasma

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Abstract: This research paper focuses on the study of Spherical Langmuir Probe I-V characteristics in Maxwellian space plasma. This work is conducted using computational techniques to create the exact plasma conditions of the experimental testing environments. The investigations address the development of a technique to model Maxwellian plasma. Three different sized Langmuir probes has been designed theoretically for ionospheric temperature 0.5eV, with the help of computational techniques; I-V traces are produced to analyze the plasma parameters. The variation of floating potential due to probe size is clearly depicted. A manifest trail in the I-V curves is the bump that occurs right after the floating potential. This feature in the transition region affects ability to determine the electron temperature, ion saturation current and plasma potential.

Keywords: Langmuir Probe, I-V Characteristic, Maxwellian Plasma, Probe Dimension

1. Introduction

In the 1920s century, Irving Langmuir introduced the concept of electron temperature and developed a Langmuir probe to measure it. Since then, the Langmuir probe has been a widely used diagnostic tool, especially for plasma analysis [1]. Physically quite simple, a conductor immersed in plasma, the complexity of the Langmuir probe lies in the interpretation of the results. The interactions between an immersed probe and its surrounding plasma are not completely understood.

Meanwhile the inception of the Langmuir probe, several physicists have devised theories to describe the complex interactions of a conducting probe immersed in a plasma. Orbital Motion-Limited (OML) theory, partially developed by Langmuir, assumed that ion current is limited by angular momentum of the ions due to temperature. Between 1926 and 1956, many probe papers disagreed on the lengths between the sheath and quasi-neutral regions. In 1957, Allen, Boyd, and Reynolds (ABR) derived a differential equation that could determine plasma potential in all directions regardless of the sheath or pre-sheath [2]. This theory is well suited to spherical probes and assumes that ion kinetic temperature is generally zero. This holds true for relatively cool plasmas consisting of mainly bulk flow. For finite ion temperature, the theory assumed that ions with small angular momentum would strike the collector, while those with larger angular momentum would miss the collector completely. These high-energy ions would not contribute to the ion density. In 1959, Bernstein and Rabinowitz solved this problem for mono-energetic ions [3]. They surmised that the angular momentum is a potential barrier that must be overcome for the ions to impact the probe. Therefore some ions do not possess sufficient energy and become trapped in closed orbits around the probe.

2. Derivation of Plasma Temperature

The Langmuir probe technique involves applying a voltage to a metallic conductor immersed in plasma and observing the collected current. The observed total current, I, is a summation of various currents such as electron and ion thermal currents, photoelectron current, secondary electron currents, etc. The benefits of the simplicity of this technique, however, are offset by the complexity of the theory required to analyze the obtained current vs. potential, or I-V, curves.

A typical current-voltage (I-V) curve for a Langmuir probe is shown in Fig. 2. Where I_{es} is the electron saturation current, V_p is the plasma potential and V_f is floating potential. According to Mott-Smith and Langmuir, the floating potential, plasma potential, plasma density and electron temperature could all be measured from the *I-V* curve consisting of a voltage sweep from negative to positive potentials [4]. A typical trace of the current voltage characteristics of plasma measured with the use of a Langmuir Probe. Many studies about Langmuir probes in Maxwellian plasma have been made, but only a few of them can be considered to have a high accuracy Laframboise's work out Langmuir probes in a collision-less Maxwellian plasma at rest is one of them [5].

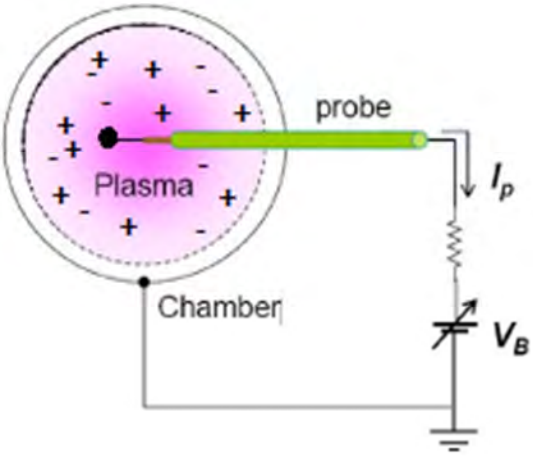

Figure 1. *Schematic of Langmuir Probe in plasma.*

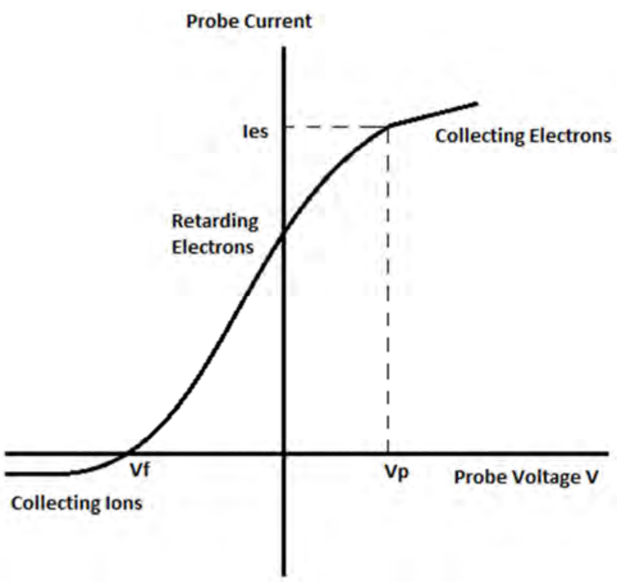

Figure 2. *A typical current-voltage curve for a Langmuir probe.*

The first important work about Langmuir probes is not surprising done by Langmuir himself. He studied different shapes of probes and derived expressions for the current from the plasma to the probe as a function of the potential difference between the plasma and the probe. Around a probe in a plasma there is a sheath with a thickness of the order of a Debye length. In this sheath, most of the potential drop between the probe and the plasma is concentrated. Langmuir assumed that the sheath had a sharp edge [6]. The current of the attracted species become a function of the sheath thickness, and Langmuir gave no expression for the sheath thickness. The equations derived by Langmuir or a negative probe in a Maxwellian plasma are:

Electron current

$$I_e = -4\pi r_p^2 ne\sqrt{\frac{kT_e}{2\pi m_e}}\exp\left(\frac{eV_p}{kT_e}\right) \quad (1)$$

Ion current

$$I_i = 4\pi ne\sqrt{\frac{kT_i}{2\pi m_i}}\left[\left(r_p+s\right)^2 - s\left(2r_p+s\right)\exp(\frac{r_p^2}{s\left(2r_p+s\right)}\frac{ev_p}{kT_i})\right] \quad (2)$$

Where r_p is the probe radius, s the sheath thickness and V_p probe potential relative to the plasma. The minus sign before the electron current is because of the negative charge of the electrons. If the sheath is very thick compared to the probe radius *($r_p << \lambda_D$)*, the ion current becomes independent of the sheath thickness. The equation for the ion current is in this case:

$$I_i = 4\pi r_p^2 ne\sqrt{\frac{kT_i}{2\pi m_i}}\left(1-\frac{ev_p}{kT_i}\right) \quad (3)$$

This current is called the orbital motion limited (OML) current. It is the upper limit for the current of the attracted species to a spherical probe. The current of the attracted species is the main problem in the theory of Langmuir probes. The probes usually have a negative potential relative to the plasma [7]. Therefore, we shall mainly study the positive ion current, but the results are also valid for the electron current when the probe is positive [8]. This research is conducted considering the case when the ion temperature T_i is equal to the electron temperature T_e, and when the plasma has no translation velocity. There is no exact explicit relation for the ion current, but some limit expressions exist. For the limit $r_p/\lambda_D \rightarrow 0$ the OML equation is valid. For the opposite limit $r_p/\lambda_D \rightarrow 0$ the ion current is

$$I_i = 4\pi r_p^2 ne\sqrt{\frac{kT_i}{2\pi m_i}} \quad (4)$$

$$\frac{s}{r_p} = 0.83\left(\frac{\lambda_D}{r_p}\right)^{2/3}\left|\frac{eV_p}{kT_i}\right|^{1/2} \quad (5)$$

Before Laframboise, Walker constructed theoretical current voltage characteristics for a spherical probe in a Maxwellian plasma. Walker used no iterative procedure for obtaining information about the distribution and the flux of the particles around the probe. He only made an inward integration from a relatively large radius, where he specified an arbitrary but small value for the potential. This method involves some approximations, and his results, which differ from the results of Lafrsmbose, are only roughly correct. Using Walker's results and Langmuir's theory Bettinger and Walker formed a relation for the sheath thickness as used by

Langmuir [8].

This equation together with Langmuir's expression provided a convenient method of calculating the ion current to a probe.

2.1. The Case $T_i \neq T_e$

In the work of Bettinger and Walker the ratio of the ion to electron temperature is not specified, but it is apparently 1. The method which gives the best approximation to the results of Laframboise seems to be to replace T_i with the arithmetic mean value of T_i and T_e. Hence the complete equation for the "sheath thickness" is [8].

$$s = 1.66 r_p \left(\frac{\lambda_D}{r_p}\right)^{2/3} \left| \frac{eV_p}{k\left(\frac{T_i + T_e}{2}\right)} \right|^{1/2} \tag{6}$$

The error of this method compared to Laframboise's results when $T_i \neq T_e$ is of the same order as in the $T_i = T_e$ case. Other possible alternates which have been tried and found to give less good approximations are that the "thickness" depends only on the ion temperature or only on the electron temperature.

When the probe voltage is made positive relative to plasma, then electrons are accelerated towards the probe. Near the probe surface there is an excess of negative charge, which builds up until the total charge is equal to the positive charge of the probe. This layer of charge, the sheath, is usually very thin, and outside of it there is very little electric field, so that the plasma is undisturbed. The electron current is that which enters the sheath through random thermal motions; and since the area of the sheath is relatively constant as the probe voltage is increases, there is fairly flat portion of the probe characteristics. This is called the region of electron saturation current.

2.2. Probe Type and Dimension

An advantage of a spherical probe is that it is easy to consider the current carried by photoelectrons emitted from the probe surface, because its contribution is almost constant independent of the sunlight direction. Specially, geometry is chosen depending on the purpose of the measurements and the platform configuration. For a spherical probe, it is not easy to get the same amount of current without breaking the OML condition for the same ionospheric conditions, because the diameter of the probe has to be increased. For a directional probe, it is possible for the apparent current to be affected by a variation of photoelectron current on the spinning platform, such an effect does not have to be considered for a spherical probe.

The DICE mission consists of two identical Cubesats launched simultaneously. Each satellite carries a fixed-bias DCP (DC Langmuir Probe) to measure in-situ ionospheric plasma densities, and an EFP (Electric Field Probe) to measure DC and AC electric fields. The DICE mission uses two separate spherical DCP sensors operating in the ion saturation region that have a measurement ion density range of 2 x 10^9 to 2 x 10^{13} m^{-3} and a minimum resolution of 3 x 10^8 m^{-3} [9]. The two sensors are deployed on separate fiberglass 8 cm long cylindrical booms that will extend into the plasma environment, from the top and bottom of the spacecraft along its spin axis.

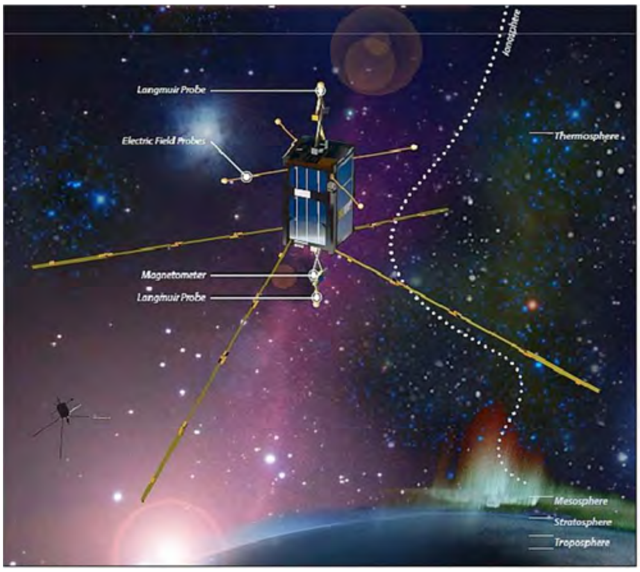

Figure 3. *Artist's rendition of the DICE spacecraft in orbit [9].*

The booms are 3 mm in diameter and support 1 cm diameter spheres. These spheres are gold-plated and conductive, but the booms themselves are electrically insulated from the plasma environment by static dissipative germanium-coated Kapton tape. Along each spacecraft's orbital path, spin-stabilized attitude coupled with the DCP deployment geometry results in at least one of the two DCP spheres always facing the velocity vector ram direction [9]. The use of a spherical probe gives the most uniform ram projected cross-section area for most of the orbital path, with the exception of high polar latitudes. The DCP sensors are biased to -4 VDC to repel electrons and allow for ion ram current measurements during flight.

It is also simple to contemplate the contribution of photoelectrons to the probe current for a planar probe, since its influence can be expressed by a simple function of the incident angle of the sunlight. If the platform is a sun oriented spinning satellite, the photoelectron contribution can be minimized by installing the probe surface parallel to the sunlight direction. Abe and Oyama have adopted the Spherical Langmuir probe for measuring small-scale electron density perturbations in the ionospheric cusp region on the ICI-2 sounding rocket [10]. In this measurement, the rocket spins with a frequency of 4 Hz, and the spherical shape was chosen to minimize the probe current variation caused by the variation of the rocket RAM direction in the spinning coordinates. A spherical probe with a diameter of 20 mm was put on a 65 mm length boom to avoid possible influences of the rocket sheath, and was located in the top-center on the rocket axis [10].

2.3. Measuring Parameters

The Langmuir Probe measures plasma parameters such as floating potential, plasma potential, plasma density, ion current density, electron energy distribution function and electron temperature. The latest system uses the most up to date probe theory available, drawing on Orbital Motion Limited and as the pressure regimes change, moving on to Allen Boyd Reynolds to account for collisions [11].

Table 1. *Typical Langmuir Probe Measuring Parameters Range.*

Floating Potential	-145V to 145V
Plasma Potential	-100V to 145V
Plasma Density	10^6 to 3×10^{13} cm^{-3}
Ion Current Density	1µA/cm² to 300mA/cm²
Electron Temperature	0.1 to 15eV
Electron Energy Distribution Function	0 to 100eV

This permits the user to obtain information on the variation of the plasma parameters as time progresses through a particular process. This feature does not require external harmonization and the timescales involved can be in range of seconds to hours.

3. Results and Discussions

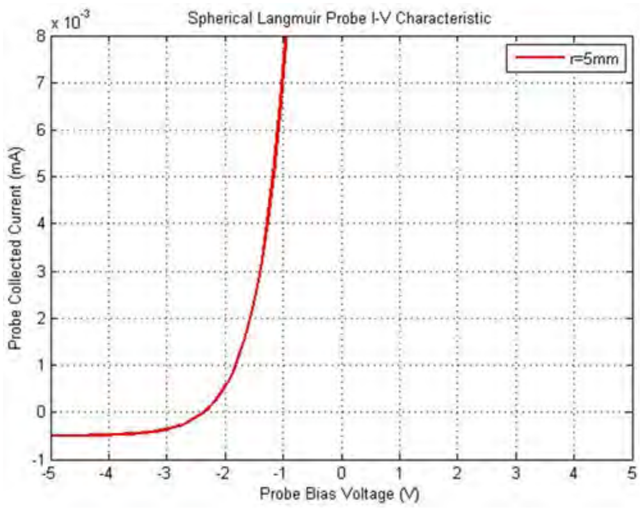

Figure 4. *Spherical Langmuir Probe I-V curve for the probe radius r_p=5mm.*

The Langmuir probe process for precise measurement of plasma parameters has been around for eight decades, deriving the parameters with accuracy from the data acquired by a Langmuir probe immersed in space plasma is still a exciting task. In the present research work theoretical study of Spherical Langmuir Probe in Maxwellian plasma are considered. This work is typically based on the *I-V* characteristic with probe radius. The main propose of this work is to study the Current-Voltage characteristic of spherical Langmuir probe and to analyzed the effect of probe radius on width of electron retradation regions. The methodology of our study includes the theoretical derivation of the relationships between various parameters and then plotting the parameters in appropriate range from a mathematical software.

The *I-V* characteristic is a essential part of dagnosis of plasma parameters. So, variation of Spherical Langmuir Probe I-V curves for different probe radius is depicted in the following figure. For this purpose, it is assumed that density, $N_e = 10^{16}$m^{-3} and the ionospheric temperature is 0.5eV. These figures illustrate the effect of radius r_p of spherical probe on the width of the electron retradation regions.

Here, the floating potential V_f = -2.4 V when probe radius r_p=5mm. This floating potential is typically negative because mobile electrons tend to strike the probe more frequently than positive ions. The knee occurs when the probe has been saturated with electrons, causing additional electrons to be repelled.

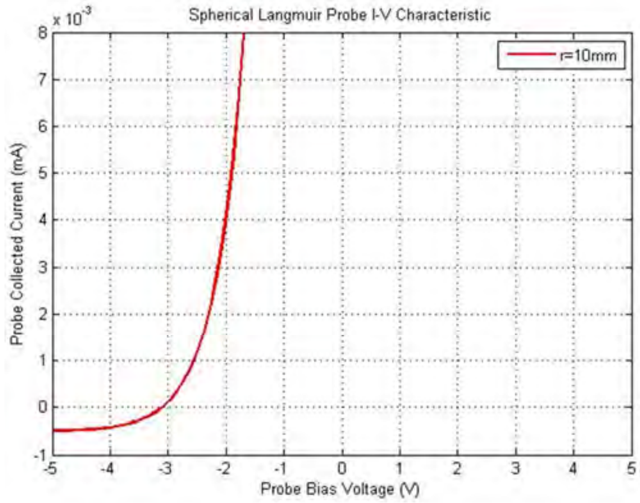

Figure 5. *Spherical Langmuir Probe I-V curve for the probe radius r_p=10 mm.*

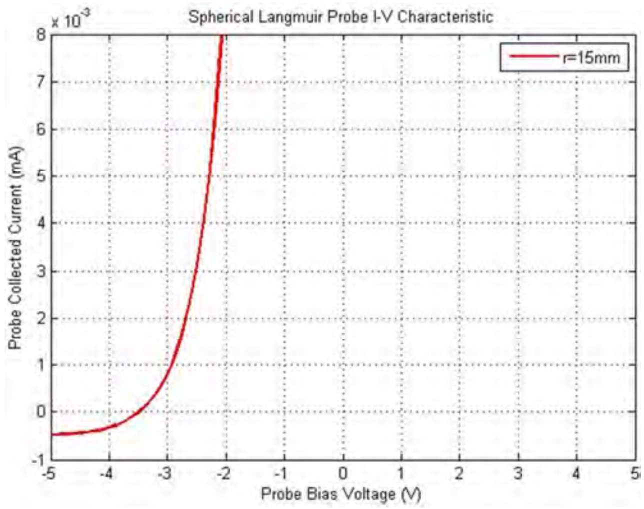

Figure 6. *Spherical Langmuir Probe I-V curve for the probe radius r_p=15mm.*

When the probe radious is increased little bit r_p=10 mm, the floating potential V_f is -3.1V. This research tested that probe radius directly proportional to the floating potential of the plasma. There is characteristic “knee” at this point because the current dependence on the probe voltage changes.

For probe potential is greater than plasma potential ($V_p > V_s$), I_e increases slowly as the collection area grows due to an increase in sheath thickness. In the Transition Region, the ion current is negligible, and the electrons are partially repelled by the negative potential V_p-V_s. When the probe voltage is well below the plasma potential, only the highest energy electrons reach the probe. As the probe voltage approaches the plasma potential, additional lower energy electrons are collected.

4. Conclusion

The concept of the Langmuir probe was developed almost a century ago and is named after its inventor Irving Langmuir. The Langmuir probe was the first diagnostic tool used for studying plasmas in detail and it is still widely used today. Langmuir probes, in principle, provide a simple and relatively inexpensive diagnostic for measuring the plasma parameters. The *I-V* characteristic of the Spherical Langmuir Probe in the Maxwellian Space plasma at 0.5eV temperature three different hypothetical probe radius are used to analyzed the variation of floating potential which are plotted in graph by using the computational software by putting the seemly ranges for various parameters. All elementary processes were extensively deliberated and most of information has been presented. And the effect of probe radius on the width of the electron retardation regions are clearly studied in this research. Thus, Langmuir probe dimension are of essential significance for investigation on laboratory plasma, ionosphere terrestrial plasma and industrial application. However, there are a number of issues in the design and interpretation of Langmuir probe characteristics which have led in the past to a wide disparity in measured parameters obtained under similar conditions. Part of this difficulty results from an imprecise knowledge of the RF discharge parameters, voltage, current and deposited power, but this has been partially resolved by the availability of the probes to make accurate measurements of the discharge RF parameters. The main objective of this work was to develop a Langmuir probe instrument for sounding rockets capable of accomplishment high-speed absolute electron density measurements, and thereby be able to detect ionospheric plasma density structures.

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