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# Laboratory Diagnosis by Langmuir Probe for Plasma Parameters Generated around the Spacecraft Model

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**Abstract**

The problem of interruption of communication between the spacecraft and the ground station due to the plasma formed around the spacecraft is one of the important and dangerous problems facing spacecraft during their return to the Earth's atmosphere. The present work focused on diagnosing the plasma parameters generated around a spacecraft model in a laboratory. A vacuum system was used to produce plasma under a working pressure of 0.1 mbar. The spacecraft model was placed inside this plasma between the cathode and the anode, and a strong magnetic field was used to confine the plasma around this model. A single Langmuir probe was used to calculate the electron temperature, electron density, Debye radius, and plasma frequency. Plasma frequency is an important and decisive factor for selecting the frequencies used in communication for spacecraft. The values of these plasma parameters were obtained with the discharge power varying from 20 watts to 100 watts for the system used in the practical experiment. Electron Temperature values ranged between values 0.389-0.982 eV, electron density, between values $4.8x10^{13}$-$2x10^{14}$ $cm^{-3}$, and plasma frequency values ranged between $6.23x10^{7}$-$1.2x10^{8}$ Hz.

**Keywords:** Plasma generates, Langmuir probe, Plasma Parameters, Spacecraft model

# التشخيص المختبري باستخدام مجس لانكمور لمعلمات البلازما المتولدة حول نموذج المركبة الفضائية

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**الخلاصة**

تعد مشكلة انقطاع الاتصال بين المركبة الفضائية والمحطة الأرضية بسبب البلازما المتكونة حول المركبة الفضائية من المشاكل الهامة والخطيرة التي تواجه المركبات الفضائية أثناء عودتها إلى الغلاف الجوي للأرض. ركز العمل الحالي على تشخيص معاملات البلازما المتولدة حول نموذج مركبة فضائية مختبريا. تم

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استخدام نظام فراغ لإنتاج البلازما تحت ضغط عمل 0.1 ملي بار. تم وضع نموذج المركبة الفضائية داخل هذه البلازما بين الكاثود والأنود، وتم استخدام مجال مغناطيسي قوي لحصر البلازما حول النموذج. تم استخدام مسبار لانغموير المنفرد لحساب درجة حرارة الإلكترون وكثافة الإلكترون ونصف قطر ديباي وتردد البلازما. يعد تردد البلازما عاملاً مهمًا وحاسمًا لاختيار الترددات المستخدمة في الاتصال للمركبات الفضائية. تم الحصول على قيم معاملات البلازما هذه بقوة تفريغ تتراوح من 20 واط إلى 100 واط للنظام المستخدم في التجربة العملية. تتراوح قيم درجة حرارة الإلكترون بين القيم 0.389–0.982 إلكترون فولت، وكثافة الإلكترون بين القيم $4.8x10^{13}–2x10^{14}$ سم$^{-3}$، وقيم تردد البلازما تتراوح بين $6.23x10^{7}–1.2x10^{8}$ هرتز.

## 1. Introduction

Plasma is a partially or completely ionized gas that is electrically neutral and contains negative electrons, positive ions, and neutral atoms [1]. Plasma behaves collectively [2, 3]. Plasma has countless applications in the industrial, medical, and military fields [4, 5, 6], but it has disadvantages, such as interrupting radio communications when it passes through plasma, which makes plasma an obstacle to communication between spacecraft and the ground station [7]. When spacecraft enter the Earth's atmosphere, they have a very high speed, which leads to the appearance of high heat as a result of friction between the surface of the vehicle and the surrounding air. This heat ionizes the air surrounding the surface of the vehicle and plasma is generated around it with a high electron density of up to $10^{13}cm^{-3}$, which makes the plasma frequency large and higher than the radio communication frequency, which makes the plasma act as a radio wave scattered and the communication between the vehicle and the ground station is cut off. This is called blackout [8]. To know the frequency of the plasma formed around spacecraft, the plasma must be diagnosed and its parameters must be known.

There are three methods that can be used to diagnose plasmas of all types: passive remote sensing, active non-contact methods, and contact methods. The first method, passive remote sensing, is used to study the Sun and extrasolar plasmas. The second method, active non-contact, is applied to geophysical plasmas such as the Earth's ionosphere, hot laboratory plasmas, and scattering of electromagnetic radiation or particle beams [9]. The third method, contact, is applied to cold laboratory plasmas and interplanetary plasmas. The Langmuir probes are an example of the contact method. It is widely used for plasma diagnosis [10].
Plasma probes are used to diagnose plasma locally by inserting the probe into the plasma and connecting it to its own electrical circuit located outside the plasma [11]. There are two important things for plasma electrical probes. First, the probe must withstand the high temperature of the plasma, and for this reason, it is made of materials that are resistant to heat and high electrical currents. The probe wire is made of tungsten and its insulating material is made of mica or heat-resistant pyrotechnic glass. The second important thing is that the probe does not affect the stability of the plasma, and this can be done by using probes with a small area compared to the dimensions of the plasma [12].

The scientist Langmuir made a number of important discoveries that enriched the branch of physics with many important contributions, especially in the field of ionized gases, which he called plasma [13]. The first person to use the electrostatic probe was the scientist Thomson, and after that Langmuir developed this probe to calculate the plasma density and the electron temperature in cold plasma, which was named after him, the Langmuir probe [14]. There are several types of probes used to diagnose plasma parameters locally, the most famous of which are the Langmuir single probe and the double probe. The function of the probe is to collect negative and positive charges according to the type of voltage applied to the probe. When a positive voltage is applied, negative electrons are collected, and when a negative voltage is applied to the probe, positive ions are collected. These probes are considered important technologies that have been studied extensively and are used especially for cold laboratory plasmas and ionospheric and space plasmas [15, 16].

In this work, plasma will be generated in the laboratory around a model spacecraft inside a plasma system, which is an evacuated glass vessel under low pressure of about 0.1 mbar, using a power supply of up to 100 kV and with different capacities. The generated plasma is characterized using a single Langmuir probe to calculate the electron temperature, plasma density, Debye radius and plasma frequency. These parameters are studied with the change in the power of the voltage supply.

## 2. Single Langmuir probe

Plasma diagnosis is very important for research and industrial purposes, and knowing the plasma parameters gives a clear idea of the plasma classification. Many methods have been used to diagnose plasma, the most famous of which is the Langmuir probe, which is considered one of the simplest practical methods that gives a specific local diagnosis of the plasma and is considered one of the direct methods in contact with the plasma. The Langmuir probe consists of a metal wire made of a material with a high melting point such as tungsten. This wire is surrounded by an insulating material of mica or heat-resistant glass, and a small part of the wire appears inside the plasma as shown in Figure 1. The effective area of the probe is calculated by knowing the diameter of the wire and the length of the wire in contact with the plasma, and it's calculated by [17]:

Where D and h are diameter of tip probe and length of probe respectively. A wire with a small area is used to reduce the effect of the probe on the plasma. A potential difference is applied at different rates and the current passing through the probe is calculated to know the characteristics of the current and voltage. From the current and voltage plot and taking the slope, the electron temperature can be calculated from the reciprocal of the slope. There are several types of probes such as emission probes [18], dual probes [19], capacitive probes, oscillation probes, probes in flowing or high-pressure plasma, and probes in magnetic field [20].

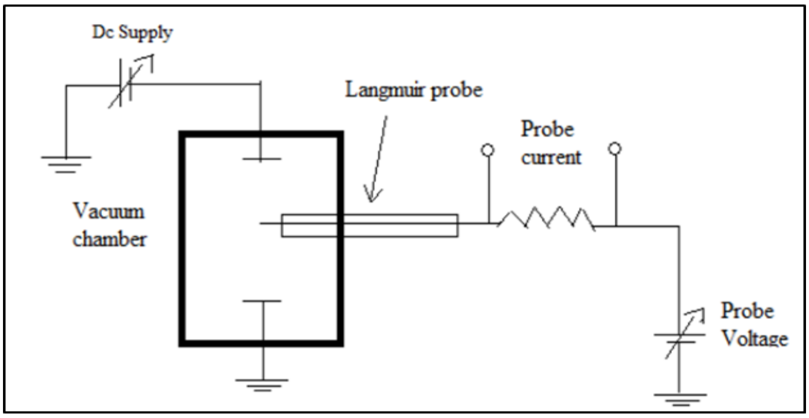

**Figure 1:** Schematic diagram of Langmuir Probe Circuit [21].

## 3. Plasma Parameter

Plasma is an ionized gas containing electrons, ions and neutral atoms. These particles are in a state of continuous random motion, each with a different temperature and different densities. To diagnose plasma, these two important parameters ($T_e$, $n_e$) must be calculated, and through them other plasma parameters can be calculated, such as the Debye radius $\lambda_D$, the number of particles $N_D$, and the plasma frequency $f_p$ [22].

### 3.1 Electron Temperature

It is possible to assume that the probe current is proportional to the current of the charged particles inside the plasma, which is an important assumption for diagnosing plasma parameters, considering that the plasma volume is much larger than the probe volume. Assuming that the particle velocities follow Maxwell's distribution, the electron velocities differ from the ion velocities, and the electron temperature is much larger than the ion temperature in cold plasma and is equal in hot plasma. The factors that determine the intensity of the probe current are the probe voltage, the effective area of the probe, and the plasma parameters. The electron temperature can be calculated from Eq. (1) [23]:

### 3.2 Electron Density

The electron density ne is given by [24]:

Where $k_B$ represents the electron temperature [K] and Boltzmann's constant [eV/K].

### 3.3 Debye radius

When disturbance occurs in the plasma due to the presence of an extraneous charge, the plasma tries to rearrange the charges around the extraneous charge in a way that reduces the effect of this charge on the stability of the plasma, so that the electrons gather around the positive charge that enters the plasma and work to form a layer of electrons called the Debye shield or Debye radius. The Debye radius $\lambda_D$ can be calculated from the following equation [25, 26]:

Where e is the electron charge, $\varepsilon_o$ is the permittivity of the vacuum equal to $8.85\ x10^{-12}$ F/m.

### 3.4 Plasma frequency ($\omega_p$)

Plasma is a medium that contains a very large number of electrons, ions, and neutral atoms, so it is subject to oscillations. Since electrons have a much smaller mass than ions, the frequency of electrons is much greater than the frequency of ions, and is called the electron plasma frequency, and is given by the equation: [22, 27]:

and natural frequency $f_p$ in Hz unit can be written as [28]:

## 4. Space Shuttle Model

A 3D printer was used to build the spacecraft model used in this work. The model was designed according to the size of the vacuum system used in this work, where the dimensions of the model were 8cm in length, 4 cm in width, and 3 cm in thickness, as shown in Figure 2. A 3D printer is a device for printing solid objects from a digital model and uses rigid plastic as the printing material.

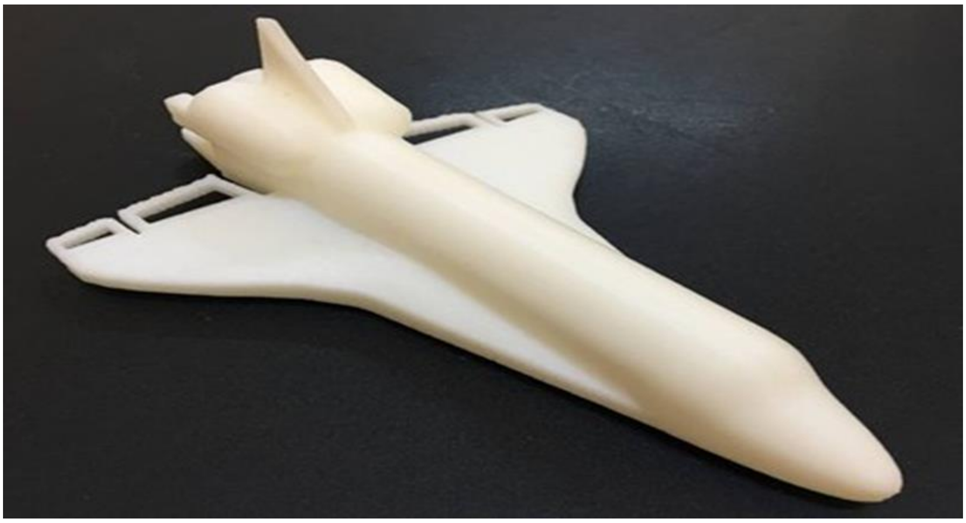

**Figure 2:** Spacecraft model length 8cm, width 4 cm, and thickness 3 cm.

## 5. Plasma Chamber

A vacuum system was used in this work to generate plasma in the laboratory. This system consists of a stainless steel base with a diameter of 40 cm containing an air evacuation hole and an opening for injecting argon or nitrogen gas. The base also contains holders for the anode and cathode and a holder for the spacecraft model. A heat-resistant glass chamber with a diameter, length, and thickness of 20, 30, and 0.5 cm, respectively, was placed on top of the base, as shown in Figure 3. The spacecraft model was located between the anode and the cathode. A two-stage vacuum pump is used to reach a low pressure of about 0.02 mbar. The work gas was argon and $N_2$, and the operating pressure was 0.1 mbar. A direct power supply was employed to produce plasma. This power produces a voltage of roughly 0-5kV and a current of 500 mA. The power supply is made up of a 5000 V 500 mA transformer, a capacitor, a bridge diode, a voltmeter, and an ammeter. The energy of the power supply changes from 25 to 100 watts to generate plasma inside the chamber. To regulate the gas's pressure inside the chamber, argon and $N_2$ gases were fed to the chamber via a fine-controlled needle valve (0 - 100 sccm), where sccm represents the standard cubic centimeters. The Thorlabs CCS100/M spectrum spectrometer, optical fiber, and collimating lens were used to get spectrum measurements. In this work, a Langmuir probe is used to characterize the plasma generated around the spacecraft model in a vacuum system. The effective area of the probe is calculated using Eq. (3). The current of the probe depends greatly on its effective area and thus affects the plasma parameters.

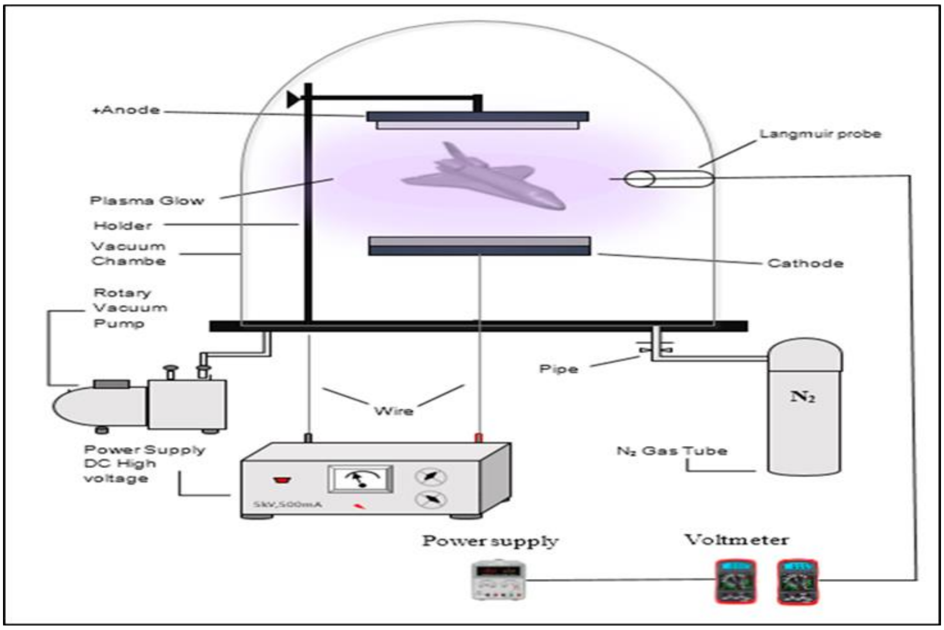

**Figure 3:** System of Laboratory Plasma with spacecraft model

A voltage difference is applied to the Langmuir probe in the range of 150 to -150 V and the current collected by the probe is measured using an ammeter and the ion current is calculated when the applied voltage to the probe is reversed, see Figure 4.

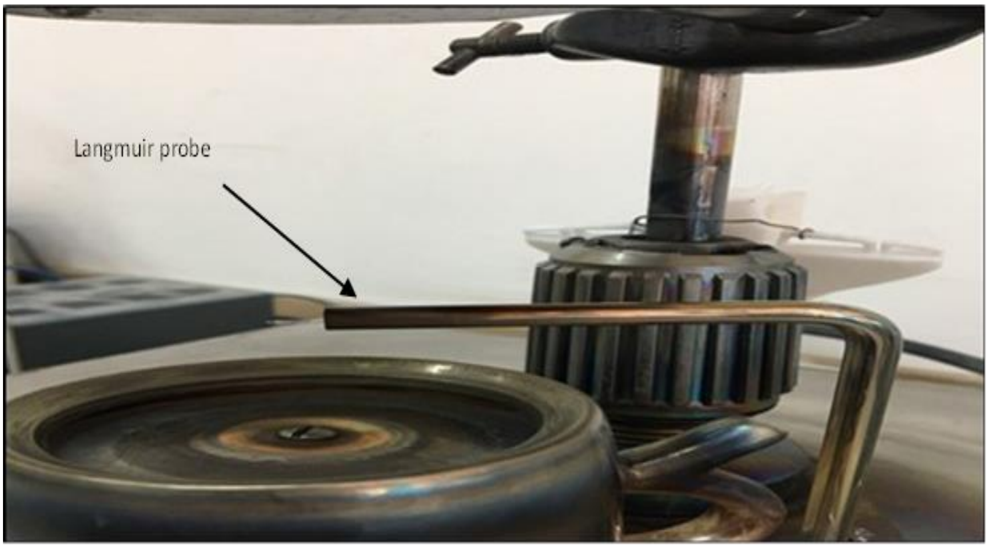

**Figure 4:** Single Langmuir probe in the range of 150 to -150 V

## 6. Results and discussion

The relationship between the current and voltage of a Langmuir probe for different values of the power is shown in Figure 5. The single Langmuir probe calculates the electron temperature and saturation current by drawing a tangent from the starting point of electron saturation and calculating the slope of the tangent. From this point, the plasma voltage can be determined as shown in Figure 5. Using Equation 1, the reciprocal of the slope and the electron saturation current can be calculated for the electron temperature, density, and other plasma parameters.

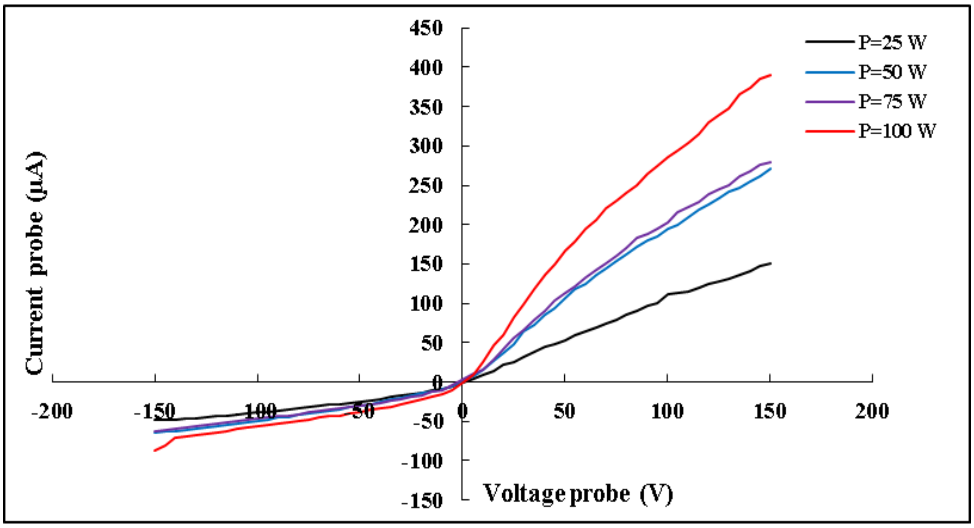

**Figure 5:** Current-voltage characteristics of single Langmuir probe.

Figure 6 shows a graph of the ln I and V. Ideally, the line should be straight, but it appears curved at high voltage values because there is no Maxwell velocity distribution at a single value.

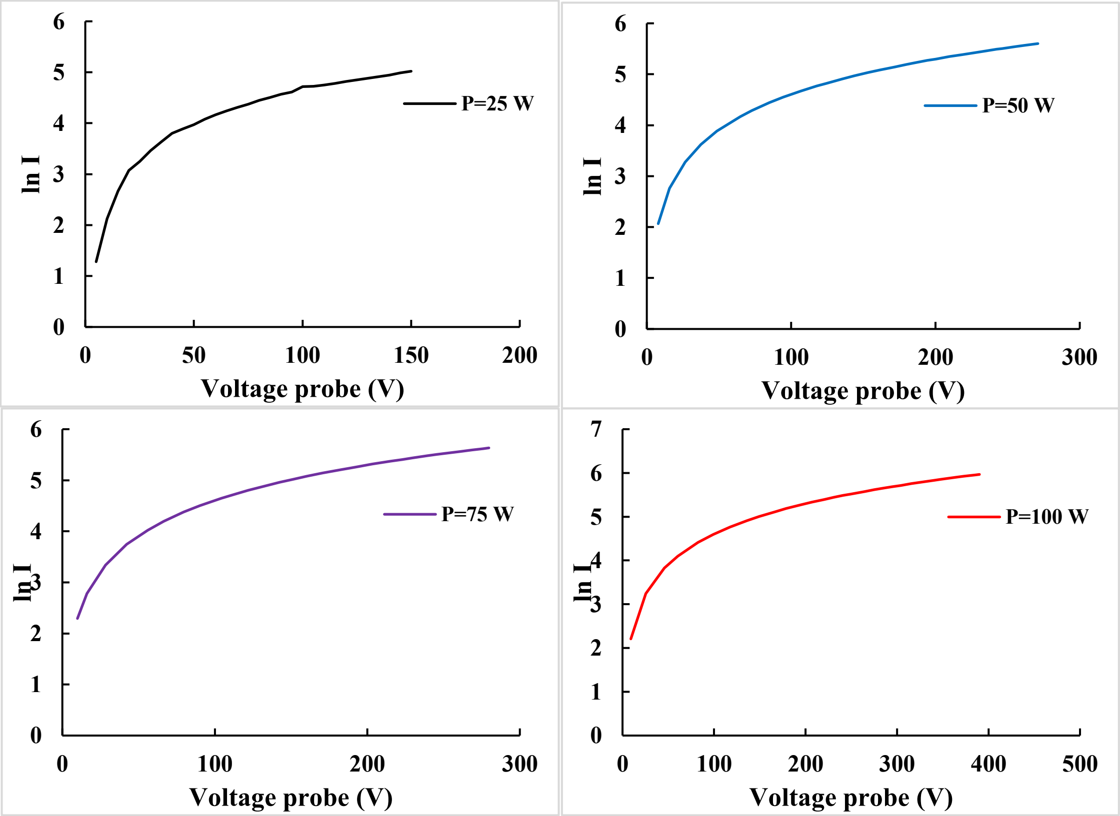

**Figure 6**. A semi-log plot of electron current from an I-V curve in a DC plasma for power values 25, 50, 75, and 100W.

Increasing the energy of the source leads to an increase in the ionization rate within the plasma, which leads to an increase in the electron density and the rate of collisions and heat exchange between the electrons. As a result, the temperature of the electrons decreases, as shown in Figure 7. The results agree with [29].

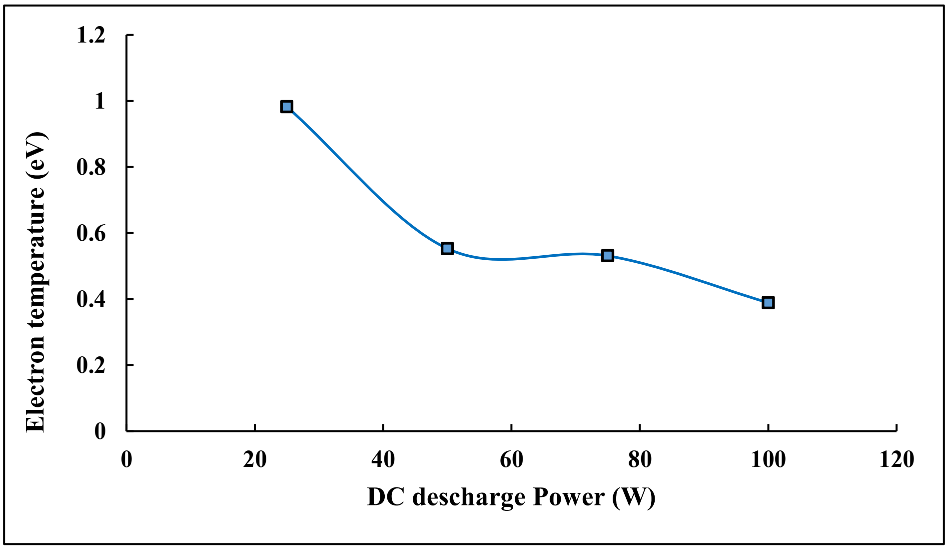

**Figure 7:** Variation of electron temperature with DC discharge power **obtained by the Langmuir probes.**

The strength of the electric field increases with the increase in the discharge energy, which leads to the acceleration of the electrons, the collisions increase, and the ionization rate increases; that is, the production of electrons increases, and the electron density increases, as shown in Figure 8. This is consistent with [30].

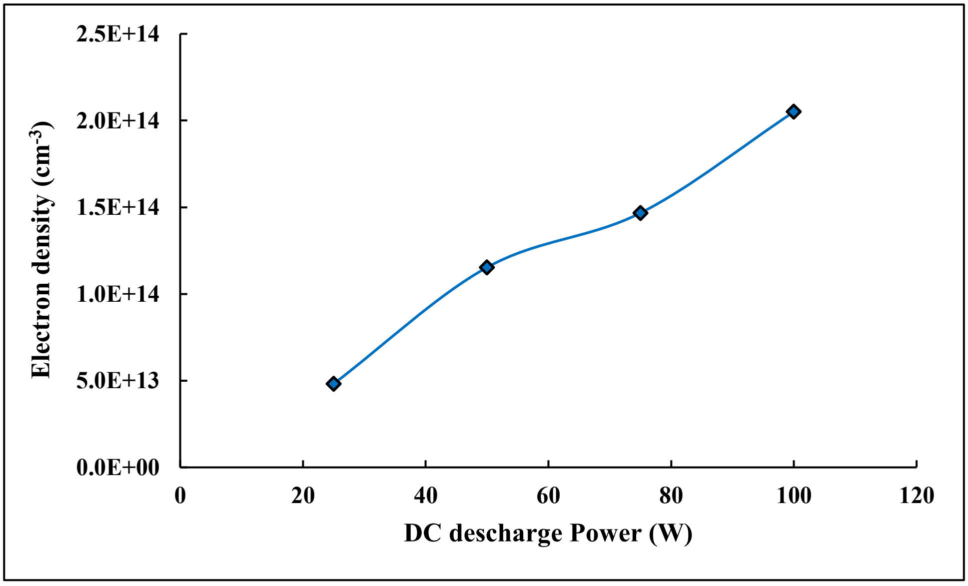

**Figure 8:** Variation of electron density with DC discharge power obtained by the Langmuir probes.

The discharge energy increases as the power supply voltage increases, which increases the electron density, thus increasing the short-distance protection, i.e., the Debye diameter decreases, as shown in the figure. This decrease is consistent with the references [31, 32]. Plasma frequency is the frequency at which electrons in the plasma oscillate. Because the electrons move at a high speed compared to the ions, they oscillate around the ions depending on the Coulomb forces. The electron frequency in the plasma is the characteristic frequency of the plasma. Increasing the discharge energy of the system increases the electron density, which increases the plasma frequency because the plasma frequency directly depends on the electron density according to Eq. (6), as shown in Figure 9.

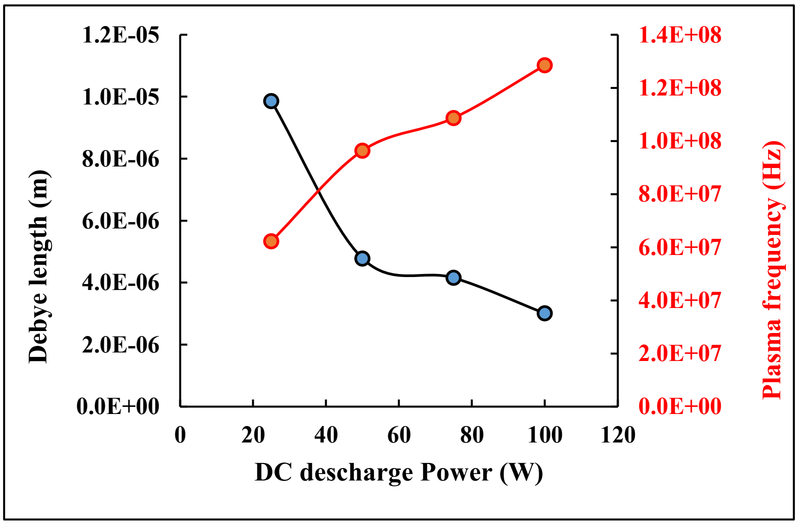

**Figure 9:** Variation of Debye length and plasma frequency with DC discharge power.

## 7. Conclusions

In this work, a Langmuir probe was used to diagnose the plasma generated around a laboratory spacecraft model. It was concluded that the small effective area of the probe and the appropriate probe voltage in the range of -150 to 150 were chosen because they reduce the noise and interference inside the plasma and give satisfactory results. It was concluded that increasing the power leads to an increase in the electron saturation current as well as the ion saturation current of the probe, and the ionization process increases. This event occurs when the spacecraft penetrates the atmosphere, where ionization increases due to the drag force. The electronic frequency of the plasma was calculated, which is an important parameter to know the frequency of disconnection between the spacecraft and the ground station. The practical side and laboratory simulations are important in the scientific aspect, especially the study of the plasma generated around spacecraft during their entry into the Earth's atmosphere, as this process poses a risk to the spacecraft and portable devices. Therefore, we conducted simulations of reality by generating plasma around a model of the spacecraft and calculating the plasma elements for different plasma powers. Among these important elements are plasma frequency, which affects communications, and electron density and electron temperature, which greatly affect the operation of spacecraft devices.

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