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Design and preliminary characterization of a helicon plasma device for aerospace propulsion.

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Abstract

The versatility of helicon plasma devices (HPDs) has led to their prominence in contemporary applications, including electric propulsion on space missions. The production of plasma through helicon discharges, which are created when gases pass through a chamber at low pressure and absorb Helicon and Trivelpiece-Gould (TG) waves, results in a plasma of high electronic density and low energy. This plasma can be utilized in a variety of applications. In order to conduct research and apply these sources, a helicon-type device was designed and constructed at the Plasma Physics Laboratory (LFP) at the University of Brasília (UnB). This article describes preliminary measurements and the device construction project.

1 Introduction

Micro and nano-satellites have attracted much attention of scientific and commercial entities due to their relative low cost. The operating lifetime of a mission can be increased by using thrusters for orbit-correction, orbit transfer, and station-keeping control. Electric propulsion can provide high values of specific impulse with low quantities of propellant. Among them,

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electrodeless thrusters are an interesting option because of their simple construction and increased lifetime compared to electric propulsion devices with electrodes. Low-power helicon thrusters, or ambipolar thrusters, are an example of electrodeless thrusters specifically designed for nano-satellites. In this thruster a background magnetic field is necessary for plasma confinement, generation of helicon waves and overall operation, and can be provided by permanent magnets, reducing the power requirement of this device. Due to the reduced size of this device, experimental studies depending on plasma diagnostics can be a challenge. For example, the plasma inside the ionization chamber can be inaccessible for a Langmuir probe. For this reason, in this paper we focus on a helicon plasma device with an increased size. This device allows to collect data using probes, which would not be possible in the case of the original device with reduced dimensions. The scaled device can give important insights on the plasma processes occurring in the smaller device.

The Helicon plasma devices (HPD) are the subject of considerable interest in the present era. Its broad applicability is due to its distinctive characteristics, including high electronic density (on the order of 10^{13} m^{-3}) and low temperatures (a few eV), which allow its use in a variety of fields [1], [2]. Recently, the application of this technology in the space area has manifested in the form of the helicon plasma thruster (HPT), a thruster that employs this type of source to generate propulsion [2]. The plasma is generated by the absorption of helicon waves, which are whistler waves with normal modes of vibration that propagate through the plasma in an axial and radial manner [1], [3]. In consideration of the aforementioned advantages, the plasma physics laboratory at the University of Brasília, which is dedicated to research in the field of electrical propulsion, designed and constructed a device of this nature for the purposes of research and applications.

Helicon waves are electromagnetic waves with frequencies between electro and ion-cyclotronic frequencies that arise in coupled plasmas. Ionization in the system is caused by two main waves: a Helicon wave and a Trivelpiece-Gould wave (TG) [4]. With the presence of a TG wave in the vicinity of the RF source, greater absorption by the plasma surface is observed. Concurrently, the helicon wave traverses the plasma core, resulting in the heating of its innermost regions [5],[6],[7]. The coupling between the plasma and the antenna is a consequence of the normal modes of vibration, which are dependent on the antenna and the magnetic field direction. Moreover, its dispersion relationship is analogous to that of a whistler wave [1], [8]. In essence, the coexistence of these two waves serves as the underlying mechanism that facilitates the generation of high-density, low-energy plasmas.

An HPD designed for electrical propulsion comprises a radio frequency (RF) source and a magnetic field that guides the plasma through a magnetic nozzle [3]. The magnetic nozzle serves as a driver in the ejection of ions and electrons, which creates propulsion through the conservation of momentum. Due to the difference in mass between the specimens, the electrons are thrown at a lower speed than the ions forming polarized areas in the plasma. This polarization creates a high drop in plasma potential (V_p), forming a structure known as a double layer, detected on plasmas by Irving Langmuir [9] and observed in helicon plasma by C. Charles and R. Boswell in 2003 [10].

In light of recent research in propulsion and the various HPDs currently built around the world, there is a clear need to develop a system for researching this type of sources. The Plasma Physics Laboratory at the University of Brasília, which is engaged in research into aerospace propulsion, has designed and constructed its first example of an HPD. The system in question comprises two glass chambers. The first, which encompasses the system with coils and an RF source. The second chamber is used for dispersion of the magnetic nozzle, where most of the measurements are carried out. The magnetic coil system is designed in such a way that different field geometries can be tested. In this manner, the initial measurements were conducted to characterize this device, including electron density, the axial profile of the plasma potential, the profile of the magnetic field, and other relevant quantities.

This article presents the preliminary measurements of electron density, magnetic field, and the axial potential profile of the developed system. Additionally, it outlines the methodology used to construct the device in the Plasma Physics Laboratory at the University of Brasília. The structure of this paper is the following. Section II presents the design and construction of the experimental device, and the set of plasma diagnostics. The results are shown in section III, including measurements and simulations of the magnetict field, and the measurements of plasma diagnostics. Finally, our conclusions are presented in Section IV.

2 Methodology

This article's methodology has the following steps: design and construction of the experimental apparatus, preliminary characterization of magnetic fields, electronic profile, and plasma potential of the thruster.

2.1 Design and Construction of the Experimental Apparatus

The experimental device is constructed with a glass tube (boron silicate) of 1000mm in length and 100mm in diameter. This tube is surrounded by two mobile coils with 730 turns of cooper wire each and it is connected to a dispersion chamber with 750mm in length and 300mm in diameter.

A helicon antenna was designed with normal modes of m = 1 or m = -1, depending on the axial magnetic field. It provide control of the parallel wave number $K_{||}$[1]. It was designed to operate between frequencies of 13.56 MHz and 25 MHz up to 1000 W of rf power. In this paper, our tests and diagnostics were made with about 25 W.

We use the COMSOL software to perform magnetic fields simulations , visualization and positioning of the magnetic configuration, shows the schematic diagram of the experimental assembly Fig. 1.

Figure 2 shows a photograph of the device under operation. Note that linear rails were added to support both magnetic coils, allowing us to test different spacing and field geometries. The working gas is Argon, which is inserted inside the vacuum chamber through a needle valve located at the edge of the first glass tube (the opposite end of the dispersion chamber). A simplified schematic of the system can be seen in Fig. 3.

2.2 Measurement system

The measurement system consists of Hall probe (Walker Scientific MG-3D), Langmuir probe, and pressure gauges. The axial Hall probe measure the axial component of the magnetic field, and can be moved along the

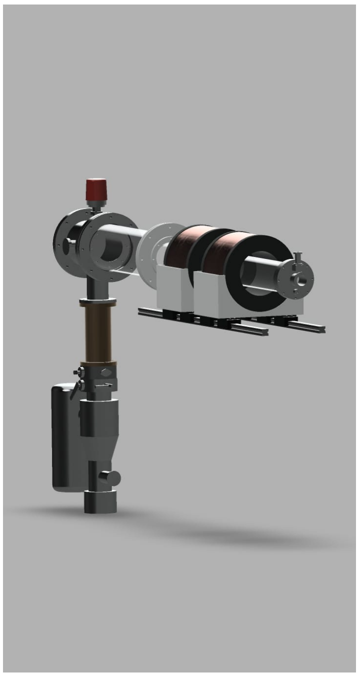

Figure 1: CAD of the experimental assembly.

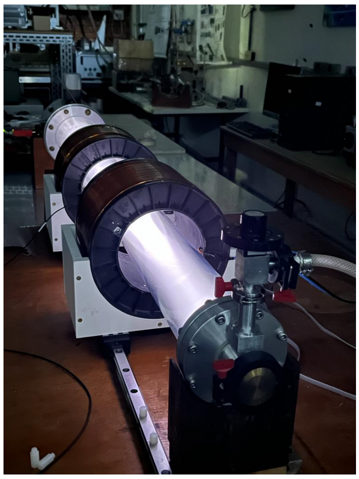

Figure 2: Plasma source assembled and its first operation.

center of the glass tube.

The Langmuir probe is cylindrical, made from tungsten wire of 0.35mm in diameter, encapsulated by alumina tubes, having the ability to move coaxially along the dispersion chamber. Its purpose was to measure the plasma potentials. A reference shunt resistor of 1 kΩ, a ramp power supply (ranging from -150V to 150V), and a parallel, true rms, multimeter complete the measuring setup. All reference potentials were connected to the metallic wall of the metallic flange of the dispersion chamber.

3 Results

3.1 Magnetic Field

The axial magnetic field for different currents is show in the Fig. 4

The coils induces magnetic fields of approximately 300G . We select this configuration to perform numerical simulations and observe if the field lines makes a magnetic nozzle in the dispersion chamber.

We can see from Fig. 5 that the magnetic nozzle is present around the conection between the two chambers, on the direction of the gradient of the magnetic field. Futhermore, we can see that most the field lines pass through on the center of the tube, confining the plasma away from the tube wall. Experimentally, we can confirm this behavior shown in the Fig.6. Therefore, we could ignore the border effects and proceed with the measurements without considering the diameter of the dispersion chamber.

3.2 Axial Potential measurements

Plasma potential measurements were conducted along the tube using a Langmuir probe. The measurements were performed from the

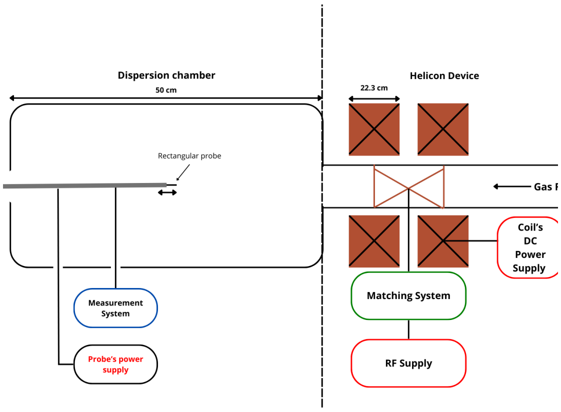

Figure 3: Schematic of the experimental s tem for plasma measurements.

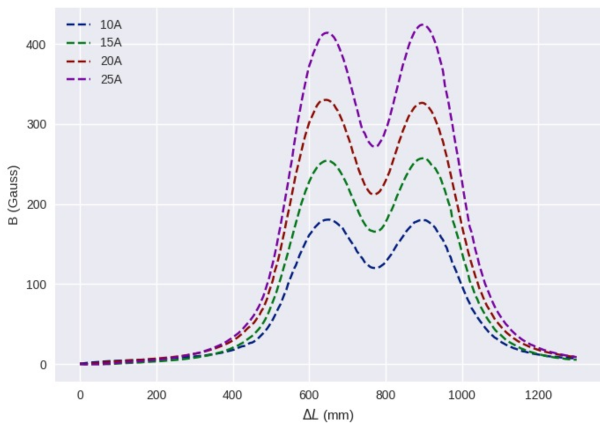

Figure 4: Intensity of the axial magnetic field at the center of the tube, for different currents.

center of the antenna to approximately 2υυ mm away, in intervals of 20 mm. Each point represents a measurement of an voltage-current (I-V) curve and their subsequent analysis to obtain electron density, plasma potential, and saturation current. Figure 7 depicts the I-V characteristic curve of the Langmuir probe for a distance of 500 mm.

The plasma potential points were obtained by plotting a logarithm graph and crossing the line that follows the growth of the curve with the line that follows electronic saturation current. Secondly, the characteristics obtained through the I-V curves, as observed in Figs. 8, 9 and 10, were plotted.

The plasma potential obtained near the antenna in Fig. 8 demonstrates its variation along the axial axis of the tube. As illustrated in the figure, the potential begins at high intensity and with noise due the proximity of the antenna, which is expected due to RF interference in the probe. However, it is still possible to observe that the plasma begins to decay rapidly at approximately 150 mm away from the antenna, indicating that it will continue to fall. This behavior is indicative of the potential

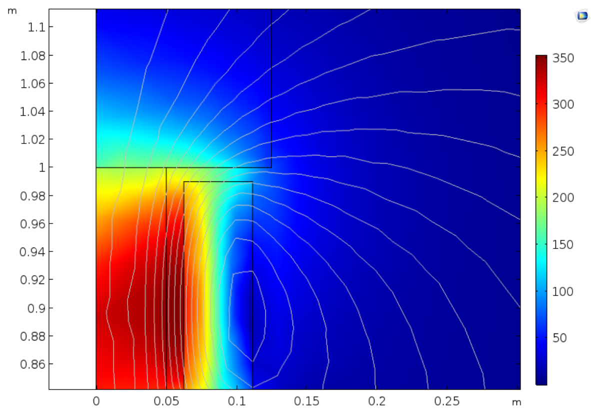

Figure 5: Simulation of axial magnetic field for a current of 15A. Continuos lines indicate magnetic field lines.

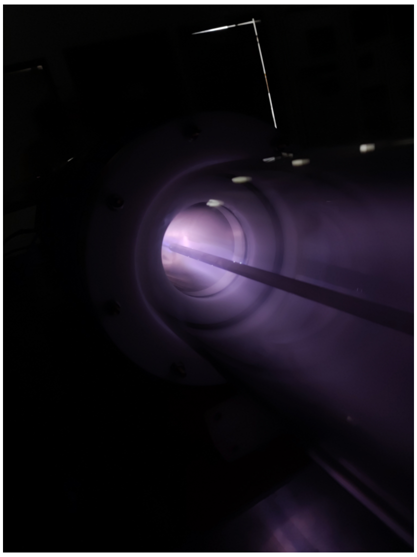

Figure 6: Magnetic Nozzle at first device qualitative test. Notice that sputtering occurs on the body of the probe indicating that some íons are gaining energy.

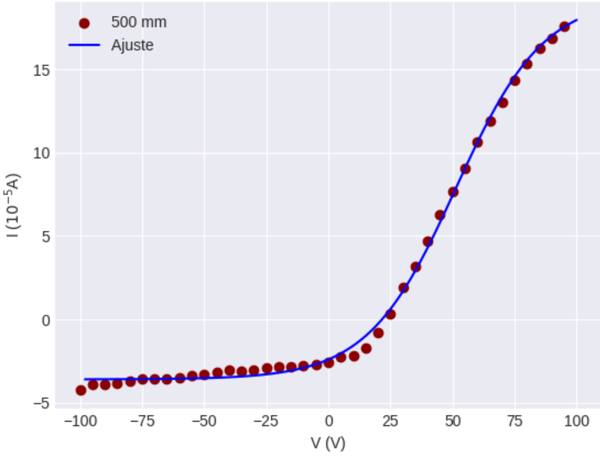

Figure 7: Characteristic I-V curve for the measurement at 500mm.

presence of a double layer in the vicinity of this region.

Fig. 9 illustrates a high electron densi in the order of 10^{13} m^{-3}. This high val demonstrates the effectiveness of a helicon l source in producing high-density plasmas ev at low power.

Moreover, as illustrated in Fig. 10, the e mation indicates a considerable ion density the area where the plasma potential is decl ing and the electron density is approximat one order of magnitude lower. This discr ancy in densities, coupled with the reducti in plasma potential, may suggest the existen of a double layer in that region, which will be subject to further investigation in the future.

The formation of double layers is a consequence of the ejection of electrons at high speeds and ions at lower speeds. The difference in speed between the two specimens

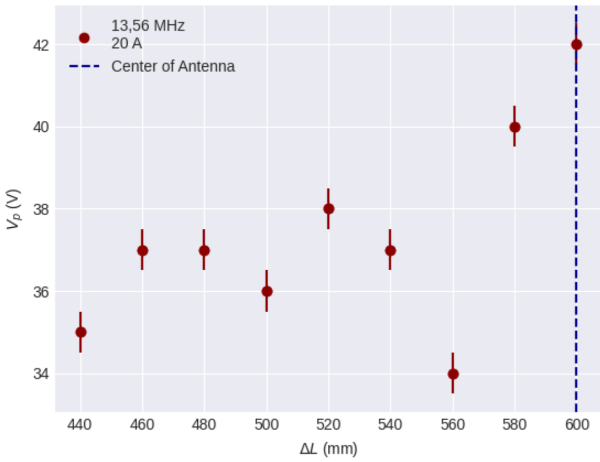

Figure 8: Plasma potential profile along the axial axis of the tube. The vertical dashed line indicates the center of the antenna

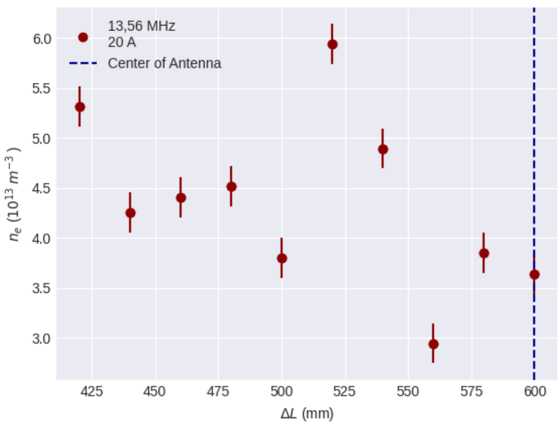

Figure 9: Electron density along the axial axis of the plasma. The vertical dashed line indicates the center of the antenna

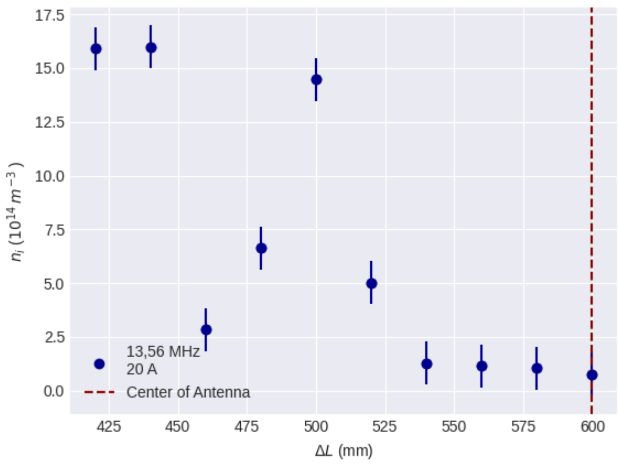

Figure 10: Ionic density estimated using the floating potential(V_f). The vertical dashed line indicates the center of the antenna

results in the creation of polarized regions with high density relative to each other, which in turn leads to a potential difference indicated by a sudden drop in plasma potential [11]. Consequently, a more comprehensive characterization of the device is necessary to confirm the presence of a double layer in our system. Furthermore, as the system is designed for propulsion, it is essential to investigate whether this double layer affects thrust.

The measurements conducted revealed that the helicon RF source is capable of producing a high electron density plasma and that there are indications an existence of double layer in the vicinity of 200 mm from the antenna on the magnetic cusp. Additionally, there is a notable amount of sputtering, suggesting that ions are being ejected from the center of the thruster towards the end of the chamber, gaining kinetic energy in the process.

4 Conclusion

Upon consideration of the presented results and the held discussions, it was observed that the helicon source met the expectations of the team. The plasma obtained reached a high electron density, on the order of 10^{13} m^{-3}, and a high ionic density was estimated, on the order of 10^{14} m^{-3}, indicating a possible concentration of ions in that region. It was observed that the plasma potential decreased as the probe was distanced from the source. Additionally, a sudden drop in the dispersion chamber was observed at approximately 200 mm from the source, in the same region where the high density was present. The observed conjunction of these features may be indicative of the presence of a double layer. To substantiate this hypothesis, it is necessary to conduct further measurements that extend over a greater distance from the antenna. Consequently, the primary experiment yielded several encouraging outcomes for the system, prompting further inquiry into the underlying causes of the elevated ionic density and the precipitous decline in potential within that region.

5 Acknowledgement

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References

[1] S. Shinohara, "Helicon high-density plasma sources: physics and applications," *Advances in Physics: X*, vol. 3, no. 1, p. 1420424, 2018. [Online]. Available: https://doi.org/10.1080/23746149.2017.1420424

[2] F. F. Chen, "A compact permanent-magnet helicon thruster," *IEEE Transactions on Plasma Science*, vol. 43, no. 1, pp. 195–197, 2015.

[3] R. Stenzel, "Whistler modes excited by magnetic antennas: A review," *Physics of Plasmas*, vol. 26, no. 8, 2019.

[4] A. Trivelpiece and R. Gould, "Space charge waves in cylindrical plasma columns," *Journal of Applied Physics*, vol. 30, no. 11, pp. 1784–1793, 1959.

[5] K. P. Shamrai and S. Shinohara, "Spectral and spatial characterization of a radio frequency power absorption in high pressure helicon plasmas," *Physics of Plasmas*, vol. 8, no. 10, pp. 4659–4674, 2001.

[6] D. Arnush, "The role of trivelpiece–gould waves in antenna coupling to helicon waves," *Physics of plasmas*, vol. 7, no. 7, pp. 3042–3050, 2000.

[7] Y. Mouzouris and J. E. Scharer, "Wave propagation and absorption simulations for helicon sources," *Physics of Plasmas*, vol. 5, no. 12, pp. 4253–4261, 1998.

[8] S. ISAYAMA, S. SHINOHARA, and T. HADA, "Review of helicon high-density plasma: Production mechanism and plasma/wave characteristics," *Plasma and Fusion Research*, vol. 13, pp. 1 101 014–1 101 014, 2018.

[9] I. Langmuir, "The interaction of electron and positive ion space charges in cathode sheaths," *Physical review*, vol. 33, no. 6, p. 954, 1929.

[10] L. P. Block, "A double layer review," *Astrophysics and Space Science*, vol. 55, pp. 59–83, 1978.

[11] I. Langmuir, "The interaction of electron and positive ion space charges in cathode sheaths," *Physical review*, vol. 33, no. 6, p. 954, 1929.

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