Experimental Studies of Helicon Double Layers for Future High Power Plasma Propulsion

Roger Walker*
ESA-ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

Nicolas Plihon†, Pascal Chabert‡, Jean-Luc Raimbault§
Laboratoire de Physique et Technologie des Plasmas (LPTP), Ecole Polytechnique UMR 7648, 91128 Palaiseau, France

The Helicon Double Layer Thruster (HDLT) concept, invented by Charles and Boswell at the Australian National University (ANU), appears to be promising for future high power electric propulsion, and needs to be investigated further. The original concept (strongly diverging magnetic field in pure argon) has been tested experimentally in a helicon reactor installed at LPTP. The double layer has been found in the same parameter space as at ANU, thus verifying their findings. The specific impulse and thrust estimates derived from flux and energy measurements in the LPTP reactor are rather low, but it is expected that these values can be improved considerably with further research. The effect of adding an electronegative gas has also been investigated experimentally. In that case, the DL was easily formed, with or without magnetic field. However, it was unstable in a wide parameter range. Performance estimates indicate that it is less promising than the original HDLT concept. Further numerical simulation and experimental work needs to focus on scaling to higher power and proving that the HDLT can function in free space vacuum conditions.

I. Introduction

Although in an early stage of laboratory experimentation at low to modest power levels, results indicate that there exists a potential for helicon-type radio-frequency plasma thrusters to operate at high power levels to produce a high continuous thrust and moderate to high specific impulse. This characteristic makes them an attractive prospect for propelling large spacecraft requiring high delta-V and reasonable mission durations. This type of thruster has the additional advantage of requiring no high-current cathode, acceleration grids or neutraliser that presently limit the operating lifetime in other electric thrusters, thus they would appear suitable for very high total impulse missions. Mission applications include human/cargo Mars missions to Mars, robotic missions with large science payloads to orbit the outer planets and their moons or even to deflect near-Earth asteroids from Earth-impacting trajectories.

A helicon source is a device capable of high-efficiency plasma generation based on the propagation of electromagnetic helicon waves to produce high density plasmas along the external magnetic field that confines the plasma within a tube. The magnetised plasma can be accelerated to produce axial thrust by a variety of methods, including plasma heating by a secondary antenna radiating at the Ion Cyclotron Resonance (ICR) frequency and expansion through a magnetic nozzle, as in the case of the Variable Specific Impulse Magneto-plasma Rocket (VASIMR) thruster; by Electron Cyclotron Resonance (ECR) heating; by capacitive discharge; or by the novel concept of an electric double layer in a diverging magnetic field, discovered by researchers at the Australian National University (ANU) who are developing/testing a Helicon Double Layer Thruster (HDLT) prototype[1-8]. The latter method is the focus of this paper. The electric Double Layer (DL) is the boundary discontinuity between two different plasmas, one of higher density, higher electron temperature and one of a lower density, lower electron temperature. The DL is represented by a sudden drop in plasma potential at this boundary. In a helicon reactor, current-free DLs have been measured with electropositive gases (xenon, argon, hydrogen) in the presence of a diverging applied magnetic field[1-9]. In this case, the high density plasma is in the source tube sustained by a helicon discharge, and the low density plasma is present external to the open end of the tube and attached where the confining magnetic field diverges. DLs have also been measured without a magnetic field by using electronegative gas (Ar/SF_6) mixtures in a similar device[10-11]. In both cases, the potential drop of the DL accelerates the higher density plasma in the source to supersonic speeds to form an ion beam, creating thrust at moderate exhaust velocity.

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* Post-Doctoral Fellow, ESA Advanced Concepts Team, AIAA member; Roger.Walker@esa.int
† Post-Doctoral Fellow, LPTP, Ecole Polytechnique, U. Paris XI; plihon@lptp.polytechnique.fr
‡ Professor, LPTP, Ecole Polytechnique, U. Paris XI; chabert@lptp.polytechnique.fr
§ Associate Professor, LPTP, Ecole Polytechnique, U. Paris XI; raimbault@lptp.polytechnique.fr

II. Overview

This paper presents the methodology, set up and results of an experimental and analytical study carried out to investigate the novel helicon double layer thruster concept for space propulsion, measure helicon double layers under laboratory conditions, estimate its performance at low power and identify further work relating to its scaling for use on high power interplanetary space missions. The main goals of the study were to:

- verify the double layer experimental results obtained by ANU by using an independent (but similar) low-power laboratory helicon reactor with Argon electropositive gas and diverging magnetic field with various diagnostic tools including a Retarding Field Energy Analyzer (RFEA)
- confirm the existence/stability/amplitude of the double layer under varying physical conditions in the reactor such as the forward RF power to the source, magnetic field strength, gas pressure, and DC-bias of the source tube
- measure the performance of the helicon double layers for different propellants, including electropositive gases like argon, and mixtures with electronegative gases such as Ar/SF_6 (which does not require a magnetic field for double layer formation)
- measure emitted ion beam and downstream plasma properties and predict the associated propulsive performance such as thrust and specific impulse

III. Experimental set-up

The experimental test activity was conducted with the helicon reactor at LPTP, Ecole Polytechnique in Palaiseau, France to achieve the outlined objectives. The LPTP helicon reactor is shown schematically and pictorially in Figure 1. It consists of a source chamber sitting on top of a 32 cm diameter diffusion chamber. This chamber is terminated by a movable plate, introduced through the bottom of the diffusion chamber, such that the diffusion chamber length can be varied between 0 and 26 cm. The source is a 14 cm diameter, 30 cm long and 0.9 cm thick pyrex cylinder surrounded by a double saddle field type helicon antenna[12]. The fan-cooled antenna is powered through a close-coupled L-type matching network by an rf power supply operating at 13.56 MHz and capable of delivering up to 2 kW forward power. The time-averaged input power was recorded as the difference between the time-averaged forward and reflected powers. The pyrex cylinder is housed in an aluminum cylinder of 20 cm diameter and 30 cm long. A metal grid attached to the other end of the source tube confines the plasma and separates it from a turbo-molecular pump that routinely maintains base pressures of order 10^{-3} mTorr. This grid can either be electrically isolated or be dc connected to the ground, which may make a big difference for the HDLT operation. The source and diffusion chambers are equipped with four coils to produce a static magnetic field of 0-200 Gauss. The discharge was run in pure Ar and in Ar/SF_6 mixtures. The partial gas pressures of Ar and SF_6 were determined by controlling the flows. The main differences between the LPTP reactor and Chi-Kung reactor at ANU in Canberra are the following:

- The pump is placed on the side of the diffusion chamber on Chi-Kung, while at the top of the source chamber at LPTP.
- The source chamber is ended by a pyrex plate on Chi-Kung, while a the LPTP source is terminated by a grid, which can be either floating or dc connected to ground.

When the two source coils around the source tube are fed with a sufficiently high current to create a magnetic field above 60 Gauss, the electric double layer is supposed to form at the interface between the source tube and the diffusion chamber, as a result of a rapid plasma expansion in a strongly diverging magnetic field. This double layer separates a high density source plasma and a low density secondary downstream plasma. The strong plasma potential drop (similar to a shock wave) accelerates the ions from the source into the diffusion chamber, thus providing thrust. The search for double layers was performed over a wide operating range of the control parameters:

- Peak magnetic field strength: 0 – 180 Gauss
- Gas pressure: 0.1 – 10 mTorr
- Forward RF power: 150 – 1000 W

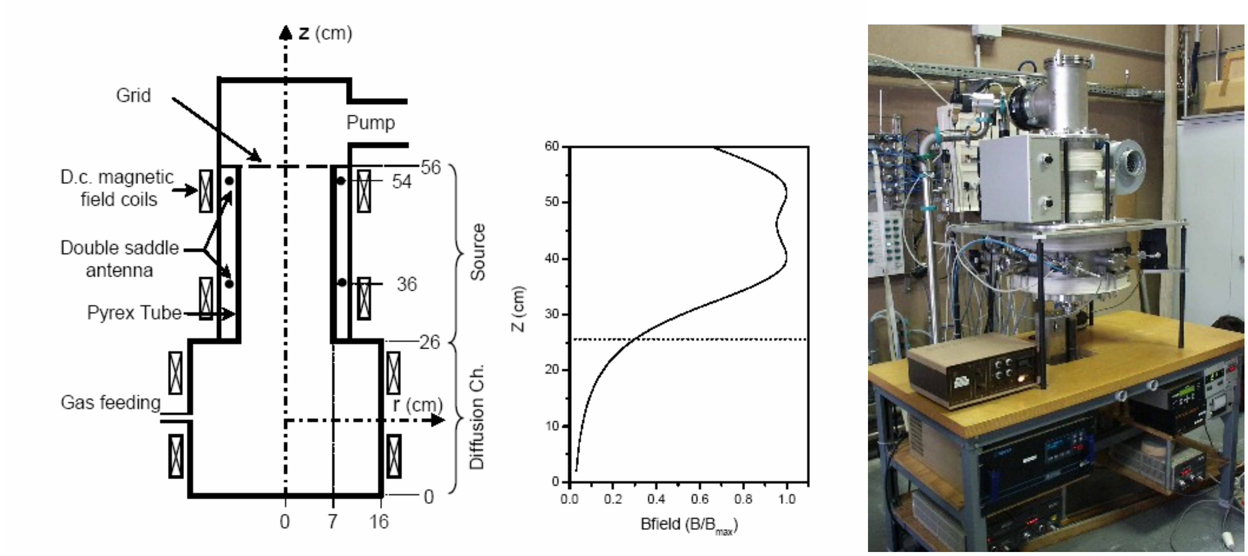

Figure 1: Schematic and image of the LPTP helicon reactor setup.

IV. Diagnostic tools

A. Langmuir probes

The measurements reported here were made both along the revolution axis (*z* axis) and along the radius of the median plane (*r* axis) of the plasma. The plasma parameters are determined using two types of electrostatic probes, shown in Figure 2. The first is a nickel planar probe having a guard ring biased at the same (negative) potential as the probe, to measure the real saturated positive ion current. The diameter of the collecting area is 4 mm and the diameter of the outer ring is 8 mm. The second is a passively compensated Langmuir probe[13], of 0.25 mm diameter and 6 mm long platinum wire tip. For stationary plasmas and time-averaged measurements during the instability (occurring in the electronegative case), the plasma potential, the electron density and the electron temperature were deduced from the *I(V)* characteristics of the cylindrical probe using a Smartsoft data acquisition system[14]. The electro-negativity, and consequently the ion densities, were measured according to the double-probe technique[15]. This technique allows to deduce from the ratio of the cylindrical probe current at the plasma potential to the positive ion saturation current measured by the planar probe.

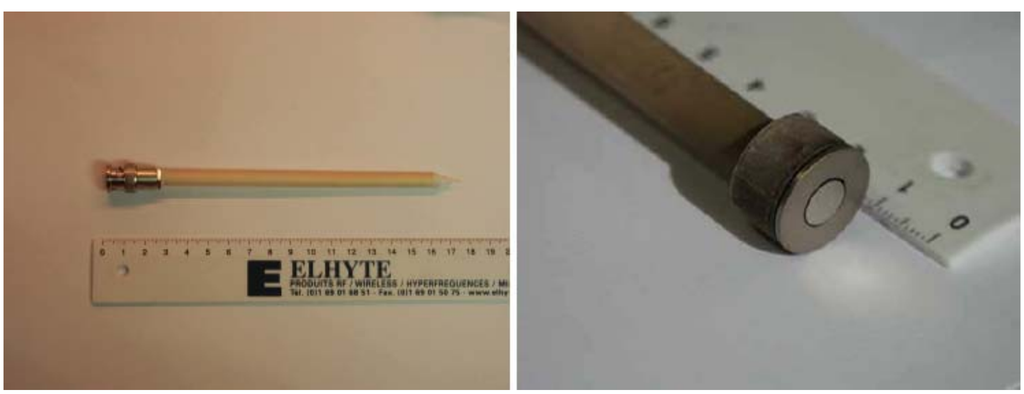

Figure 2: Pictures of the Langmuir (left) and planar (right) probes.

B. Retarding Field Energy Analyzer

LPTP developed a Retarding Field Energy Analyzer consisting of four grids and a collector plate[16-18]. The schematic of the RFEA is shown in Figure 3. The analyzer was differentially pumped. It was composed of four grids made of nickel wires of 11 microns in diameter spaced by 40 microns; each grid had a 60 percent transparency. The entrance grid was grounded, a second grid was biased at -50 V to repel the electrons, the third grid was used to select the ion energy by scanning the voltage from 0 to 200 V, and a fourth grid was inserted before the collector in order to minimize the effect of secondary electrons[17]. The grids were spaced by 0.25 mm so that the total system length was about one millimeter. The ion current to the collector was recorded as a function of the dc voltage applied to the discriminator. When assembled, the analyzer is 35 mm long by 50 mm in diameter and the plasma particles enter the analyzer through a 2 mm hole in a 0.3 mm thick stainless steel orifice plate, in electrical contact with the analyzer housing, which is connected to the grounded diffusion chamber of the reactor.

The Ion Energy Distribution Function (IEDF) is then computed from the first derivative of the ion current to the collector as a function of the dc voltage applied to the discriminator. The ion distribution function is centered around the plasma potential with a dispersion due to the device resolution. A best fit was made to the distribution using a gaussian function, with the maximum of the gaussian being the plasma potential. Working out the ion saturation (the current measured for discriminator voltages below the plasma potential), it is possible to compute the ion density in the downstream plasma.

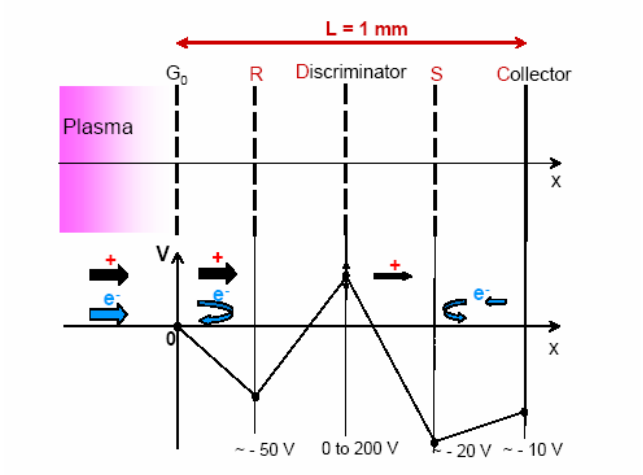

Figure 3. Schematic of the four-grid RFEA.

In the case of a measurement downstream of the double layer, a double bumped IEDF is expected, with one bump centered at the plasma potential, and one bump corresponding to an ion beam accelerated by the double layer. Then, the ion saturation current has got two components: the first one is due to the ion beam, whose speed depends on the DL potential amplitude, and the second one is due to the local ions generated in the downstream plasma. Figure 4 shows a picture of the RFEA design, to be inserted from the bottom of the diffusion chamber.

Figure 4. Pictures of the RFEA.

V. Experimental results

A. Electropositive Double Layer with Diverging Magnetic Field

To find the double layer, the plasma potential was first measured by the Langmuir Probe as a function of the altitude (the Z-axis in Figure 1), hoping to identify a potential step. The measurements were conducted for two different low pressure argon plasma (0.5 and 1 mTorr) with two different magnetic field amplitudes (45 and 90 G).

The plasma potential showed two different levels over altitude in all four cases (the potential being higher in the source), but the levels were joined by a smooth potential gradient rather than the expected step characteristic of the double layer. In view of these results, it was concluded that the double layer could not be measured with the Langmuir Probe since the DL may have been perturbed when pierced by the Langmuir probe.

The RFEA experiments were then carried out downstream of the predicted double layer in an attempt to identify its existence. Indeed, it was found that the double layer was formed when operating at low pressure and high B field. Ion distribution functions were measured by the RFEA such as the one shown in Figure 5. The distribution presents two peaks, an evidence of the ion beam resulting from the DL formation. These peaks can be fitted by a least mean square method by two gaussian peaks with the same dispersion (which is typically 6 V in the DL case). The measurement corresponds to the collection of two distinct populations of ions: (i) the local ions that fall through the sheath of the grounded analyzer and (ii) the beam ions accelerated into a beam through the DL.

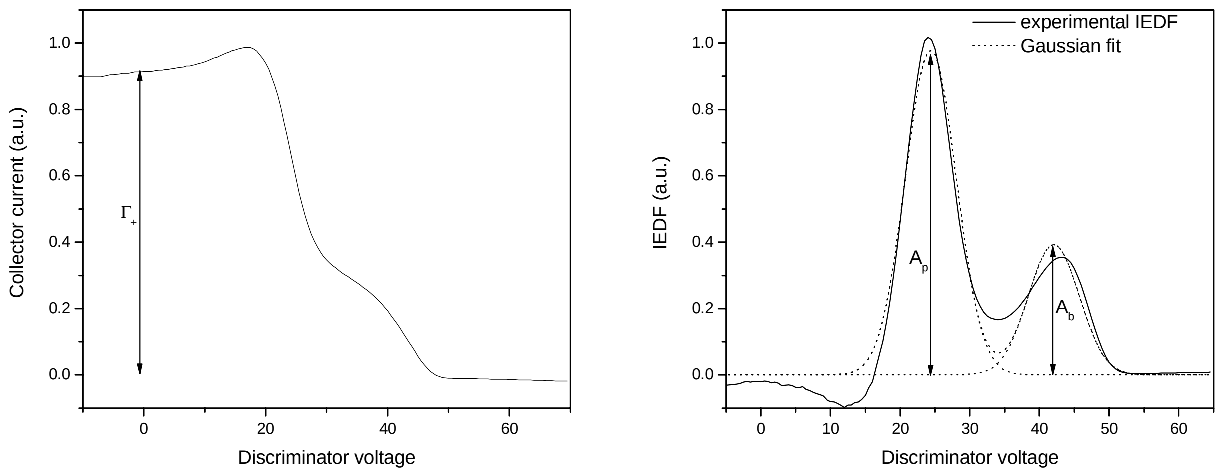

Figure 5: Typical acquisition signal from the RFEA. (a) Collector current as a function of Discriminator voltage for a 0.1 mTorr, 90 G, 250 W discharge, with the RFEA located on the median plan of the diffusion chamber (z = 14cm). (b) IEDF and best fit with double gaussian of same dispersion.

Figure 6 shows results obtained at 0.17 mTorr, 90 G, 250 W as a function of the axial position. For positions below 27 cm, the IEDF clearly shows two peaks while only one single peak is present above that altitude. The data can be analysed as follows: the plasma potential and plasma density are roughly constant below 27 cm, with the presence of a beam at 42 V, whose amplitude is increasing exponentially when going upwards; above 27 cm, one single peak at about 42 V is obtained, with a plasma density 10 times higher than downstream, and increasing when moving up into the source tube. This strongly suggests the presence of an abrupt increase of the plasma potential at z ≈ 27 cm, associated with a dramatic increase in the plasma density, i.e. the double layer. This double layer is associated to the presence of a beam in the low potential region, whose speed is determined by the high potential region. The plasma density is determined with an electron temperature assumed to be spatially homogeneous, which was measured to be 5±0.5 eV at 0.17 mTorr in the diffusion chamber.

The voltage difference between the beam and local plasma component being 13 eV, the beam speed can be calculated as being equal to $\sqrt{5}$ (or 2.2) times the Bohm velocity. The beam measured downstream of the DL is therefore supersonic. The higher the DL amplitude for a given electron temperature, the higher the specific impulse. At 10 cm downstream of the double layer, the beam density is estimated to be 0.3 the local plasma density, which is consistent with the results obtained at the ANU.

The presence of a sufficiently high and diverging static magnetic field is required to get a double layer. Figure 7 shows a parametric study of the formation and behaviour of the double layer as a function of the magnetic field strength. These results were obtained with the RFEA at z = 20 cm, at a pressure of 0.17 mTorr, and a power of 250 W. For B field below 45 G, the IEDF shows only one peak, with a density being fairly high (10^{16} m^{-3}). Above 45 G, the IEDF shows evidence that a double layer exists. While the plasma density is slightly decreasing with increasing B field (from $3\text{x}10^{15}$ m^{-3} at 45 G to $1\text{x}10^{15}$ m^{-3} at 90 G), the plasma potential is slightly increasing from 28 V at 45 G to 30 V at 180 G. But the main characteristic is that the double layer amplitude (around 15 V for these conditions) increases very slowly for B field above 45 G. The beam density is only slightly fluctuating and seems to follow the local plasma density behaviour. However, it is difficult to compare beam densities for different operating conditions since the position of the DL and the upstream density could vary. These results are consistent with those obtained at the ANU and some conclusions could be given as for propulsion requirement at a given power: the double layer amplitude seems to be independent of the B field above a critical value, thus limiting the amount of dc current required to generate the moderate B field (namely 45 G in our system). Although the DL amplitude is independent of the magnetic field magnitude, it may depend on the gradient.

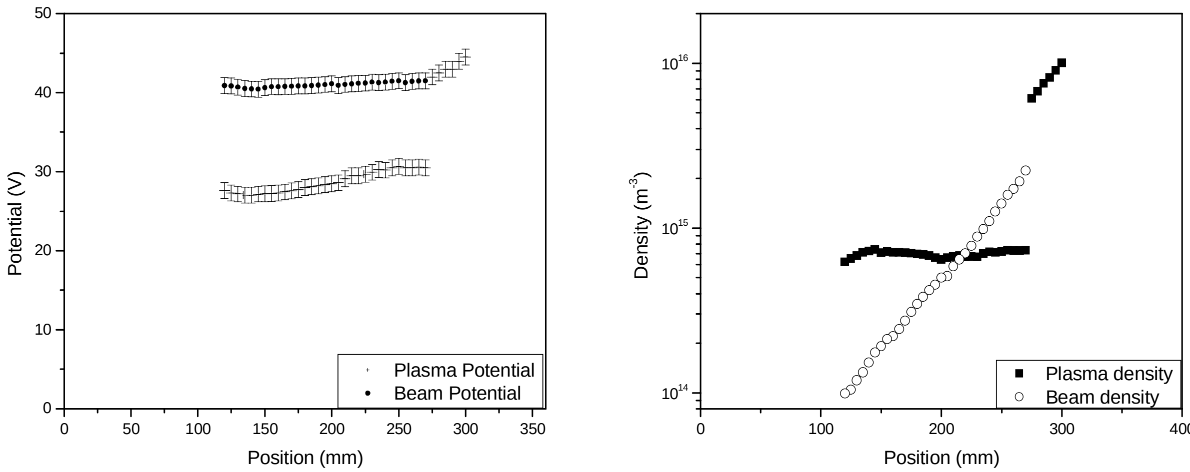

Figure 6: Evidence of double layer existence in pure argon at 0.17 mTorr, 90 G, 250 W: (a) local plasma potential and beam potential as a function of axial position, (b) plasma density and ratio of beam flux to local flux as a function of axial position.

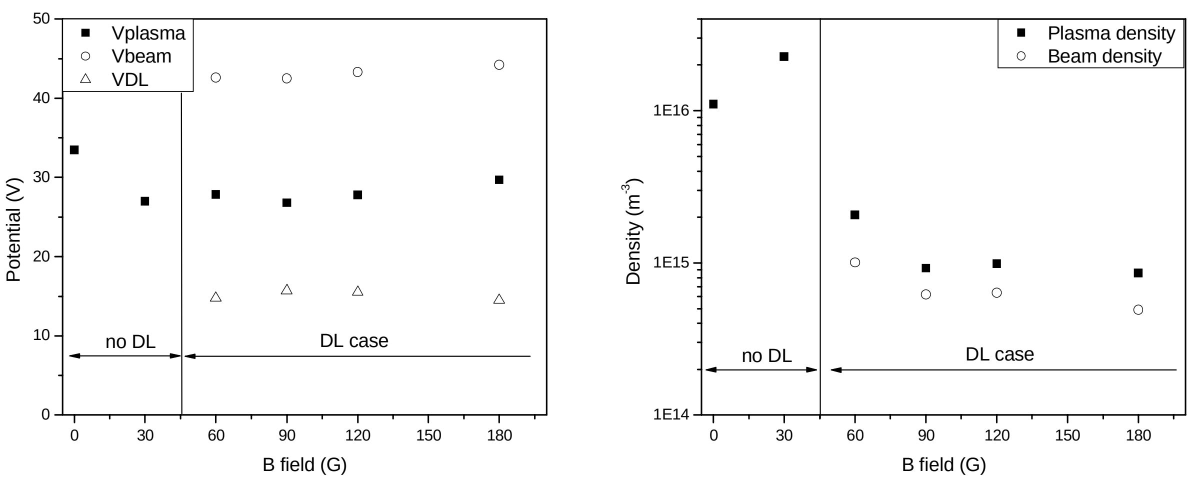

Figure 7: Influence of the static magnetic field amplitude at 0.17 mTorr, 250W. The RFEA is located at z = 20 cm. (a) local plasma potential and beam potential as a function of magnetic field strength, (b) plasma density and beam density as a function of magnetic field strength.

The double layer only appears at sufficiently low operating pressure. Figure 8 presents the influence of the pressure on the DL characteristics for a 90 G magnetic field and a operating power of 250 W for a RFEA positioned at z = 20 cm. At gas pressures above 3 mTorr only one peak is measured and no DL is present. Below 1 mTorr, two peaks can be determined, thus giving evidence of a DL. When decreasing the pressure the plasma potential downstream of the DL remains constant, while the upstream potential increases. Thus the DL potential increases drastically with decreasing pressure. The beam flux is also increasing with decreasing pressure; which is consistent due to the increase in acceleration from the DL potential and decrease in collision frequency. The plasma density is scaling as expected: decreasing with decreasing pressure, since the electron temperature required to sustain the discharge is increasing. No discharge could be sustained below 0.08 mTorr. However, below 0.10 mTorr, the measured IEDFs show only one peak. Thus only a small window in pressure could lead to the formation of a DL.

This feature was also clearly evidenced at the ANU. For propulsion requirements, the highest specific impulse is obtained at the lowest pressure, but on the other hand the thrust may not be kept constant since the density is decreasing with decreasing pressure. Once again these trends have already been published by the ANU group. A slight discrepancy in terms of absolute values (DL amplitude, pressure window etc.) arises between the ANU data and the results presented in this paper. However, these are fairly small and could be explained by the fact that we measure the pressure with a gauge that is designed to run in the range 0-100 mTorr. Therefore, our measured pressure below 0.5 mTorr could easily have absolute errors of about 50%.

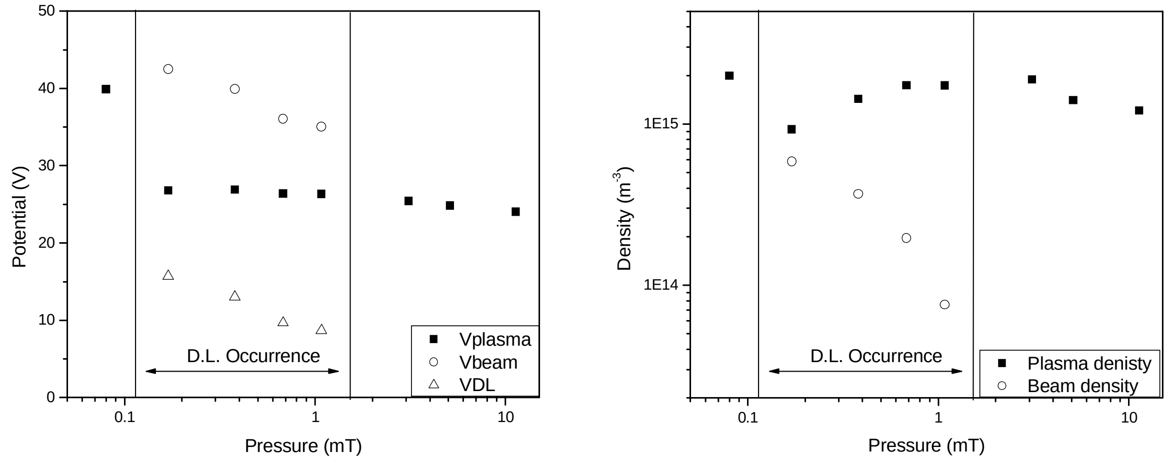

Figure 8: Influence of the pressure at 250W for a 90 G magnetic field. The RFEA is located at z = 20 cm; (a) local plasma potential and beam potential as a function of magnetic field strength, (b) plasma density and beam density as a function of operating pressure.

For future interplanetary exploration, the scaling up to high power is very important. The influence of the rf power at given pressure and magnetic fields was therefore experimentally investigated. The experimental results shown in Figure 9 have been acquired at 0.2 mTorr and a magnetic field of 90 G. When increasing the power, the plasma potential keeps on decreasing, while the plasma density increases quasi linearly. The power coupling to the plasma might drastically change from 250 W (capacitive or inductive coupling) to a few thousands W (wave mode coupling), thus the decrease in plasma potential is to be expected. The plasma density is also known to scale proportionally to the power. One important result is that the DL amplitude remains constant (less than 5% fluctuations) from 150 W to 1000 W, which is an important result for propulsion requirements. On the other hand it appears that the beam density is not increasing at the same rate as the local plasma density. However, due to the experimental set up limitations one cannot give any definitive conclusion for space propulsion.

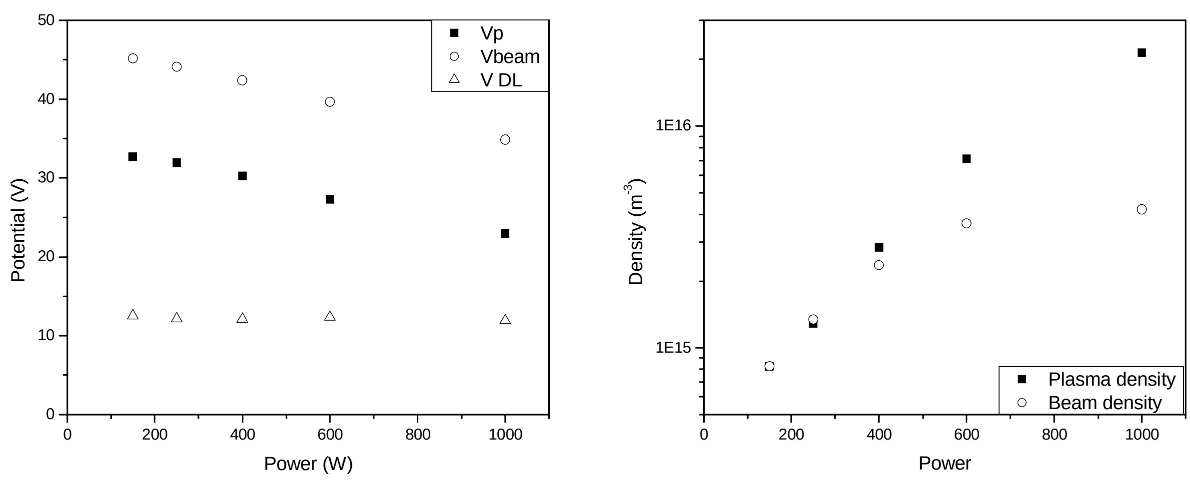

Figure 9: Influence of the power at 0.2 mTorr for a 90 G magnetic field. The RFEA is located at z = 23 cm. (a) local plasma potential and beam potential as a function of axial position, (b) plasma density and ratio of beam flux to local flux as a function of axial position.

A time resolved acquisition system was set up to measure the ignition and the time development of the DL. To get some insight into the DL formation, the discharge was operated pulsed, with a 750 µs on period and 500 µs off period that allows the plasma to extinct between pulses. The RFEA discriminator voltage bias is kept constant during 256 pulses and increased step by step afterward. The collector current is acquired on a large memory scope, averaging over 256 periods to reduce noise measurements (the temporal behaviour has been checked to be reproducible between each pulse). The data are computer-processed to obtain time-resolved IEDFs. These are given in Figure 10. These IEDF data are then processed to follow the amplitude and potential of the two peaks, corresponding to beam and plasma components. The beginning of the 'on' time is located at t=20 µs, and only one peak is present before t=50µs. Then the beam potential is quickly set to 45 V (over 10-20 µs), while the downstream plasma potential keeps on decreasing (from 38 to 30 V) over the next 50 µs. The amplitudes of both the beam component and local plasma components are increasing and saturates after 150 µs of operation, with the same time scale for both peaks and giving a DL formation time of 130µs.

The influence of changing one of the boundary conditions of the source tube, namely how the source tube is ended, was also investigated. It appears that the position of the glass tube in the ANU ChiKung experiment plays an important role in the beam amplitude[4]. The LPTP reactor is operated with the pumping system set at the end of the source tube, thus the tube needs to be ended by a grid. However, three different configurations have been experimentally studied. (a) an insulating grid terminates the plasma, with about 2 cm of grounded metal between the pyrex tube and the grid, (b) same as (a) with a pyrex tube inserted to shield the grounded metal parts from the plasma, (c) a conducting floating grid terminates the plasma at the end of the pyrex tube. All results presented above and in the next section for electronegative gas mixtures were with the condition (a), namely a insulating grid with a piece of grounded metal at the end of the pyrex tube. Figure 11 shows direct RFEA measurements and processed IEDF normalized to one at the plasma potential, when the RFEA is placed at z = 20cm, for a 0.17 mTorr, 90 G, 250 W plasma. The ion saturation flux is the same within less than 3%; and the peak amplitudes are decreasing by a few percent (8% from geometry (a) to geometry (c)). A noticeable variation of the potentials is observed: the local plasma potential is decreasing: 26.5 V, 25.5 V and 24.5 V, while the beam potential is increasing: 42.5 V, 44.2 V, 46.5 V, for geometry (a), (b) and (c) respectively. However the broadening of the peaks slightly increases when scanning from geometry (a) to geometry (c) for unexplained reasons.

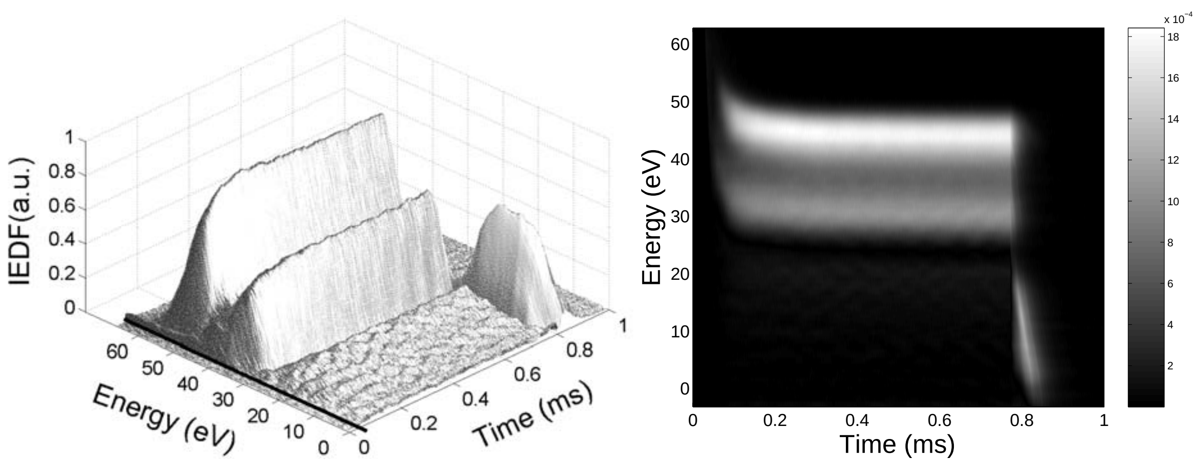

Figure 10: Time resolved IEDF during pulsed operation of the discharge at 0.2mTorr, 90 G, 250 W. The RFEA is at z = 20 cm. (a) 3d mapping of the IEDF, (b) gray level image.

These results are significantly different from those published[4] which showed that the beam component relative to the plasma component could triple when changing the position of the end plate by only 2 cm. Interestingly, the double layer was found for all boundary conditions, including the dc-connected (condition a) case. It is therefore concluded that the DL is not necessarily current-free. All experiments conducted show the same trends as ANU in terms of pressure, B field, and position whatever the source boundary conditions. As shown in Figure 11, the DL amplitude changed noticeably with the boundary conditions, the higher DL amplitude being obtained for the floating conducting grid: the DL amplitude increases from 16 V (condition a) to 22 V (condition c) while all other experimental parameters are kept constant.

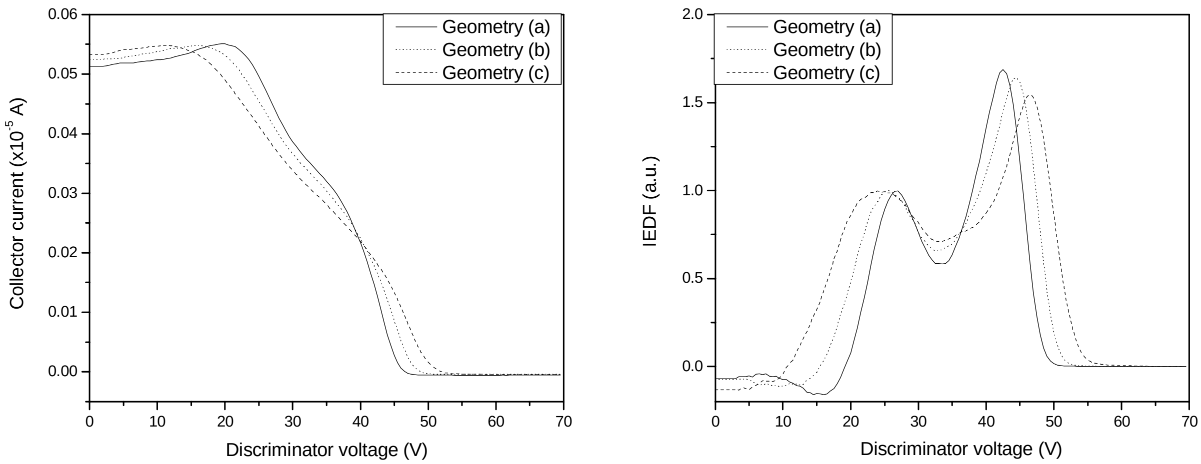

Figure 11: Influence of the boundary conditions on the measured IEDFs. Direct measurements from the RFEA and computed IEDFs for operating conditions 0.17 mTorr, 250 W and a magnetic field of 90G.

B. Electronegative Double Layer without Magnetic Field

A double layer has also been observed in the same device when operating without a magnetic field. The condition for double layer occurrence is that the plasma contains a noticeable fraction of negative ions. Experiments were made with Ar/SF_6 mixtures since SF_6 is known to be very efficient in producing negative ions. When the negative ion fraction is above a critical threshold, a double layer forms at the interface between the source and the diffusion chamber[10]. The amplitude of that DL is lower than the one obtained with a magnetic field. However, it was possible the measure the presence of an positive ion beam in the diffusion chamber that was accelerated by the DL and to investigate the influence of the operating parameters on the beam characteristics.

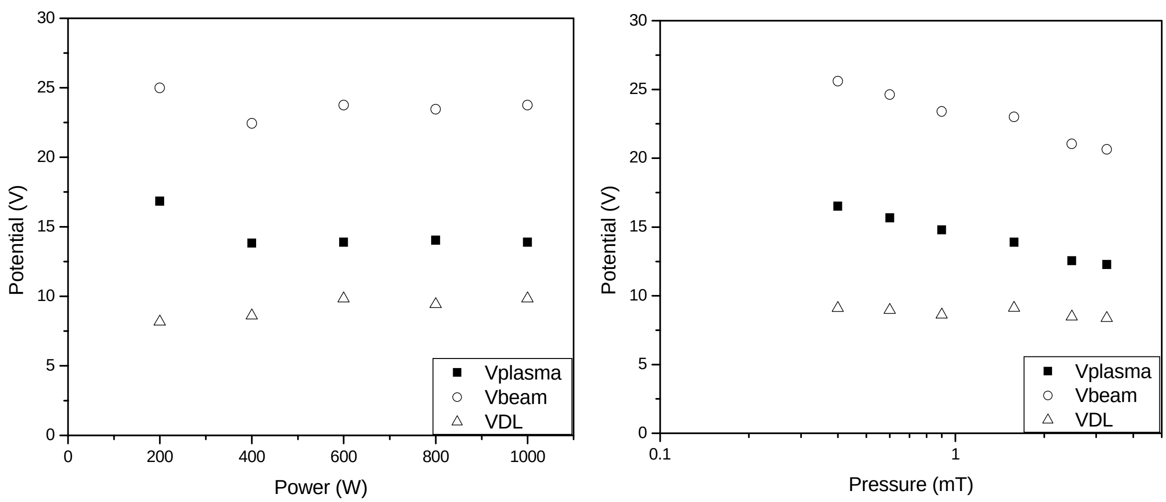

Figure 12: Evolution of plasma potential, beam potential and DL amplitude as a function of power and pressure for a 10% SF_6 mixture at 1 mTorr, at z = 14 cm.

The Ion Energy Distribution Function (IEDF) was measured using the RFEA in the presence of the electronegative double layer. The mean free path for charge exchange is inversely proportional to the total neutral gas pressure and is 3 cm at 1 mTorr. Since the RFEA holding structure is not infinitely small compared to the vessel size, it is not possible to measure IEDFs at positions closer than 3 to 5 cm to the DL. Thus measurements are only possible at low pressure (around 1 mTorr). The experimental data are fitted by either a single-gaussian function, or a double-gaussian function when two bumps are present. The plasma potential and beam potential are then deduced from the position of the maxima of each gaussian. We can conclude that the double layer amplitude is between 6 and

7 V and remains fairly constant when positioning the RFEA at z = 14 cm and varying the power, and the pressure, as shown in Figure 12.

As the SF_6 concentration is further increased to 25%, the discharge becomes unstable, entering a downstream instability regime. Using a time-resolved Langmuir Probe system we were able to measure the temporal evolution of the plasma parameter spatial profiles. Figure 13 presents the plasma potential measured on the reactor axis as a function of altitude, and as a function of time. The x-axis is the time, normalized to the instability period, and the y-axis is the position (the diffusion chamber bottom is at z = 0 cm). The interface between the source and diffusion chambers is at z = 26 cm and is shown by a black dotted line. It seems that the double layer is born at the interface between the two chambers, as it was proposed for electropositive gases[19], and moves downward as time evolves. The double-layer formation frequency and the propagation speed are such that the first double layer has not reached the bottom of the diffusion chamber when a new double layer forms upstream. Consequently, at a given time during the instability cycle, there are two potential drops in the diffusion chamber. The propagation speed is small, about 250 m/s, and mostly constant although the double layer seems to slightly speed up at the end of its travel, when the new double layer is formed. The plasma parameters are only slightly modulated in the source region, thus, it does not seem that the instability is driven by the source.

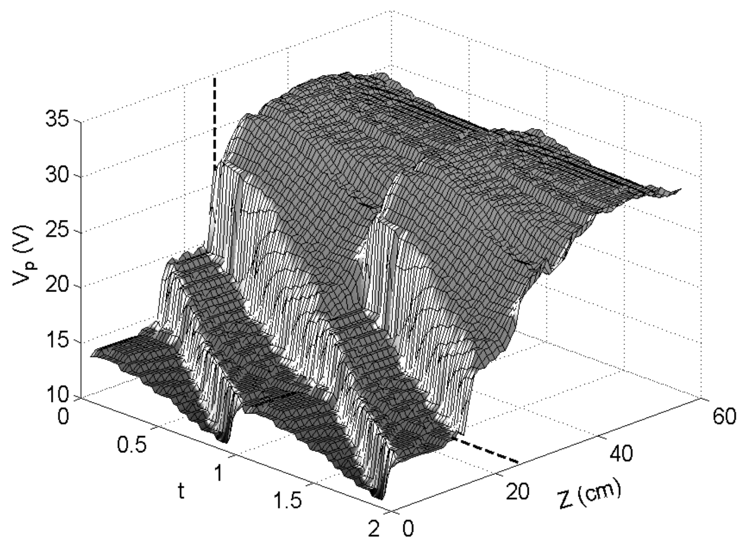

Figure 13: 3D mapping of the plasma potential, showing the propagation of the unstable double layer for a 25% SF_6 mixture at 1 mTorr, 600W.

VI. Conclusions

The presence of a stable double layer was detected with electropositive gas (Argon) and diverging magnetic field in the helicon reactor at LPTP. Formation of the double layer occurred after 130 microseconds at gas pressures of 0.1 to 1 mTorr and magnetic field of above 45 Gauss, according to the measurements made. The results obtained are broadly similar to those obtained by researchers at Australian National University, who first discovered the Helicon double layer and proposed the HDLT concept. This finding independently replicates and validates the ANU measurements of the double layer in their Helicon reactor.

Variations of the LPTP Helicon reactor operating parameters (RF power, gas feed pressure, magnetic field strength) were performed with electropositive gas (Argon). Results have confirmed that the acceleration of ions through the double layer (characterised by the voltage drop of the double layer) is only weakly influenced by magnetic field strength or input RF power, but is significantly influenced by the gas pressure. The lower the pressure, the greater the voltage drop at the double layer, and the higher the ion acceleration out of the thruster, thus the greater the exhaust speed and therefore the specific impulse. The maximum voltage drop of the double layer was 25 V, giving a specific impulse of over 900 s. Higher values of up to 1500 s have been observed at ANU.

Measurements of the ion beam downstream of the double layer indicate that the density of beam ions drops off significantly within a distance of 10 cm. This would compromise the axial thrust that can be produced. A value of 0.3 mN was estimated for Argon discharge with an rf power of 600 W (based on flux measurements at 7 cm from the DL), compared to a theoretical maximum of 15 mN. However, it is not clear whether this is due to the influence of the laboratory setup which is very constrained in this case (only a very small diffusion chamber is used downstream which cannot maintain vacuum pressure, whereas in space there would be free space and vacuum) or a characteristic of the double layer itself. Only tests of a HDLT thruster prototype in a large vacuum chamber facility could firmly answer this question.

The presence of double layers was also detected with electronegative gas (Ar/SF_6 mixture) and without a magnetic field. The lack of a magnetic field means that an eventual spacecraft thruster based on the helicon double layer would not need magnetic coils in this case and would therefore be much lighter. However, it was found that the voltage drop of the double layer is not as strong as with electropositive gas (only 7 V instead of 25V) and therefore the obtained specific impulse is about 50% less and not very attractive for propulsion. Some slight improvements in specific impulse were found where unstable double layers were formed and propagated from the helicon source at a speed of 250 m/s and at a frequency near 1 kHz. This allowed two separated double layers to be travelling downstream simultaneously. Unfortunately, the backflow of negative ions from the downstream plasma through the double layer and back into the helicon source tube was found to counteract the outflow of electropositive ions by about 25%, thus compromising the thrust by this amount. Thus, it was concluded that the electronegative helicon double layer is not so attractive for space propulsion at this initial stage of study.

It is emphasized that such a laboratory setup with a small diffusion chamber containing ejected plasma at relatively large pressure does not realistically mimic the conditions of a thruster operating in a space environment, where the surrounding pressure is negligible. Although these small-scale tests are useful to understand double layer formation, the confined diffusion chamber walls and non-vacuum may itself influence the measurements made and/or alter double layer formation conditions. Hence, a fuller understanding of the double layer under free-space vacuum conditions needs to be gained via theoretical research, numerical simulation, and full-scale tests of a thruster prototype in a fully-equipped electric propulsion facility with large vacuum chamber.

Further work could study improving the thrust by increasing the source ionization efficiency, ie. increase the input power and find the appropriate magnetic field for a maximum of helicon wave ionization. It seems possible since the double layer is robust, i.e. exists at high power. The crucial question for the scaling up to high power, apart from the associated thermal problems, is to predict via numerical simulation the maximum power at which the double layer still exists. Further experimental work could be done to attempt to improve the DL amplitude (and hence the specific impulse) by adding a dc-biased grid at the upper end of the tube to increase the source potential.

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