

An experimental investigation of alternative propellants for the helicon double layer thruster

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Abstract

Ion energy distribution functions are measured using a retarding field energy analyser located 7.5 cm downstream of a helicon double layer plasma source, respectively, operating with four molecular gases: nitrogen (N_2), methane (CH_4), ammonia (NH_3) and nitrous oxide (N_2O). For radiofrequency powers of a few hundred watts, and a magnetic field diverging from about 0.013 T (130 G) in the source to about 0.001 T (10 G) in the exhaust, an ion beam is detected for each propellant over a very similar operating pressure range (~ 0.023 Pa (0.17 mTorr) to ~ 0.267 Pa (2 mTorr)), as a result of spontaneous electric double layer formation near the exit of the plasma source. The characteristics of the ion beam versus operating pressure closely follow those previously obtained in argon, xenon and hydrogen. The ion beam exhaust velocity in space is found to be in the 17–19 km s⁻¹ range in N_2 , 21–27 km s⁻¹ range in CH_4 and NH_3 and 14–16 km s⁻¹ range in N_2O .

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Over the past few decades, plasma processing (etching, sputtering, deposition, surface treatment) for microelectronics [1], optoelectronics [2] and fuel cell [3] applications has been closely associated with the development of various types of magnetized or non-magnetized inductive sources (electron cyclotron resonance sources, helicon sources, transformer coupled plasma sources) and their operation with molecular gases (SF_6 , CF_4 , SiH_4 , CH_4 , H_2 , O_2) [1]. The recent study of current-free electric double layer (DL) formation in these sources [4–8] and the diagnostic of the ion beam formed by acceleration in the potential drop of the DL has led to new applications of this phenomenon to space science and plasma propulsion [9]. The spontaneous formation of current-free double layers in the magnetic funnel of the solar corona has been proposed [10] and the natural occurrence of DLs in the auroral cavity has been measured and modelled [11].

A new electric propulsion system, the helicon double layer thruster (HDLT), where the source of thrust is the large area

ion beam generated by the DL, is also under investigation [12]. The presence of the DL in helicon plasma sources has already been evidenced for a variety of gases (argon [13], hydrogen [6] and xenon [12]). The properties of the DL investigated by Plihon *et al* [7] in the very electronegative sulfurhexafluoride helicon plasma strongly differ from the properties of the electropositive argon DL [9]. Here we report on the first experimental evidence of the double layer and ion beam formation for four molecular gases not previously investigated, nitrogen (N_2), methane (CH_4), ammonia (NH_3) and nitrous oxide (N_2O), to study new applications of the HDLT for future space missions and to give some insight into the possible use of the HDLT with hydrazine (N_2H_4), the standard though highly toxic chemical rocket fuel (a non-authorized gas in Australia).

The double layer has already been investigated for pure H_2 and pure O_2 plasmas and the choice for the four 'new' gases was motivated by on-site availability, structural variety and safety of operation: N_2 , N_2O (N_2 in a more complex structure) and NH_3 , a molecular gas combining nitrogen and hydrogen atoms

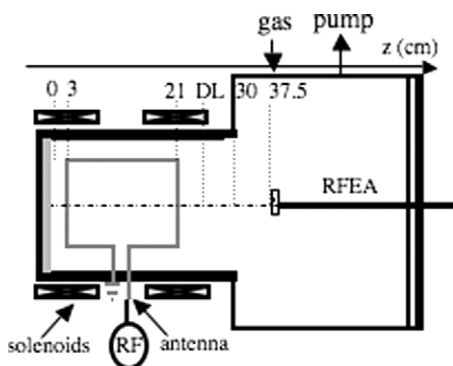


Figure 1. Experimental set-up showing the helicon double layer plasma source attached to the vacuum chamber holding the RFEA; also shown is the DL position previously measured in argon [9].

and from which hydrazine is derived, were chosen. Methane (CH_4), a gas used on a regular basis in the laboratory for the plasma deposition of catalysed carbon electrodes for low temperature fuel cells [3] and which contains four hydrogen atoms (similarly to N_2H_4), was also chosen.

Relevant work using these gases are numerous: since an effective method of obtaining reactive atomic nitrogen is the use of radiofrequency (rf) plasmas, nitrogen plasmas have been used in various thin film processes, for example, plasma enhanced molecular beam epitaxy of GaN [14] and low temperature nitridation of silicon dioxide for gate dielectrics [15]. In recent years, nitrous oxide has been employed as an oxidizing agent in the microelectronics and optoelectronics industry: rf or microwave N_2O plasmas are used in oxidation processes such as oxidation of cadmium telluride oxide films [16], oxidation of polysilicon in non-volatile memories [17], oxidation of silicon nitride dielectric in metal–insulator–metal capacitors [18] or oxidation of hydrogenated amorphous silicon [19]. For those applications, less ion damage is usually obtained when using an N_2O plasma rather than a pure O_2 plasma. Similarly, a rf or microwave NH_3 plasma can be used as a dry passivation process of GaAs surfaces [20] or to passivate amorphous SiC thin films for photoluminescence enhancement [21]. In addition, NH_3 plasmas are of great interest in surface functionalization of polymers for biomaterial applications [22, 23].

2. Experimental set-up

Here, the helicon double layer plasma is created in the CHI KUNG source which has been described in detail previously [9] and on which the HDLT prototype is based [12, 24]. The experimental set-up is shown in figure 1. It consists of a 15 cm diameter, 31 cm long pyrex tube surrounded by two axial solenoids (centred at $z = 1.5$ and 21 cm) and attached to a 30 cm long, 32 cm diameter earthed aluminium diffusion chamber. The closed end of the source is terminated by a glass plate. The system is pumped down to a base pressure of $\sim 2.7 \times 10^{-4}$ Pa (2×10^{-6} Torr) using a 1501 s^{-1} turbo-molecular/rotary pumping system connected to the side of the diffusion chamber. The molecular gas is injected via a chamber side port and the operating pressure in the chamber is measured

using a baratron gauge. The 18 cm long double-saddle field antenna that surrounds the pyrex tube and has been flipped horizontally and rotated anticlockwise by 90° compared with the initial DL experiment [9], is fed from a radiofrequency (rf) matching network/generator system operating at 13.56 MHz. A divergent magnetic field decreasing from about 0.013 T (130 G) in the source to about 0.001 T (10 G) in the middle of the pumping vessel is generated using equal currents of 6 A in the axial solenoids [9]. The latter are double wound and the actual current in the copper wire is 3 A. $z = 30$ cm is defined at the source/chamber interface.

A retarding field energy analyser (RFEA) is positioned on the main axis at $z = 37.5$ cm with its aperture hole about 1 cm off axis and facing the helicon DL plasma source to measure the current versus discriminator voltage $I(V_d)$ characteristic and obtain its derivative, the ion energy distribution function (IEDF), using a deconvolution method previously described [9]. The presence or not of an ion beam in the IEDF obtained with the RFEA located downstream and facing the plasma source strongly suggests that the double layer is present although conclusive evidence would be the direct measurement of the plasma potential profile along the z -axis using an RFEA or an emissive probe. This measurement has been previously carried out for argon using an RFEA [13] and showed a new class of double layers, namely a current-free electric double layer in an expanding magnetized rf plasma [9].

Electric double layers have been thoroughly investigated for the past few decades: laboratory double layers are usually classified according to the experimental system, e.g. discharge tubes with [25, 26] or without [27] constriction, anode double layer systems [28, 29], single to triple plasma devices [30, 31] and Q machines [32]. In the majority of these systems the double layers are essentially voltage or current-driven as opposed to the more recently investigated current-free (zero net current) double layers, for example in the two-electron-population expanding plasma device [33, 34] and in an expanding magnetized plasma [9]. In the present system, the main parameters corresponding to the spontaneous formation of the DL in argon are the operating pressure (less than about 0.267 Pa [2 mTorr]), the rf power (higher than a few tens of watts) and the magnetic field in the source (above about 0.005 T [50 G]). Here the typical parameters for the DL containing plasma [9] are a density of 10^9 to 10^{11} cm^{-3} , a plasma potential in the source (upstream of the DL) of 50–100 V leading to typical exhaust beam velocities of a few tens of km s^{-1} (with a typical ion temperature of about 0.2 eV measured by laser induced fluorescence), a DL potential drop of a few volts to a few tens of volts and a DL strength of 3–5 times the downstream electron temperature. The latter is about 5 eV at 0.04 Pa (0.3 mTorr).

The aim of this study is an investigation of the DL and ion beam formation using four molecular gases, nitrogen, methane, ammonia and nitrous oxide. The safety procedure for the last two gases is drastic and only a basic set of experiments are carried out. A rf power of a few hundred watts is used to couple the plasma for each propellant. The main investigated parameter is the operating pressure.

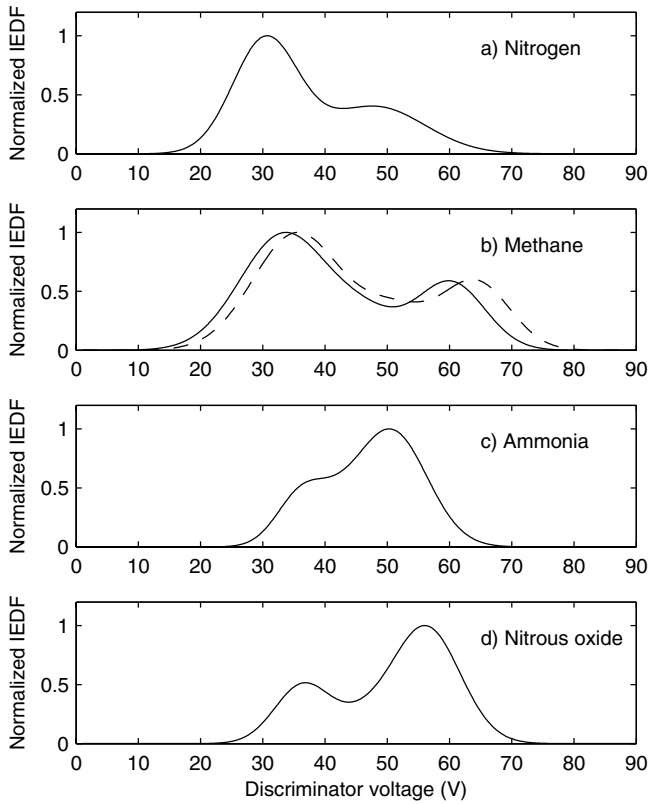


Figure 2. Normalized IEDF measured with the RFEA placed at $z = 37.5$ cm for (a) N_2 , (b) CH_4 , (c) NH_3 and (d) N_2O at an operating pressure of ~ 0.045 Pa (0.34 mTorr) and a rf power of 250 W for N_2 and CH_4 and 390 W for (c) NH_3 and (d) N_2O ; the dotted curve in figure 2(b) is the 390 W case for CH_4 . The current in each axial solenoid is 6 A and generates a dc magnetic field decreasing from about 0.013 T (130 G) in the source to about 0.001 T (10 G) in the diffusion chamber [38].

3. Results and discussion

The normalized IEDF obtained about 1 cm off the main axis at $z = 37.5$ cm for a pressure of about 0.045 Pa (0.34 mTorr) is shown in figures 2(a)–(d) for nitrogen, methane, ammonia and nitrous oxide, respectively. Each IEDF corresponds to the sum of two Gaussians not shown in figure 2 for clarity. The rf power was fixed at 250 W for nitrogen and methane, and at 390 W for ammonia and nitrous oxide. The dotted curve in figure 2(b) also shows the 390 W case for methane and the corresponding IEDFs show a shift of only a few volts between the two rf power cases.

The IEDFs corresponding to the four propellants show the presence of two peaks, a low energy peak which corresponds to a population of cold ions near the probe ($V_{\text{chamber}} = 30\text{--}35$ V) and a high energy peak which corresponds to the ion beam ($V_{\text{beam}} = 50\text{--}65$ V). It has been previously shown [9] that the high energy peak results from ion acceleration in the potential drop V_{DL} of a double layer spontaneously formed near the open end of the source and here $V_{\text{DL}} \sim (V_{\text{beam}} - V_{\text{chamber}}) \sim 15\text{--}29$ V at 0.045 Pa (0.34 mTorr). V_{chamber} and V_{beam} are, respectively, defined at the centre of the low and high energy Gaussians obtained using the deconvolution method [9]. The IEDFs obtained for nitrogen and methane exhibit a larger

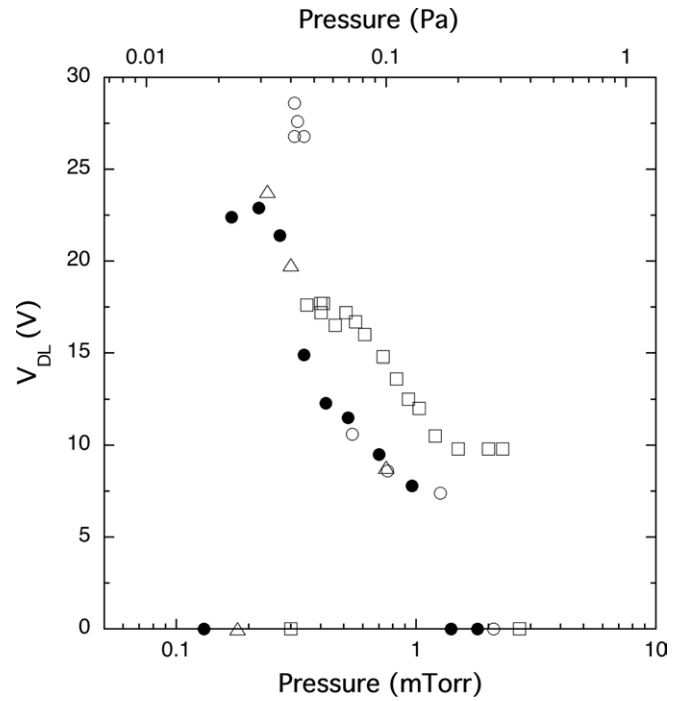


Figure 3. Double layer strength V_{DL} versus operating pressure for N_2 (open squares), CH_4 (open circles), NH_3 (black circles) and N_2O (open triangles); same rf power and magnetic field conditions as for the solid curves in figure 2.

amplitude of the low energy peak compared with that of the high energy peak, similarly to the IEDF obtained for argon for similar operating conditions [9]: in argon the double layer was created at about $z = 25$ cm, i.e. about 12 cm upstream of the RFEA [13]. For ammonia and nitrous oxide, the IEDFs exhibit a lower amplitude of the low energy peak, suggesting that the RFEA is closer to the double layer since the beam density decays exponentially along the expansion as a result of ion-neutral charge exchange collisions [35].

For each gas, a study of V_{DL} versus pressure is carried out experimentally and the results are shown in figure 3, respectively. A general trend is observed for all four gases, which is in good agreement with previous experimental [9] and theoretical [35] studies in argon: above about 0.267 Pa (2 mTorr) and below about 0.023 Pa (0.17 mTorr), no ion beam is detected and no DL solutions are analytically found. Between these two cut-off values V_{DL} increases when the pressure is decreased. The complete IEDF data set is shown for nitrogen and ammonia in figures 4 and 5, respectively (using a colour map adequate for reading in black and white). These plots show that both the ion beam energy and the ion beam/downstream plasma flux ratio increase with decreasing pressure. The results for CH_4 are similar to those obtained for N_2 . Figure 5 shows a large fraction of beam ions for NH_3 when compared with N_2 for most of the DL pressure range (0.04–0.19 Pa (0.3–1.4 mTorr)). A transition is seen at 0.04 Pa (0.3 mTorr) for NH_3 and below that threshold, the low energy peak has a much larger amplitude than that of the high energy peak similarly to the IEDF measured at about 0.13 Pa (1 mTorr) for N_2 (figure 4). This transition could result from a change in the DL position possibly associated with a change in the plasma

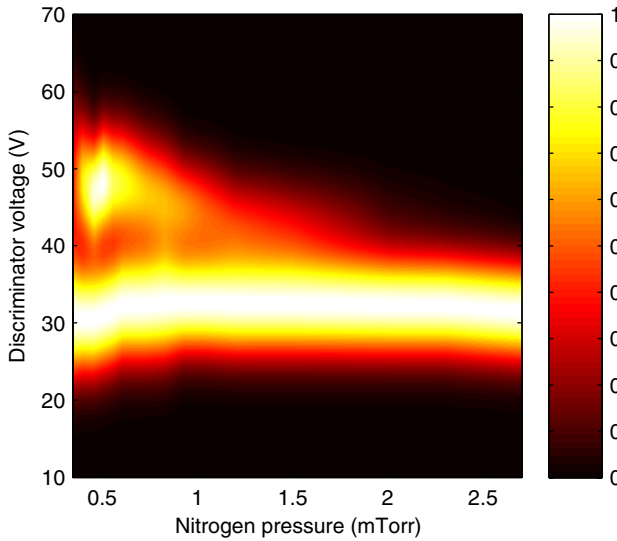


Figure 4. Normalized IEDF versus operating pressure for N₂; same rf power and magnetic field conditions as for the solid curves in figure 2; pressure range in Pascals as in figure 6.

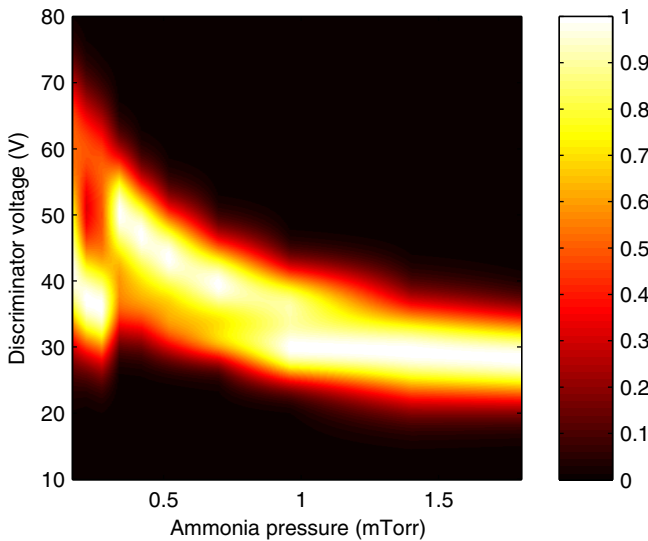


Figure 5. Normalized IEDF versus operating pressure for NH₃; same rf power and magnetic field conditions as for the solid curves in figure 2; pressure range in Pascals as in figure 6.

coupling mode/tuning and/or from a greater density gradient between both sides of the DL. Detailing the plasma coupling and the gas phase composition for each propellant by using mass spectroscopy [36, 37] is well beyond the scope of this paper and here we are primarily concerned with the presence or not of the DL and ion beam for propulsion applications. Although a fraction of the gas molecules might be dissociated by the discharge (especially for rf powers exceeding 500 W), no pressure increase was observed when coupling the plasma and, for the present operating conditions, we will assume an average ion mass equivalent to that of the molecule (28, 16, 17 and 44 g mole⁻¹, for N₂, CH₄, NH₃ and N₂O, respectively).

The ion beam energy is plotted in figure 6 for all gases. It has been previously correlated with the high plasma potential in the source [9] and the beam energy corresponds to the plasma

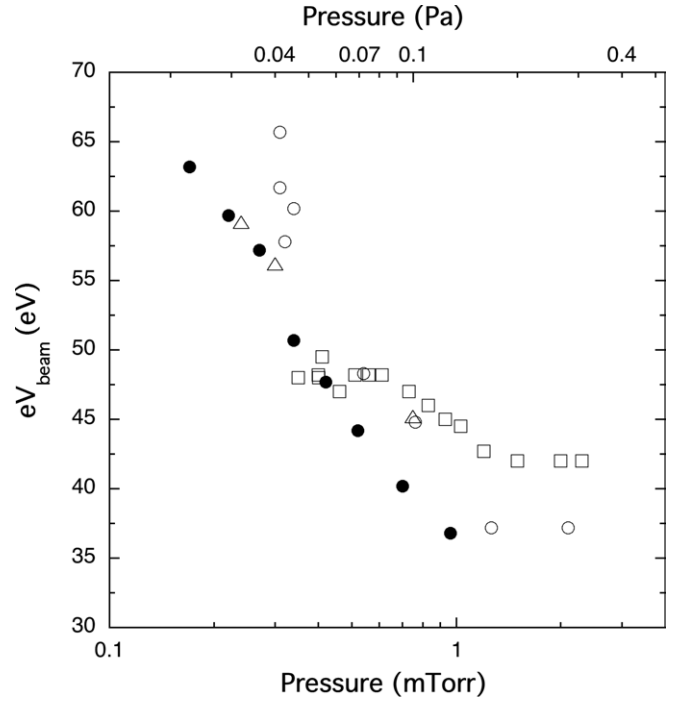


Figure 6. Ion beam energy eV_{beam} versus operating pressure for N₂ (open squares), CH₄ (open circles), NH₃ (black circles) and N₂O (open triangles); same rf power and magnetic field conditions as for the solid curves in figure 2.

potential just upstream of the double layer [38]. In calculating the ion exhaust velocity we assume that in space the potential at infinity equals the potential in the plasma source, and therefore the ions exiting the thruster gain the full plasma potential:

$$v_{\text{exhaust}} = \sqrt{\frac{2eV_{\text{beam}}}{M}}, \quad (1)$$

where e is the electron charge and M is the ion mass. The ion exhaust velocity is, respectively, plotted in figure 7 for all gases. The exhaust beam velocity ranges from 17 to 19 km s⁻¹ in N₂, 21 to 27 km s⁻¹ in CH₄ and NH₃ and 14 to 16 km s⁻¹ in N₂O. It can be seen that the operating pressure range can be considered similar for all propellants. On first approximation the velocity scales with the square of the ion mass for a constant geometry and magnetic field structure. Previous studies have shown that a change in the system geometry [35, 39] or in the magnetic field structure [9, 40, 41] will also significantly affect the ion beam exhaust velocity. The characteristics of the ion beam versus operating pressure closely follow those previously obtained in hydrogen [6], suggesting that the HDLT could successfully operate with the ammonia-derived chemical compound hydrazine (N₂H₄), the standard though highly toxic chemical rocket fuel.

A telecommunications spacecraft of 4000 kg at launch typically embarks 2000 kg of hydrazine and nitrogen tetroxide propellant for a lifetime of 10 years. The usage of this fuel is practically three quarters for transfer from geostationary transfer orbit to geostationary orbit and one quarter for keeping station on the geostationary position over 10 years, which requires typically a velocity increment of 50 m s⁻¹ per year. At

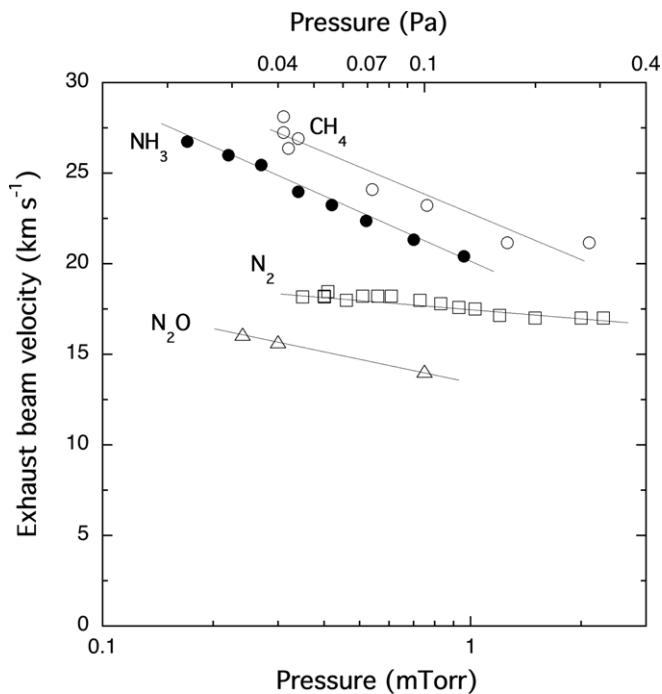


Figure 7. Exhaust beam velocity v_{exhaust} versus operating pressure for N_2 (open squares), CH_4 (open circles), NH_3 (black circles) and N_2O (open triangles); same rf power and magnetic field conditions as for the solid curves in figure 2; the straight lines serve as a visual guide only.

the end when all the propulsion systems cease to operate, the satellite starts drifting in an inclined orbit and transmission has to cease to avoid perturbing other satellites' transmissions. It is also a requirement that at the end of its life the satellite shall be moved to a graveyard orbit at least 100 km higher than the operational geostationary orbit. Such a manoeuvre requires enough fuel to give an increment of velocity of 10 m s^{-1} to the satellite. In practice on a satellite of the class outlined above, the station keeping is provided by chemical bi-propellant systems which stop operating when one of the two components run out and large bubbles of gas are injected into the propulsion motors. At this point the pressure in the tanks is around $3 \times 10^5 \text{ Pa}$ (3 bar) and between the liquid left on the surface of the empty tank, that left in the other tank which has not yet run dry and the pressurant gas, there are some 15–20 kg of unused liquid and gas. Using such a mass of residual fluid in an engine giving an effective specific impulse of 800 s provides for 60–80 m s^{-1} of velocity increment at the end of the chemical propulsion life which equates to an additional year of useful operations and safe placement in the graveyard orbit.

Although a more complete study is needed for the further understanding of the NH_3 and NO_2 double layers in particular, preliminary results obtained with a lower magnetic field (solenoid current of 2 A instead of 6 A), a rf power of about 390 W and a pressure of about 0.033 Pa (0.25 mTorr) show no ion beam and no DL in agreement with previous results [38]: a transition from a simple expansion to a double layer containing plasma expansion has been measured in argon for a solenoid current between 2 and 2.5 A. For a pressure of

about 0.033 Pa (0.25 mTorr) and a solenoid current of 6 A, a higher rf power of about 540 W showed a DL potential drop of 22 V for NH_3 (compared with 21.4 V at 390 W) and 27.3 V for NO_2 (compared with 23.8 V at 390 W), respectively; at 250 W, the drop was 15.5 V for NH_3 and surprisingly, no ion beam was observed for NO_2 . Except for the latter result all measurements seem to indicate that the main parameter requirements (pressure, rf power, magnetic field) for DL formation are rather similar to those previously obtained in argon: for the present magnetic field conditions and an operating argon pressure of about 0.04 Pa (0.3 mTorr), the ion beam density was found to increase linearly with rf power in the 200–1200 W range with a corresponding DL potential drop decrease of only 5 V. Although the prevailing paradigm is that the DL is formed directly by the magnetic nozzle [40], the geometric expansion is a parameter which has to be taken into consideration [35, 39]. In addition, the higher ion beam/downstream plasma flux ratio measured for NH_3 and for NO_2 compared with N_2 , CH_4 and argon could result from a DL location closer to that of the RFEA and/or from a greater density gradient between the two edges of the DL. These results suggest that the gas type adds a degree of complexity to the current-free helicon double layer.

4. Conclusion

The present experimental results demonstrate the ability of the HDLT to operate with various types of chemicals allowing new opportunities for future space mission. In particular the HDLT could generate thrust from manned spacecraft refuels without tapping on the precious classical fuel. On commercial spacecraft chemical thrusters stop operating at relatively high pressure of a few bars, and at the end of a mission there is a significant mass of fuel and pressurizing gas left in the tanks. With the addition of an HDLT which operates at very low pressure for various types of propellants, these normally unused residual liquids and gases can be used to provide additional velocity increment, thereby allowing the nominal mission to be extended to the 'last drop of fuel' with the capability to still be able to de-orbit the spacecraft. The experimental results also suggest that plasma-surface deposition or activation processes which could benefit from complex ions or neutral beam can be envisaged.

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