Helicon Double Layer Thruster Performance Enhancement via Manipulation of Magnetic Topology

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The thrust and plasma parameters generated by a Helicon Double Layer Thruster operating at a power level of 250 W with krypton propellant has been evaluated for peak magnetic field strengths of 0 to 270 G. Results show that the thrust levels achieved are dependent on the position of peak magnetic field in relation to the plasma source. Alignment of peak field strength with the plasma source exit produces higher thrust levels compared to identical test conditions where the location of peak field strength occurs near the rear of the plasma source. Thrust and plasma number density increases with increases field strength for the test conditions investigated. A maximum thrust of 4.0 ± 1.1 mN was measured for $B_{peak} = 150$ G. Plasma parameters determined with the use of a non RF compensated Langmuir probe demonstrate number densities of the order of 10^{16} m^{-3} in the thruster plume and corresponding electron temperatures of approximately 5 eV.

I. Introduction

The Helicon Double Layer Thruster (HDLT) is an electrode free radio frequency power driven device described in detail in Reference.[1] This relatively new propulsion device provides a means of generating thrust without the use of a system of grids to extract and accelerate ions. The exhaust plasma is macroscopically neutral, therefore an external beam neutraliser is not required. The ions generated by the HDLT have energies in the range of $10 - 100$ eV[2] which is approximately an order of magnitude lower than the exhaust ion energies of Hall effect thrusters and electron bombardment ion thrusters.[3] As a result thruster channel erosion rates are reduced and the likelihood of damage to spacecraft surfaces due to sputtering by high energy ions is reduced. These characteristics have established the HDLT as a possible alternative propulsion system for missions requiring extended lifetimes.

At this early stage of HDLT development investigations have primarily concerned plasma characterisation and gaining insight into the fundamental physics of operation of the device. The thrust generation mechanism for the HDLT has yet to be identified. Theories exist which state that electrostatic pressure i.e. ion acceleration across the double does not contribute to generating thrust but rather the combination of

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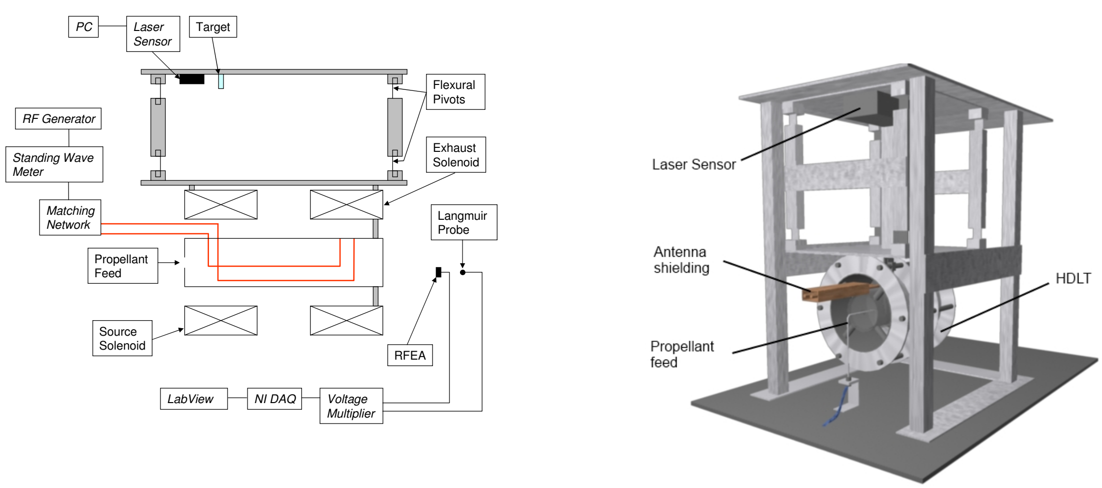
magnetic field pressure and plasma pressure are responsible.[4] It has been stated in literature that the thrust generated by helicon discharges may be described in terms of plasma density, electron temperature and the cross sectional area of the plasma source at its exit.[5,6] The use of plasma nozzles is well established in spacecraft propulsion. The force exerted by magnetic fields on a discharge generates a directed plasma flow and force is imparted as ions detach from the magnetic field.[7–9] Investigations have shown that magnetic fields not only act as nozzles but can also influence plasma characteristics. Experiments using layered permanent magnets to produce the desired field has shown increasing field strength increases ion beam energy and hence thruster performance up to a saturation point. Plasma characteristics were shown to be insensitive increases in field strength above a peak strength of 200 G for a 250W argon discharge.[10] Evaluation of the impact of peak solenoid field strength for a HDLT with a source tube diameter of 150 mm and length 310 mm demonstrated increasing ion beam energy as the peak exhaust field strength was increased from approximately 60 G to 240 G, the authors proposed that manipulation of field strength may be used to throttle thruster performance.[11] Experimental investigations have shown that double layer strength is insensitive to variations in operating power[12] and magnetic field.[10] However, the potential drop across the double layer and corresponding ion beam energies has been shown to increase with decreasing diffusion chamber pressure but double layer strengths saturate above a threshold of $7T_e$.[2] Therefore, as a means of improving thruster performance options for increasing double layer strength are limited if deemed to play any role in thrust generation.

Considering these factors an obvious focus area for HDLT performance enhancement is the identification of optimal magnetic field topologies that provide maximum double layer strength and ion beam current. Initial assessment of the thrust produced by laboratory model HDLTs operating with electromagnets[12] and permanent magnets[13] have demonstrated levels up to 3 mN for maximum RF input powers of $\sim$ 700 W for peak field strengths of 100 G and 200 G respectively with krypton and argon propellants. The current investigation compares the thrust and plasma parameters generated for various magnetic field topologies for a fixed RF input power and propellant flow rate. Trends between thruster performance and peak field strengths are presented.

II. Experimental Apparatus



(a) Schematic of experimental set up (not to scale)

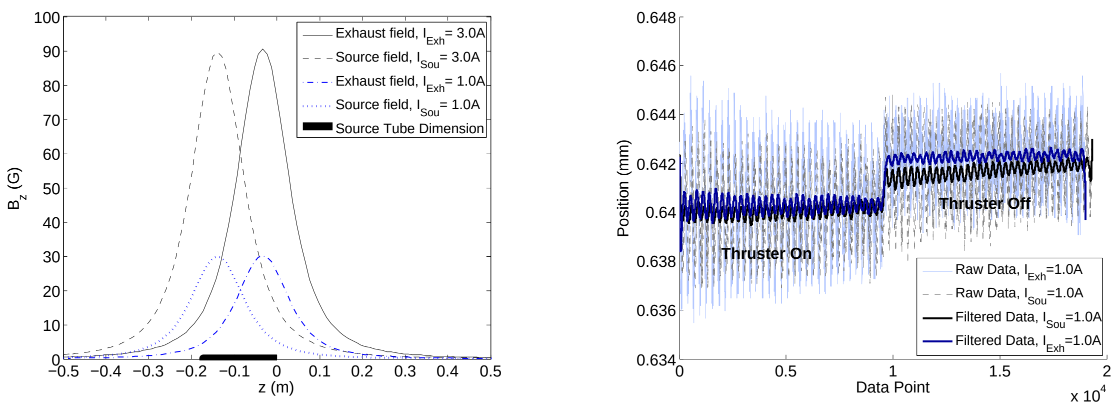
(b) HDLT mounted on thrust stand rear view

Figure 1. Experimental set up

Figure 1 shows a schematic of the experimental apparatus used in the current investigation. A plasma source tube with an outer diameter of 80 mm, inner diameter of 75 mm and length 172 mm is mounted within a solenoid former. The exhaust solenoid terminates flush with source tube exit and the rear of the source solenoid is flush with the rear of the plasma source. A double saddle antenna is used to drive power deposition at a frequency of 13.56 MHz. To ensure maximum power deposition to the plasma an RF circuit consisting of a matching network, standing wave meter and RF generator is tuned to enable maximum forward power to the discharge. The HDLT is mounted onto a pendulum type thrust stand (see Fig. 1(b)), the propellant feed line and antenna are mechanically isolated from the thruster in order to minimise damping of the system. Electrical harnessing to the solenoid, which are the only physical connection to the thruster/thrust stand system consist of flexible wiring in coil configurations to minimise frictional forces. The thrust stand is calibrated using a stepper motor controller to displace a known mass in order to determine thrust stand displacement for a given applied force. The resulting displacement is determined via triangulation by a laser optical displacement sensor that is mounted on the thrust stand.

The thrust generated by a non optimised laboratory model HDLT has been determined using the experimental set up described above for peak magnetic field strengths up to 270 G. The magnetic field is supplied by either the exhaust or source solenoid. Plasma parameters on the central axis of the HDLT plume have been determined using a non RF compensated Langmuir probe[14] and retarding field energy analyser (RFEA). The following section presents data for a fixed RF input power of 250 W and propellant flow rate of 16 sccm (1 mgs^{-1}) of krypton.

III. Experimental Results



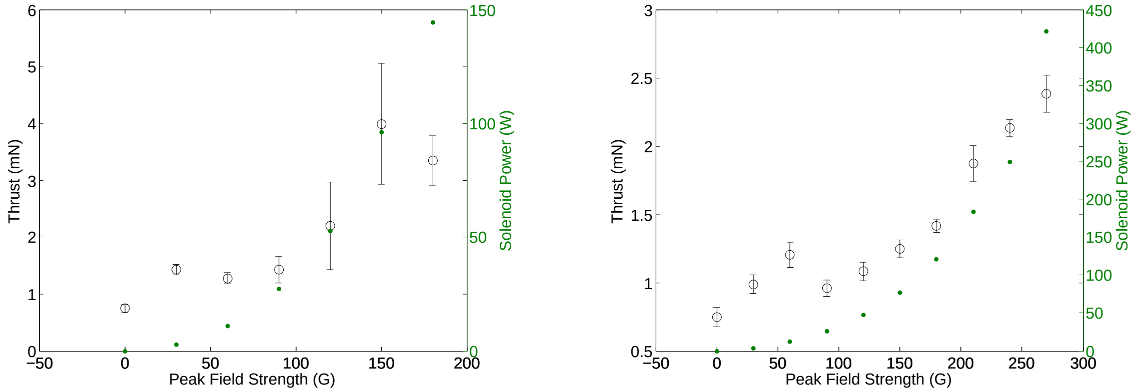
(a) Comparison of peak axial magnetic field strengths for applied solenoid currents of 1.0 and 3.0 A, peak positions are relative to the HDLT source tube with $z = 0$ at the source exit

(b) Representative raw data from laser sensor outputs for two magnetic field configurations producing 1.13 mN for $I_{Exh} =$ 1.0 A (blue line) and 0.96 mN for $I_{Sour} = 1.0$ A (black line) for P = 250 W

Figure 2. Axial magnetic field strength and representative raw data

The axial magnetic field distribution for applied currents of 1.0 and 3.0 A are shown in Fig. 2(a) for the exhaust and source solenoids. The exhaust solenoid consists of a 335 turn magnet while the source solenoid is comprised of 440 turns of copper wire with a diameter of 1.4 mm. Figure 2(a) shows the change in axial position of peak field strength in relation to the geometry of the source tube as well as the increasing magnitude of field strength with increasing applied current. The output of the laser displacement sensor shown in Fig. 2(b) demonstrates the change in relative position of the thrust stand for the HDLT firing compared to the null position corresponding to thruster off. A calibration factor is applied to the resulting displacement to determine the thrust produced, see Fig. 3.

The thrust generated by the HDLT demonstrates the general trend of increasing magnitude with increasing applied magnetic field strength. The level of thrust produced is sensitive to the position of peak field strength as increases in exhaust field strength result in a greater rate of increase in thrust relative to increases in source field strength. For a peak field strength of 180 G the thrust produced with the use of the exhaust solenoid is approximately double that achieved using the source solenoid. This may be explained qualitatively by the distribution of field lines within the plasma source. Optimal performance is expected when field lines do not intercept the boundaries of the plasma source as losses of ionised species and electrons to the source walls will be minimised, electron lifetimes will be increased which may aid collisional excitation and ionisation processes within the source resulting in increased ion fractions and thrust.



(a) Thrust as a function of increasing exhaust field strength (b) Thrust as a function of increasing source field strength

Figure 3. Thrust (open circles) and solenoid power (filled green circles) as a function of increasing peak axial magnetic field strength for an RF input power of 250 W with a propellant flow rate of 16 sccm of krypton.

Figure 4 shows the current collected by the RFEA as a function of discriminator voltage and the corresponding ion energy distribution function. The probe was placed on the thrusters central axis 10 cm downstream of the source exit. A plasma potential of 26.0 V is obtained which shows good agreement with Langmuir probe data. The ion energy distribution function clearly shows a secondary ion population representative of ion acceleration by a double layer, indicating that the phenomena is present for peak field strengths as low as 30 G.

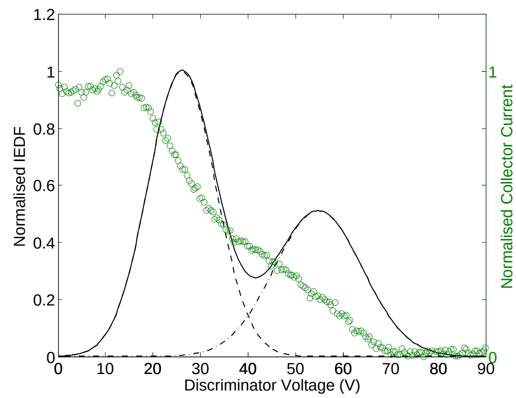
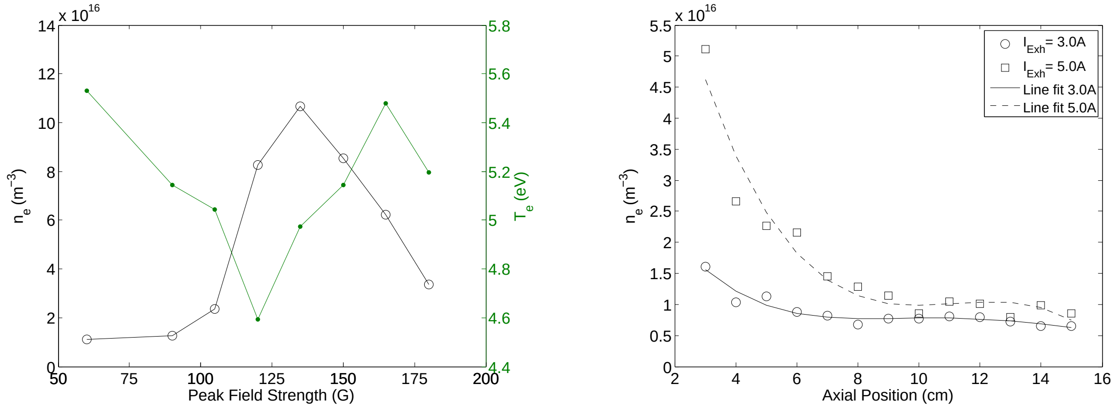


Figure 4. Current voltage characteristic (circles) for an applied source solenoid current of $I_{sou} = 1.0$ A, resulting ion energy distribution function (−) and Gaussian fits to raw data (−−,− · −) with $V_P = 26.0$ V and $V_{Beam} = 54.8$ V

The relationship between field strength, electron temperature, number density and axial position is explored in Fig. 5. There is a a rapid increase in number density for field strengths greater than approximately 100 G peaking at $n_e = 1 \times 10^{17}$ m^{-3} for 135 G after which density decreases. Conversely the electron temperature decreases achieving a minimum of $T_e = 4.6$ eV at 120 G. The axial profile of the number density on the central axis of the HDLT plume displays decreasing density with increasing distance from the plasma source as expected, see Fig. 5(b). Increasing peak magnetic field strength from 90 to 150 G corresponding to an applied current of 3.0 and 5.0 A respectively results in increased number density for all axial positions investigated. The observed increase in number density for $B_{Peak} = 90$ G to $B_{Peak} = 150$ G corresponds to an increase in thrust from 1.4 ± 0.6 mN to 4.0 ± 1.1 mN. It should also be noted that other factors may influence the magnitude of thrust produced by HDLTs including plasma source geometry and propellant flow rate, these parameters are beyond the scope of the present investigation.

IV. Conclusion

The performance of a non optimised laboratory model HDLT has been characterised for various magnetic field configurations. The thrust determined via direct thrust measurements in 30 G increments from zero to 180 G and zero to 270 G for the exhaust and source fields respectively shows increasing thrust levels with increasing magnitudes of peak field strength. Alignment of the region of peak field strength to locations near the exit of the plasma source was shown to increase the thrust levels attained. RFEA and Langmuir probe measurements demonstrate the presence of a high energy ion population and show decreasing number



(a) Number density (open circles) and electron temperature (filled green circles) in the HDLT plume 30 mm downstream of the source exit for various exhaust field strengths

(b) Number density profiles for applied exhaust solenoid currents of 3.0 A (circles) and 5.0 A (squares) corresponding to 90 G and 150 G respectively

Figure 5. Plasma parameters for varying peak exhaust field strength and axial position for an RF input power of 250 W with a propellant flow rate of 16 sccm of krypton.

densities with increasing distance from the plasma source.

The results presented indicate that HDLT performance may be enhanced by judicial use of magnetic field topologies but a trade off exists between the peak field strength achieved and power consumption of electromagnets. Future work will focus on improving the thrust to power ratio of the HDLT. The thrust generation mechanism of the thruster should also be identified in order to assess the relative importance of specific processes regarding plasma generation and acceleration.

Acknowledgments

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