Thrust Measurements of a Small Scale Helicon Double Layer Thruster

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Abstract: The Helicon Double Layer Thruster (HDLT) uses a helicon plasma source to generate ions which are subsequently accelerated across a spontaneously forming double layer potential. Convenient scalability of this technology has been postulated based on the occurrence of double layers in planetary aurora, solar flare phenomena and laboratory plasmas. Thrust measurements of HDLT devices of different sizes is currently under investigation in order to find the dominant ion acceleration mechanism at each scale and assess the fundamental physics of operation, with the aim of determining routes to performance optimisation. Recent experiments at the Australian National University suggest a link between thermal ion magnetisation and the formation of an ion beam through ion energy distribution measurements in a system of similar geometry to the HDLT. Here, initial experiments to examine the effect of ion magnetisation on thrust levels through direct thrust measurements is presented for an imposed magnetic field of 0-110 G with 200 W of input RF power. Thrust levels are shown to increase linearly to a maximum of 0.62±0.03 mN followed by a sharp decrease in thrust at higher values of peak magnetic field strength.

I. Introduction

Miniaturisation of satellites and their payloads pioneered by Surrey Satellite Technology Ltd and the Surrey Space Centre, has led to the emergence of highly functional low cost satellites. The reductions in mass and cost afforded by the use of resistojets in place of standard chemical propulsion technologies has led to widespread use on board many small satellite platforms[1].[2] The increasing capabilities, higher power platforms and success of small satellites has spurred interest in miniaturisation of more advanced propulsion technologies in the hope that higher performance over the resistojet may be found. A new class of plasma thruster employing the simple generation of a radio-frequency (RF) wave excited plasma and subsequent ion acceleration to form a quasi-neutral exhaust plume has been the subject of both theoretical and experimental interest. The lack of complex parts such as acceleration grids or neutralising hollow cathodes, and the efficiency with which RF plasmas may be generated motivate the pursuit of miniaturisation of this technology

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for use on board small satellites. This simple and robust mechanical design may also be suitable for missions requiring long operational lifetimes. Laboratory models of the Helicon Double Layer Thruster (HDLT) have demonstrated the formation of low divergence supersonic ($\sim 2.1C_s$) ion beams downstream of a spontaneously forming current free double layer using a range of atomic and molecular propellants[3].[4] This has led to the suggestion of using the HDLT as a deorbiting/orbit maintenance technology utilising residual fuels.

Similar thrusters not explicitly invoking a current free double layer as an ion acceleration stage have received theoretical and experimental treatment. Limits to thrust production of 5-20 mN for $P_{rf} \sim$ 500-2000 W[5] based on energy balance relations have been derived, as well as empirical measures of ionisation fraction[6](often quoted as near 100 %) for simple expanding (in some cases helicon antenna excited) plasmas.[7] Across the range of expanding RF plasma thrusters there are a number of mechanisms cited for the production of thrust, including ambipolar diffusion and detachment of plasma, magnetic nozzle acceleration, and "single layer" sheath acceleration.[8] Much work has been done to characterise the ion energy distribution of the HDLT under a range of experimental conditions as well as theoretical and experimental treatments of the formation of current free double layers which has led to an increased understanding of the possible mechanisms of thrust production[9].[10]

A study recently conducted at the Australian National University demonstrated a possible link between the formation of a double layer ion beam and the magnetisation of upstream thermal ions[11] which may have interesting implications to the scaling of the thruster to smaller geometries, as this would provide a simple way to initiate ion beam formation given the source tube radius. These experiments were performed across a range of plasma source tube sizes (4.6-15 cm internal diameter) across two different experimental devices, the ElectroMagnets ex-panding Plasma machine at Iwati University (EMPI)[12] and the Chi-Kung device of the Australian National University. Both devices take the form of source tubes of various diameters attached contiguously to a diffusion chamber, rather than a fully immersed thruster system. It was postulated that the decrease in wall losses, as a result of the radial ion constriction, leads to an increase in plasma density gradient at the source tube exit. Double layer formation generally increases the density of the plasma just upstream of the high potential side as electrons are accelerated into the source tube region increasing ionisation in that area.[13] The aim of this investigation is to assess the impact of ion magnetisation on the thrust generated by a small scale HDLT through direct thrust measurements, in order to increase understanding of the thrust mechanisms present in the HDLT and guide future design of optimised thrusters at small scales. This paper presents initial experiments to examine the effect of magnetic field strength on thrust levels achieved by the fully immersed "mini-HDLT" through direct thrust measurements for an imposed magnetic field of 0-110 G with 200 W of input RF power.

II. Experimental Apparatus

Previous attempts to indirectly measure thrust levels of the HDLT and similar devices have focused on paddle-ended pendulums, onto which the exhaust plasma is impinged.[14] Here, direct measurements are made using a thrust stand custom built at the Surrey Space Centre (SSC). The thrust stand, shown in Fig. 1 is comprised of a fixed plate from which a moving plate is suspended and together form a simple pendulum. The thruster and a reflective target is attached rigidly to the moving plate and using a triangulation laser, which is accurate to 0.1 μm, the displacement between the fixed and moving plate can be measured. The thrust stand has received extensive characterisation in terms of force response and plasma noise interaction.[15] The Mini-HDLT is composed of a 40 mm inner diameter, 172 mm long quartz tube, which is supported at the centre of two solenoid formers. About the formers are two independently controllable solenoids, capable of generating magnetic fields of up to 400 G at

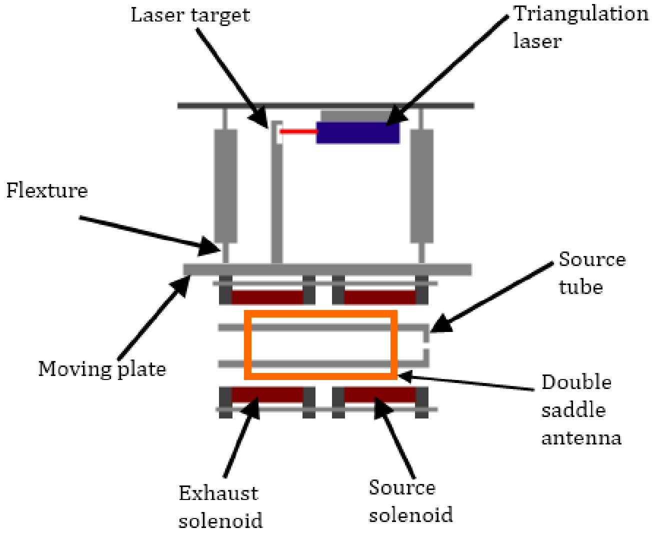


Figure 1: Plan view of the HDLT mounted on the SSC thrust stand.

the mid point of the source tube. Electrical connections to the solenoids are made through insulated thin flat copper straps which run between the fixed plate and the moving plate. These connections were found to have a minimal effect on the free movement of the pendulum system.

A double saddle antenna coated in boron nitride and connected to a Pi matching network supplies 13.56 MHz RF power to the plasma. Propellant is introduced through a 5 mm diameter hole at the centre of the back of the source tube and is fed through a stainless steel pipe which is not connected rigidly to any part of the thruster. The propellant flow is controlled by a Bronkhurst flow controller capable of delivering up to 200 sccm of gas. The experiments were carried out inside the "Pegasus" vacuum testing facility which consists of a 1x1x1.2 m chamber connected to a turbo molecular pump, which has a pumping speed of 1800 l/s. The system is capable of a base pressure of 0.007 mTorr, however for these experiments the pressure was maintained at 0.6 mTorr by introducing an Argon flow of 70 sccm.

III. Methodology

A. Thrust Stand Calibration

The above apparatus was assembled, ensuring that the movement of the moving plate was mechanically isolated from the antenna and propellant feed. Calibration of the thrust stand was carried out by suspending a known mass from the moving plate by a cotton line of fixed length. The mass was then moved parallel to the moving plate through a fixed displacement using a stepper motor and a pulley system and then returned to its resting position a total of two times for one data set (see Fig 2). This procedure was then repeated 10 times. Figure 2 shows unfiltered calibration data and the results of a low pass filter, demonstrating the minimal impact of the filtering process on the displacement data. The calibration factor was found to be 0.421 mm/N for an applied calibration force of 2.84 mN.

B. Thrust Measurements

The diffusion chamber pressure in the EMPI experiment was maintained at 0.6 mTorr for the 4.6 cm outer diameter source tube using Argon propellant, which in the SSC vacuum chamber, corresponds to a propellant flow of 70 sccm. The input RF power was maintained at 200 W throughout the experiment as per the EMPI experiment and care was taken to ensure less than 1 W was reflected. To replicate the magnetic field conditions, both source and exhaust solenoids were used for each measurement, and the input current was increased from 0-3.5 A per solenoid in 0.5 A increments, which corresponds to a combined peak source region field strength of 0-110 G. Before thrust measurements were made, the natural thrust stand oscillations were allowed to damp to an amplitude of under 0.1 mm. The plasma was initiated and tuned and data was acquired for a total of 120 s, deactivating the thruster at t =40 s, and the solenoids at t =80 s. This process is then repeated 10 times, for each field strength. A butterworth low pass filter was used to remove the thrust stand's natural oscillation in order to aid visual inspection and allow identification of the "thruster off" point in order to ensure that the thrust stand displacement is due to thruster operation and not an erroneous measurement. The displacement is found by calculating the zero point crossing of the corresponding derivative of the data (see Fig 3b) to accurately find the inflection points of the step transitions.

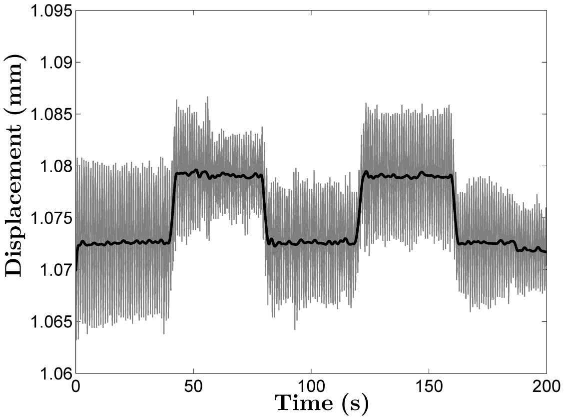
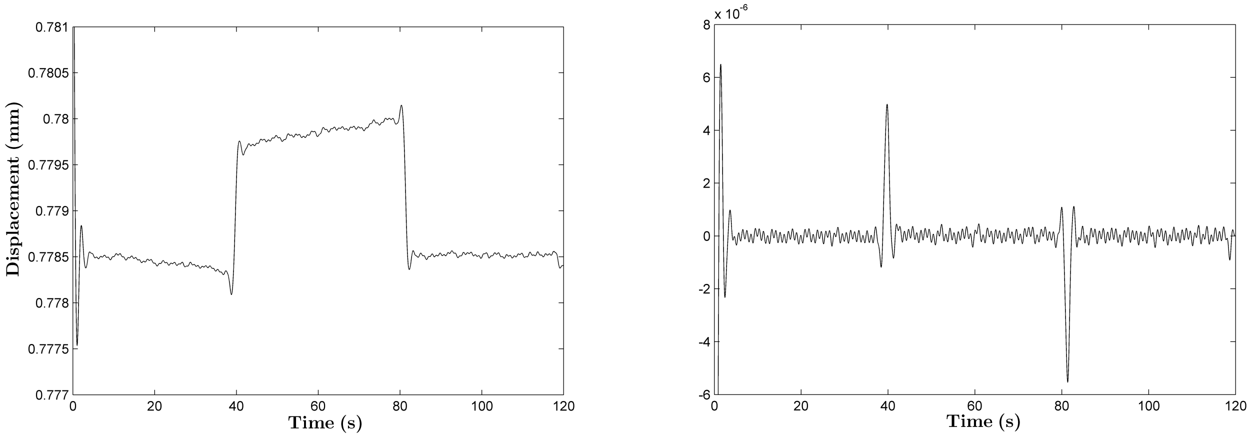


Figure 2: Example of filtered (black) and unfiltered/raw (grey) calibration data.

IV. Results

Figure 3 shows an example of the thrust data collected during the experiments. The thruster is active between t= 0 s and t=40 s. A clear change in moving plate displacement at the point which the thruster is deactivated can be seen at t=40 s. At t= 80 s the solenoids are deactivated and a displacement can be seen due to an ampere force between the solenoids' electrical connections which run between the fixed and moving plate.

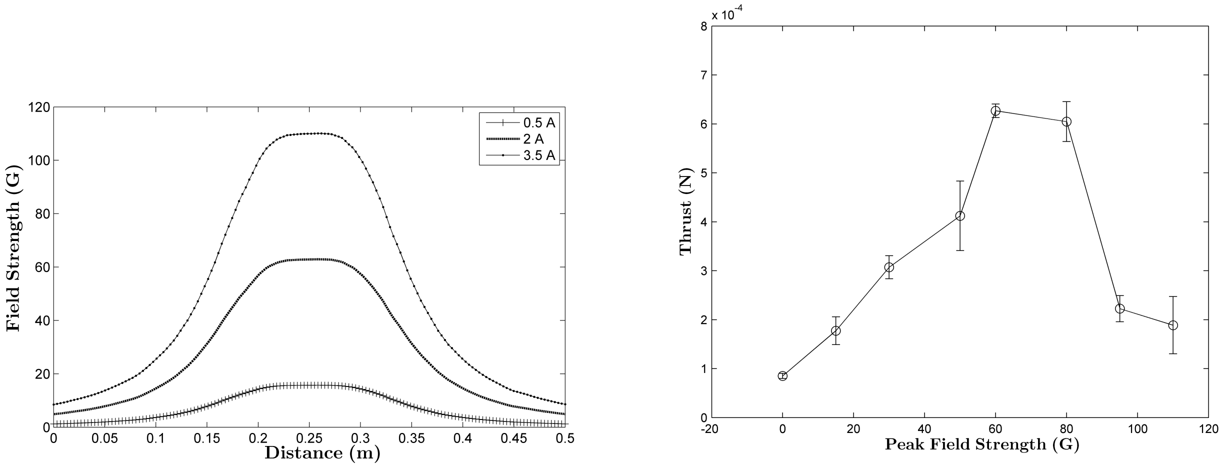


(a) Filtered displacement data

(b) Derivative data

Figure 3: Filtered and derivative data for 80 G imposed field. The drift in displacement present in (a) was prevented from skewing the thrust data by finding the zero intersect in the derivative data to ensure the true displacement is measured.

Figure 4a shows the axial magnetic field profile inside the source tube, which achieves its peak at ∼0.25 m. This preliminary study used a maximum field strength of ∼110 G. In the original ANU study, a field strength of 195 G was found to trigger the transition to a double layer supporting plasma and thus the formation of an ion beam for the 4.6 cm diameter source tube. Figure 4b shows a linear increase of thrust with increasing field strength up to a maximum of 0.62 ± 0.03 mN. Previous investigations into HDLT thrust levels have been conducted using both a paddle ended pendulum[14] and a pendulum thrust stand[16].[17] Takahashi reported thrust levels of ∼0.7 mN at 200 W using a higher field of ∼ 200 G and a 6.4 cm source tube and a comparable pressure of 0.6 mTorr. The slightly higher thrust obtained by Takahashi may be attributed to the higher magnetic field used, although the nearly linear trend shown in figure 4 suggests that only marginally higher fields may be needed to match the performance, and does not account for the large difference in field strength. The use of permanent magnets and the presence a cusp point in the source tube region[12] may modify the ion current exiting the source tube, although ion energy distribution measurements would be required to confirm this. Measurements carried out by West[18] produced thrust levels of 57 μN for a 15 cm diameter source tube, 100 W of RF input power, a higher field strength of 138 G and a background pressure of 0.38 mTorr. The thrust versus power results of Pottinger[16] show that a power increase of 100 W leads to ∼0.3 mN increases in thrust for a 0.4 mTorr, 100 G magnetic field plasma generated in a 8 cm diameter source tube, which suggests that large differences in the thrust levels between the experiments of West and those reported in this investigation are likely not due to differences in power levels. Without measurements of the electron temperature and ion beam energy distribution of the plasma used in the current study the cause of the discrepancies cannot be explained since the formation of double layers are heavily dependant on the pressure[10] and magnetic field[1911] used to generate the plasma. The fields used in this study are not sufficient to fully magnetise the thermal ions and the larmour radius can be calculated as 66.5 mm, assuming an ion energy of 0.2 eV[11] using $R = v_i\omega_i$, where v_i and ω_i are the ion thermal velocity and the ion gyro-frequency respectively, which means the the current study does not satisfy the criteria for double layer formation documented by Takahashi. There is no evidence in this study to suggest the presence of a current free double layer according to all metrics found in the literature therefore acceleration may be due to more fundamental forces such as area expansion/ambipolar diffusion, however langmuir probe measurements are required to verify this hypothesis. The sharp decrease in thrust levels seen at field strengths higher than ∼60 G are currently unaccounted for and future experiments will repeat these measurements over a wider range of field strengths in order to confirm this trend.



(a) Magnetic field profiles

(b) Mean thrust versus peak field strength

Figure 4: Thrust versus peak field strength for 70 sccm propellant flow (background pressure 0.6 mTorr), 200 W RF power. The error bars represent the standard deviation centred about the data point.

V. Conclusion

The effect of the imposed magnetic field strength from 0-110 G on the thrust produced by a small scale HDLT of source tube diameter of 40 mm was investigated. Thrust was shown to increase linearly with increasing magnetic field strength to a maximum of 0.62 ± 0.03mN for 200 W input power and a $\sim$60 G imposed magnetic field with 70 sccm of Argon propellant flow. This compares well with the $\sim$0.7 mN at 200 W thrust levels measured in[17] using a pendulum type thrust stand and a permanent magnet HDLT although discrepancies in the strength of the magnetic fields are unaccounted for. The effect of full ion magnetisation on the thrust levels was not measured in this investigation, further experiments to conclude this study will extend the upper range of magnetic fields used up to 200 G, as well as record ion energy distribution functions, electron temperatures and plasma density using a langmuir probe in order to directly compare thrust levels with those found in the literature.

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