

Performance Characteristics of a 5 kW Laboratory Hall Thruster

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ABSTRACT

The University of Michigan and United States Air Force Research Laboratory have jointly developed a 5 kW class Hall effect thruster. This thruster was developed to investigate, with a variety of diagnostics, a thruster similar to that specified by IHRPT goals. The configuration of this thruster is adjustable so that diagnostic access to the interior of the thruster can be provided as necessary, and to allow for the exploration of various thruster geometries. At nominal conditions, the thruster was designed to operate at 5 kW with a predicted specific impulse of 2200 s. The actual operating parameters at 5 kW were 2326 s specific impulse, with 246 mN of thrust at an efficiency of 57%. These conditions are comparable to those of thrusters under commercial development, making the information learned from the study of this thruster applicable to the understanding of its commercial counterparts.

INTRODUCTION

Current generation Hall thruster research has concentrated primarily on the 1.5 kW class of thrusters since they have been of primary interest for commercial and military satellite use. However, as indicated by industry trends and IHRPT goals, the Hall thruster market is expanding beyond the 1.5 kW class thruster to both sub-kW thrusters for small satellites and high power thrusters for orbit transfer missions. Of particular interest for orbit transfer are thrusters of the 5 kW class. Several commercial thrusters, including the SPT-140¹ and T-160² stationary plasma thrusters and the D-100³ anode layer thruster, are under development for this role. In order to keep their research as relevant as possible to future Hall thruster users, the University of Michigan and the United States Air Force (USAF) are moving toward studies of 5 kW class Hall thrusters. Unfortunately, from a research standpoint, 5 kW

Hall thrusters are few in number at this time; and those that do exist are intended primarily for flight qualification use and are not well suited for basic research purposes.

With these facts in mind, the University of Michigan and the USAF decided to jointly develop a 5 kW class Hall thruster for basic research purposes. The goal was to develop a thruster that would be well suited for diagnostic access, particularly internal diagnostic access, so as to gain a better understanding of the basic physics of its operation. Additionally, the thruster would be easily modifiable so that the effect of changes in thruster configuration could be examined. This thruster would also remain permanently in the possession of the University of Michigan and USAF, allowing the undertaking of uninterrupted long term research projects.

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With its 6 m X 9 m Large Vacuum Test Facility (LVTF), the University of Michigan is uniquely qualified among American universities to study a large, high power Hall thruster. The USAF is currently building a 10' X 24' vacuum chamber at their new Edwards AFB facility which will be dedicated primarily to high power Hall thruster research.

The design of the thruster was a three step process. First, an analysis of Hall thruster characteristics⁴ was used to determine the nominal diameter and specific impulse, as well as the predicted thrust and efficiency, of a 5 kW class thruster. The result of this analysis was a thruster discharge chamber diameter of 169 mm with a nominal specific impulse goal of 2200 s. This I_{sp} is near the IHRPT specified goal for thrusters on orbit transfer missions. Second, stationary plasma thruster design equations⁵ were used to determine the other hall thruster dimensions (discharge chamber width, discharge chamber depth, pole separation, etc.) with respect to the thruster diameter. The decision to build a stationary plasma thruster, as opposed to an anode layer thruster, was based on a greater familiarity with SPT design methods and on the wider discharge chamber which would allow greater interior diagnostic access. Finally, based on the expected necessary magnetic field requirements, QuickField™ 3.4 - a 2 ½ dimensional magnetic field code - was used to determine a lower bound on the size of the magnetic pole pieces, cores, and screens so as to avoid magnetic saturation. A comparison of predicted and measured magnetic field strengths is shown in Figure 1. Negative distance is into the discharge chamber.

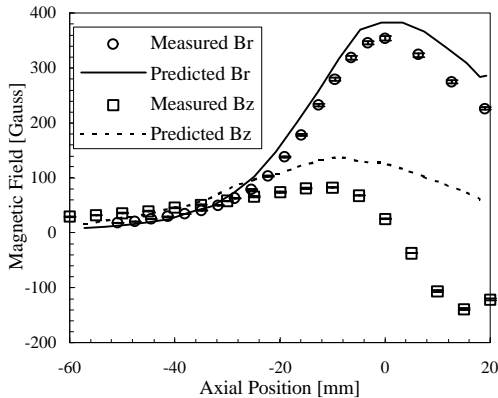


Figure 1: Magnetic Fields

The resulting design underwent a critical design review in late November 1997 at the University of Michigan and, following several minor changes, fabrication began at the Air Force Research Laboratory in December 1997. The thruster, shown in Figure 2, was completed in March 1998. The magnetic components of the thruster were machined from cast iron due to its excellent magnetic properties and ease of machining. The anode was fabricated from 347 stainless steel. The discharge chamber was machined from a 50% boron nitride / 50% silicon dioxide ceramic and the inner pole piece guard disk was machined from pure boron nitride. Not shown in Figure 2 was the cathode used for this thruster, an engineering model Hollow Cathode Assembly, which was generously loaned to the University of Michigan by the NASA Lewis Research Center.



Figure 2: University of Michigan/USAF 5 kW Hall Thruster

EXPERIMENTAL GOALS AND SETUP

Testing of this 5 kW Hall thruster was done in two locations: Chamber 6 of the Air Force Research Laboratory's Electric Propulsion Lab at Edwards AFB, CA and the LVTF of the Plasmadynamics and Electric Propulsion Laboratory at the University of Michigan.

Chamber 6 at the Air Force Research Laboratory's Electric Propulsion is a 5' X 8' vacuum facility evacuated by a single Stokes

mechanical pump and blower, 4 copper cryopanel maintained at 25 K by 4 APD cold heads and model HC-8C helium compressors and an APD 22" cryopump. Heat load to the cryopanel is minimized by a pair of shrouds coated with low emissivity paint and chilled by a Polycold™ refrigeration unit. This configuration yields a total pumping speed of 26,000 l/s of xenon with a base pressure of 8×10^{-7} Torr as measured by a MKS Model 919 Hot Cathode Ionization Gauge. Propellant flow was maintained by an array of Unit Model 8100 mass flow controllers, calibrated specifically for xenon. Flow rates were verified by comparison with measured flow rates into a known volume.

Due to the small size of Chamber 6, it was determined that performance measurements taken in it would not be accurate. Therefore, the goal of tests was to establish stable thruster operation before it was transferred to the University of Michigan for performance measurements and other studies. Figure 3 shows the thruster and cathode installed in Chamber 6.

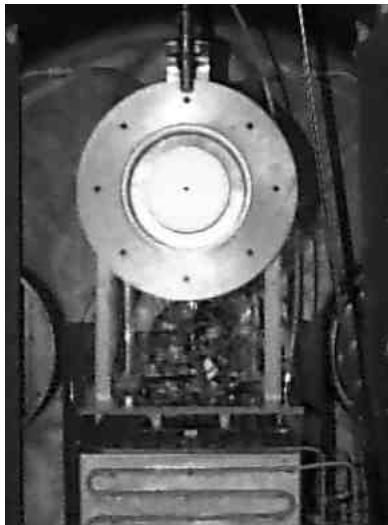


Figure 3: Thruster installed in Chamber 6 of Air Force Research Laboratory

Thruster power was provided by laboratory power supplies. The main discharge was supplied by an Electronic Measurements Model ESS. The inner and outer electromagnets were powered separately by two Electronic Measurements Model 20-30 supplies. The cathode heater and keeper supplies were a

Kepeco ATM 36-15M and KEPCO JQE 100-5 respectively. A filter with 10.4Ω equivalent resistance in series with the discharge current and a $50 \mu\text{F}$ capacitor in parallel was used to damp out thruster oscillations.

Tests at the University of Michigan were performed in the Plasmadynamics and Electric Propulsion Laboratory's 6 m X 9 m LVTF. This is the same facility used in previous work at PEPL⁶, but prior to these tests, it was refitted with four CVI Model TM-1200 Re-Entrant Cryopumps, each of which is surrounded by a LN₂ baffle. These cryopumps, which have replaced the diffusion pumps previously used for high vacuum work, provide a xenon pumping speed measured at 140,000 l/s with a base pressure of less than 3×10^{-7} Torr. Propellant flow was monitored by two MKS Model 1100 Flow Controllers and controlled by two VACOA MV-25-ST needle valves. The thruster is shown mounted in the chamber in Figure 4.

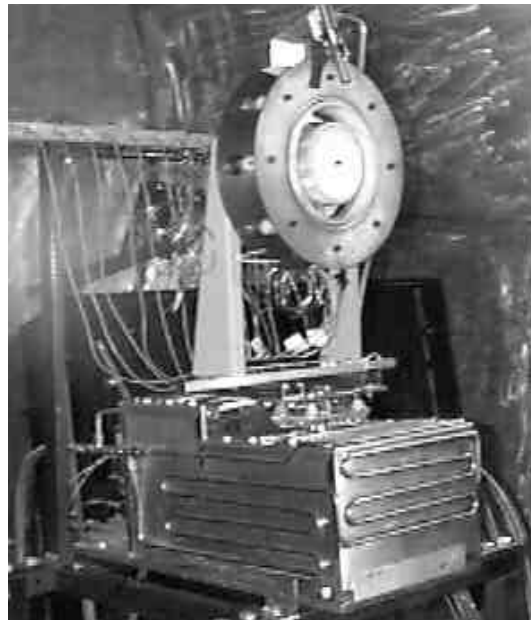


Figure 4: Thruster Installed in PEPL Large Vacuum Test Facility

Thruster power was provided by laboratory power supplies. The main discharge was supplied by a Sorensen Model DCR 600-16T . The inner and outer electromagnets were powered separately by a Kikusui Model PAD 55-10L and a Kikusui Model PAD 35-10L respectively. The cathode heater and keeper

were a Sorensen Model DCR 150-18B and a Kikusui Model PAD 55-6L respectively. The discharge circuit of the thruster was electrically isolated during operations. A filter consisting of 1.3Ω equivalent resistance in series with the discharge current and a $95 \mu\text{F}$ capacitor in parallel was used to damp out thruster oscillations.

Current/Voltage characteristics were determined by igniting the main discharge and increasing the discharge voltage until a stable current plateau is reached. The electromagnet currents were kept constant up to 200 V, then adjusted so as to minimize the discharge current.

The primary goal of the tests at Michigan was to measure performance in order to ensure that future measurements would be relevant to the understanding of the operation of commercial thrusters. To that end, the thruster was mounted on a NASA LeRC type inverted pendulum thrust stand⁷. Performance was measured at discharge voltages ranging from 200 V to 500 V, and at discharge currents of 6 A, 8 A, and 10 A; which correspond to anode flow rates of 58 sccm, 79 sccm, and 105 sccm. For all cases, the cathode flow rate was set at 6 sccm.

In addition to thrust measurements, Faraday and Langmuir probe measurements were taken in a radial sweep, 0.5 m from the thruster. The Faraday probe⁷ had an area of $4.34 \cdot 10^{-4} \text{ m}^2$ and was biased to -50 V to repel electrons. The Langmuir probe⁸ had a collection area of $2.85 \cdot 10^{-4} \text{ m}^2$, a length to diameter ratio of 16, and used a 497Ω shunt resistor to measure current. Faraday probe measurements were taken on a continuous sweep from $+70^\circ$ to -70° relative to the thruster centerline, while Langmuir probe measurements were taken over the same interval at discrete 10° increments. Measurements were taken at each performance operating condition.

EXPERIMENTAL RESULTS

Stable operation of the thruster was obtained in Chamber 6 of the AFRL. Figure 5 shows the thruster operating at an anode flow rate of 60 sccm and 2.5 kW discharge power. In particular, note the focused central core seen in this image.



Figure 5: Thruster Firing in AFRL Chamber 6

Current/Voltage characteristics were determined for the three anode flow rates examined. The results are shown in Figure 6.

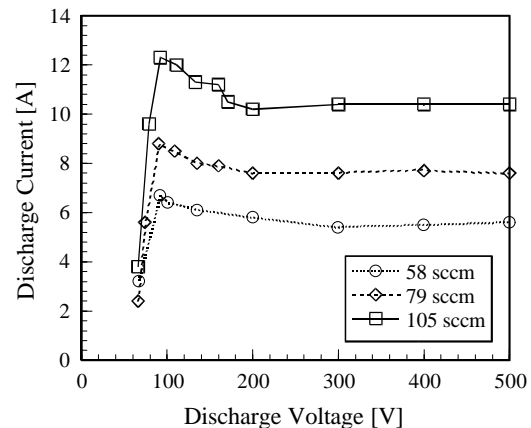


Figure 6: Current/Voltage Characteristics

Note that the current increases beyond the current plateau before decreasing to a steady value at each anode mass flow rate. For several operating conditions, current and voltage traces were recorded on an oscilloscope. Figure 7 shows a trace with the thruster operating at $\sim 5 \text{ kW}$ (487 V, 10.3 A).

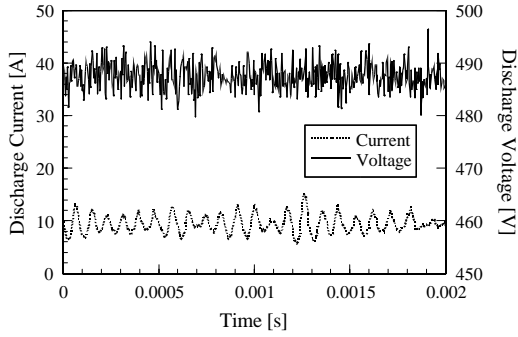


Figure 7: Current and Voltage Traces

The performance measurements are shown in Figures 8 through 10. Both cathode and anode mass flow are accounted for in the calculation of specific impulse and efficiency. For each performance parameter, the data for the three anode mass flow rates are presented versus discharge voltage. During testing the tank pressure was $7.3 \cdot 10^{-6}$ Torr for an anode mass flow rate of 58 sccm, $9.3 \cdot 10^{-6}$ Torr for 79 sccm, and $1.1 \cdot 10^{-5}$ Torr for 105 sccm. These pressures are corrected for xenon and are the average of the readings on two ion gauges.

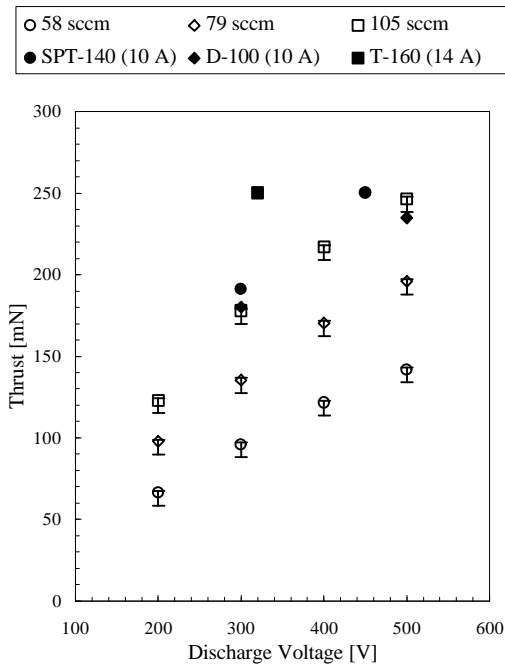


Figure 8: Thrust vs. Discharge Voltage

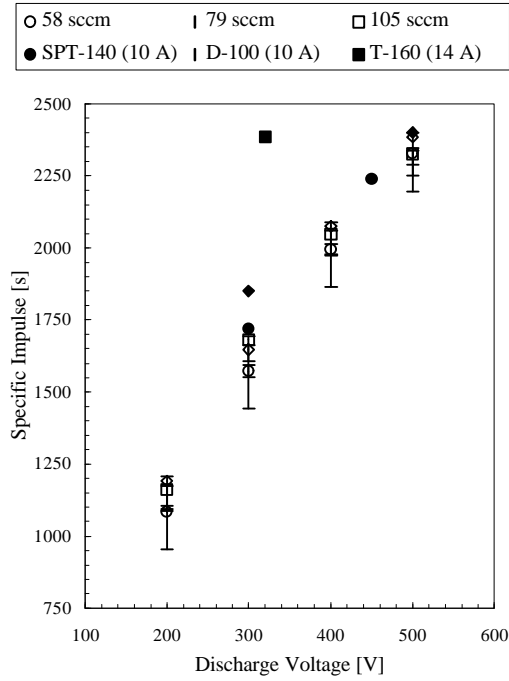


Figure 9: Specific Impulse vs. Discharge Voltage

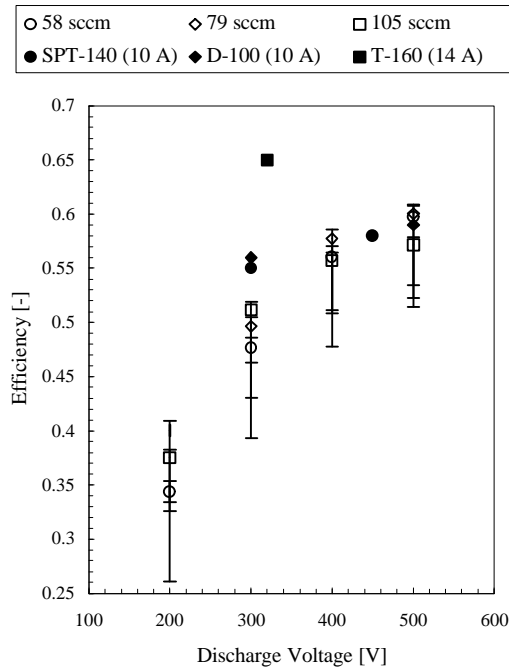


Figure 10: Efficiency vs. Discharge Voltage

This data is in excellent agreement with the performance values for commercial thrusters included for comparison.^{9,10,11} The SPT-140 was tested at Fakel at pressures of $2.5 \cdot 10^{-4}$ to

$3.6 \cdot 10^{-4}$ Torr, the D-100 was tested at JPL in a 3.1 m X 5.1 m vacuum chamber that had a base pressure of $1 \cdot 10^{-7}$ Torr and a measured xenon pumping speed of 48,000 l/s, and the T-160 was tested at NIITP in a 1.6 m X 6.3 m vacuum chamber.

Ion current density information calculated from the Faraday probe measurements is given in Figures 11 and 12. Figure 11 shows the change in ion current density as the anode mass flow rate, and thus discharge current, is increased at a constant 400 V discharge voltage. Figure 12 shows the change as the discharge current is increased at an anode mass flow rate of 79 sccm (~8 A discharge current). The estimated error in the ion current density was $\pm 5\%$, with an uncertainty in position of $\pm 3^\circ$. For all cases, approximately 80% of the ion current between $\pm 70^\circ$ was between $\pm 20^\circ$.

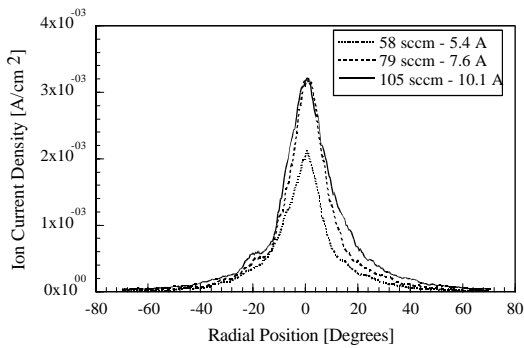


Figure 11: Ion Current Density at Constant Discharge Voltage

Note that as the discharge current is increased, the ion current density increases at first, then plateaus. This behavior was seen at all discharge voltages.

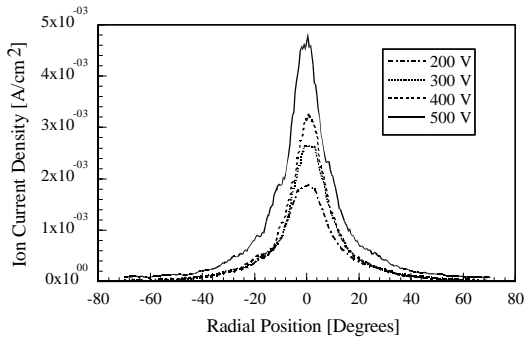


Figure 12: Ion Current Density at Constant Discharge Current

As the discharge voltage is increased, the ion current density increases and does not plateau as was seen when the discharge current was increased.

Electron temperature data from the Langmuir probe measurements is shown in Figures 13 and 14. Figure 13 gives the electron temperature at a constant 500 V discharge as the anode mass flow rate is increased. Figure 14 shows the change in electron temperature as the voltage is increased for a constant flow rate of 58 sccm (~6 A discharge current). The estimated error in the electron temperature was $\pm 5\%$, with an uncertainty in position of $\pm 3^\circ$

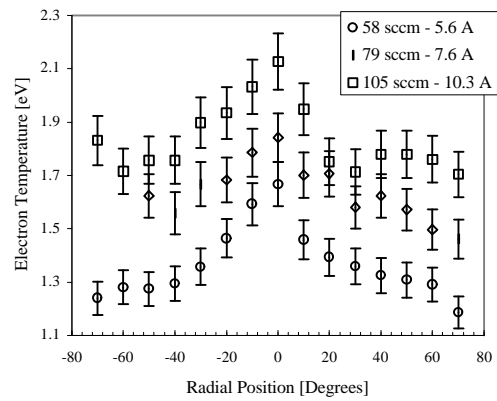


Figure 13: Electron Temperature at Constant Discharge Voltage

As the mass flow rate is increased, the electron temperature increases steadily at all radial positions.

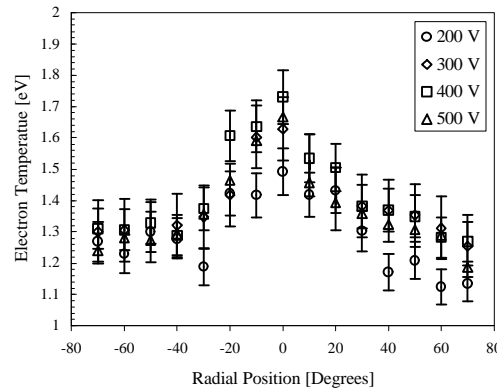


Figure 14: Electron Temperature at Constant Discharge Current

As discharge voltage is increased from 200 V to 300 V, the electron temperature increases. However, as the voltage is increased beyond 300 V, the electron temperature remains constant.

Electron number density data from the Langmuir probe measurements is shown in Figures 15 and 16 for the same cases as with the electron temperature. From theory, the error in electron number density is $\pm 50\%$.

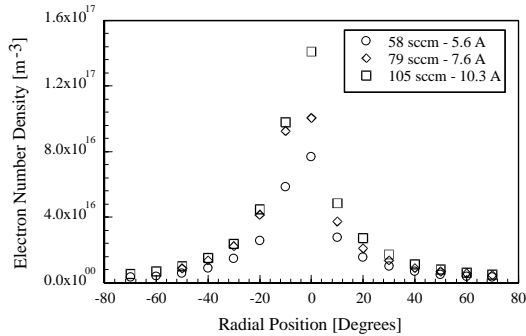


Figure 15: Electron Number Density at Constant Discharge Voltage

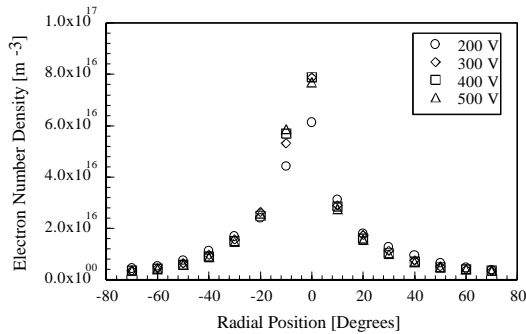


Figure 16: Electron Number Density at Constant Discharge Current

The electron number density follows the same trends as the temperature with increasing discharge voltage and current. The spread with radial position, however, is much narrower and is, as expected, similar to the Faraday probe measurements of ion current density.

CONCLUSIONS

The thruster described herein has many excellent properties. It is easy to start and operate, reaching a current plateau at discharge voltages above 200 V. The performance measurements indicate that it is comparable to thrusters under commercial development.^{9,10,11}

Both visual and Faraday probe measurements indicate that the plume is well focused. It is believed that these characteristics indicate that information learned from the study of this Hall thruster will be applicable to 5 kW thrusters in general.

FUTURE WORK

The behavior of this Hall thruster will continue to be characterized through the use of the diagnostics employed at PEPL; including the Retarding Potential Analyzer¹², the Neutral Particle Flux probe¹³, and the Molecular Beam Mass Spectrometer¹⁴. High speed reciprocating probes are planned for internal diagnostics.¹⁵ It will also serve as the test bed for the new PEPL Laser Induced Fluorescence system, currently under development.

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