Performance characterization of a small low-cost Hall thruster

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Abstract: The 44-mm-diameter Western Hall Thruster (WHT-44) was designed and built at Western Michigan University's (WMU's) Aerospace Laboratory for Plasma Experiments (ALPE). The 200-W, Hall effect thruster (HET) was built for under $2100. Plume characterization maps were generated to determine whether such a low cost HET can be used as a way to enter the HET research community. Plume studies were performed on the WHT-44 inside ALPE's 1-m-diameter by 1.5-m-long vacuum chamber. A Langmuir probe, Faraday probe, and retarding potential analyzer (RPA) were used to make time averaged plume measurements. Mass flow rate, vacuum chamber pressure, and telemetry data were continuously recorded during probe operation. With these probes, data related to beam shape, and divergence were measured. The resulting data are used to determine spatially resolved electron temperature, ion number density, floating potential, plasma potential, and electron energy distribution function.

Nomenclature

λ_D	=	Debye length
ε_o	=	permittivity of free space, 8.85×10^{-12} F/m
θ	=	faraday probe position
a,b	=	non-dimensional factors
A_p	=	Langmuir probe collection area
e	=	electron charge, 1.60×10^{-19} C
I_{probe}	=	Langmuir probe collected current
I_d	=	discharge current
I_k	=	keeper current
I_m	=	magnet current
m_i	=	ion mass, $131 \times 1.67 \times 10^{-27}$ kg for Xe
$n_{i,e}$	=	ion and electron number density
P_f	=	facility pressure
T_e	=	electron temperature
V_b	=	Langmuir probe bias voltage
V_p	=	plasma potential
V_d	=	discharge voltage
V_k	=	keeper voltage

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I.Introduction

THE 44-mm diameter Western Hall Thruster (WHT-44) is a 200 W Hall effect thruster (HET) designed to be a low cost entry-level research platform for universities with limited resources. The WHT-44 was designed to operate at a nominal 200 W of discharge power (Figure 1), has a 44 mm outer diameter, and is meant to operate using Xe gas.[1]

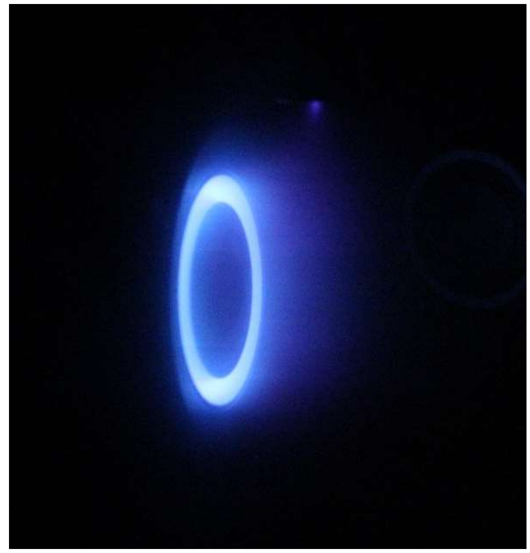

Figure 1. WHT-44 Operating at 130W of discharge power.

II.Experimental Setup

This section details the testing environment of the WHT-44 and the processes by which the thruster was tested.

A. Facility

Operation of the WHT-44 was conducted in the Western Michigan University Aerospace Laboratory for Plasma Experiments (ALPE) vacuum facility. The facility utilizes a 1 m diameter, 1.5 m long stainless steel chamber outfitted with a single CTI-250F cryogenic pump with a capacity of roughly 2000 l/s nitrogen. Gas flow was regulated using two Alicat MCV mass flow controllers and power was supplied using laboratory grade Lambda Genesis and Sorensen DLM power supplies. Thruster telemetry and facility pressure were continuously monitored using two National Instruments USB DAQs and a LabView script. Probe positioning motion control was performed by a separate workstation, two linear 380 mm Velmex tables, and one rotary table, creating a typical Cartesian probe positioning system and a fixed radius theta positioning system. Probe data were collected and synchronized with the tables on this same workstation.

B. WHT-44 and Cathode

A heaterless 1.6 mm Bantam hollow cathode purchased from Plasma Controls, LLC was used to start and operate the thruster. This cathode was placed at the thruster's 12'o'clock position and based on magnetic field mapping, oriented such that the cathode discharge was inside the magnetic lens seperatrix.[2] The cathode centerline was positioned 11.6 mm forward of the thruster face and the cathode discharge was 29.9 mm above thruster centerline (Figure 2)

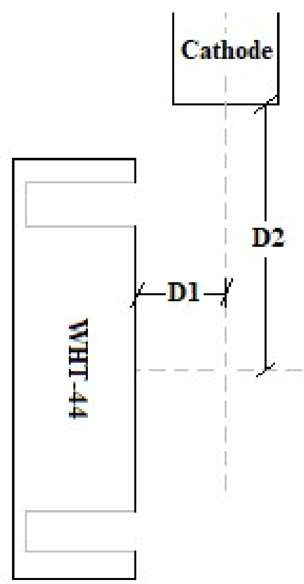

Figure 2. Relative orientation between thruster and cathode. *D1 is 29.9 mm and D2 is 11.6 mm.*

C. Diagnostic Probes

A slowly swept cylindrical Langmuir probe (LP), retarding potential analyzer (RPA), and a Faraday Probe (FP) were used to obtain plume properties and behavior.

The LP was constructed with 6.35 mm long, 0.25 mm diameter tungsten wire. Probe bias voltage (V_b) was swept from -10 to 25 V using a LabView controlled Keithley 2400 source-meter. Three sample averaging and single line cycle integration were applied. A 270 mm x 270 mm area forward of the thruster face by 95 mm and offset by 50 mm was swept in a 1 cm grid. The individual I-V traces were analyzed to determine the electron temperature (T_e), ion number density (n_i), Debye length (λ_D), and plasma potential (V_p) at each point within the grid.[3]

The RPA was physically positioned similarly to the LP; however, a smaller area of 160 mm x 160 mm area was probed. The RPA utilizes four aligned and electrically isolated grids and a collector housed in 16 mm stainless steel tube. The first grid was allowed to float, the repelling grid was held to -60V to filter beam electrons, the suppressing grid was held to -26V to reduce secondary ions emitted from the collector, and the retarding grid was swept from 0 to 500 V. Both collector current measurement and the retarding grid potential were provided by a Keithley 485 source-meter. A second derivative Druyvesteyn method was used to estimate the most probable ion energy of every point within the sample grid, as well as the Ion Energy probability Distribution Function (IEDF) of a single point in the plume forward of thruster discharge.[4]

An FP with collector radius of 10 mm was radially swept using a rotary table. The probe collection area and guard were biased to -15 V, and current was monitored using a Keithley 2400 source-meter. The FP was positioned roughly two thruster diameters from the discharge exit plane and swept from 0° to 180° while position and collected current were logged. The collected current to probe angle data were analyzed to determine both beam current and the 95% beam divergence half angle.[5]

D. Thruster Operating Parameters

The thruster was operated at two test points that were determined through inspection of thruster operation and observation of stable discharge operating currents. The first test point was a 130 W discharge power condition operating with a discharge voltage of 200 V and a current density of 117 mA/cm^2. The second thrust point was a 200 W discharge power condition operating with a discharge voltage of 200 V and a current density of 155 mA/cm^2. A summary of these two operating points is shown in Table 1. Facility pressure exceeded 5E-4 Torr for both thruster operating points.

Table 1. Thruster Operating Parameters

Parameter	130W Thrust Point	200W Thrust Point
V_k/I_k	11V/0.3A (6sccm)	10V/0.2A (1sccm)
V_d/I_d	200V/0.66A (6sccm)	200V/1.04A (9sccm)
I_m	0.30A	0.25A
P_f	7E-4 Torr	5.6E-4 Torr
Electrical Status	Body Floating	Body Floating

III. Results

This section outlines the results for each of the probes used during this experiment.

A. Faraday Probe

FP data were plotted as a function of probe angle for both operating points. The current was used to find beam divergence (Figure 3). This was done by first averaging the $\theta = 0°$ to 90° probe angle data with the $\theta = 90°$ to 180° probe data and then integrating the z-component of beam current with respect to the probe angle. The divergence half-angle was calculated to be the angle at which 95% of the beam current was contained. The divergence half angles at the 130 W and 200 W conditions are 66.5° and 71.3° respectively.

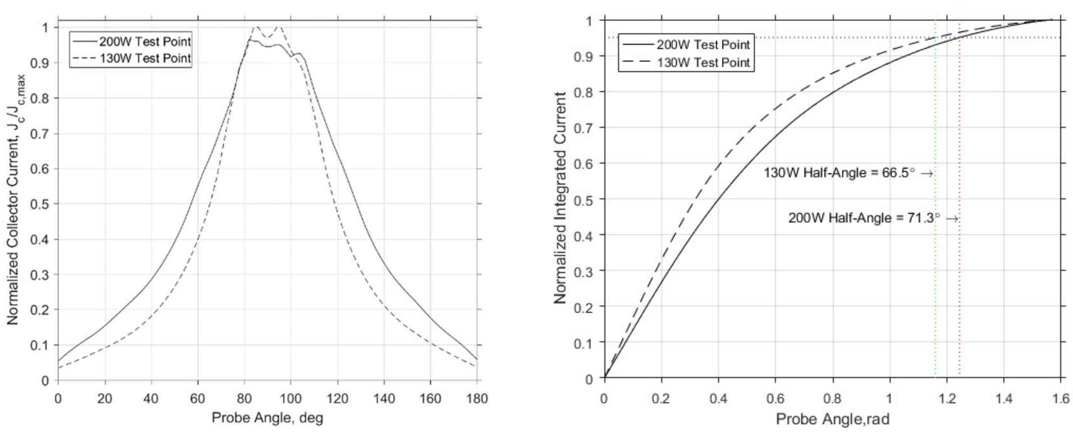

Figure 3. Faraday Probe Data for 130 and 200W operating points. *Uncorrected Faraday probe data (left) and beam divergence calculation results (right).*

B. Retarding Potential Analyzer

The most probable ion energy for each RPA trace was calculated using the first derivative of the obtained current vs. retarding potential data. Most probable energy was plotted as a function of downstream location, and this is shown in Figure 4. The energy level of ions exiting the thruster is generally between 160 and 200 eV for both operating conditions in which discharge voltage was 200 V. The results of the Druyvesteyn method IEDF for a similar point located 105 mm downstream of a discharge is displayed for both power conditions in **Error! Reference source not**

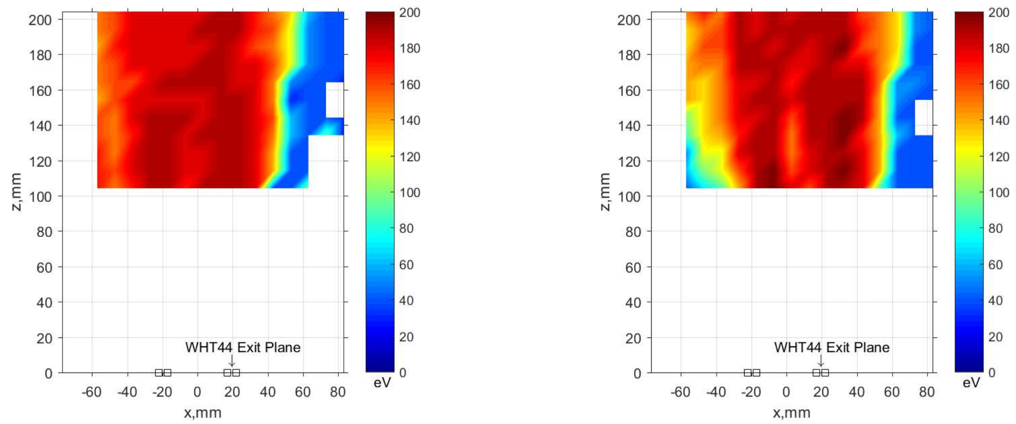

Figure 4. Most probable ion energy level. *130 W condition (left) and 200 W condition (right).*

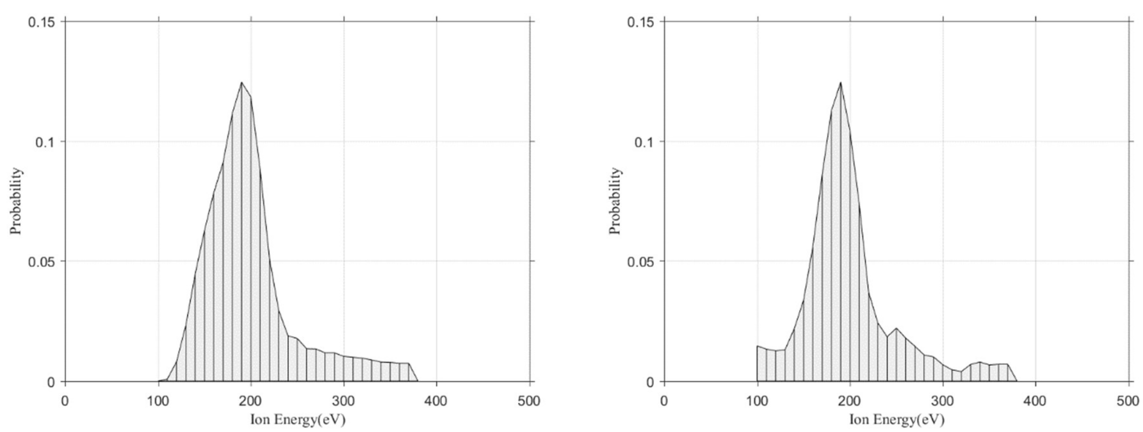

Figure 5. IEDF for ions 105 mm downstream of the WHT-44. *130 W condition (left) and 200 W condition (right).*

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C. Langmuir Probe

LP current vs. voltage traces were processed in accordance with Ref. 2. The Debye length, λ_D, is used to determine the operating regime of the LP. The LP can operate in thin sheath where $r_p/\lambda_D > 50$, transitional sheath $3 < r_p/\lambda_D < 50$, or orbital motion limited (OML) $r_p/\lambda_D < 3$. The LP in this experiment was operating exclusively in the OML regime. Briefly, a preliminary ion number density, n_i, and electron temperature, T_e, were used to calculate λ_D using Eq. (1).

$$\lambda_D = \sqrt{\frac{\varepsilon_o T_e}{n_e e}} \tag{1}$$

where ε_o is the permittivity of free space and e is the electron charge. For OML, two non-dimensional factors $a = 2\sqrt{\pi}$ and $b = \frac{1}{2}$ are used to calculate ion number density using Eq. (2).

$$n_i = \frac{1}{aA_p}\sqrt{2\pi m_i}e^{-1.5}T_e^{b-0.5}\left[\frac{dI_{probe}^{1/b}}{dV_B}\right]^b \tag{2}$$

Operating regime is determined from the calculated ion number density, and Eq. (1) and Eq. (2) are recalculated until a convergence of ion number density and λ_D are achieved. This process was automated using a MatLab script.

Surface maps of LP data are plotted for V_p, T_e, λ_D, and n_i. Shown in Figure 6 are two sample plots of ion number density for the 130 and 200 W power conditions. Full plume maps are in the appendix.

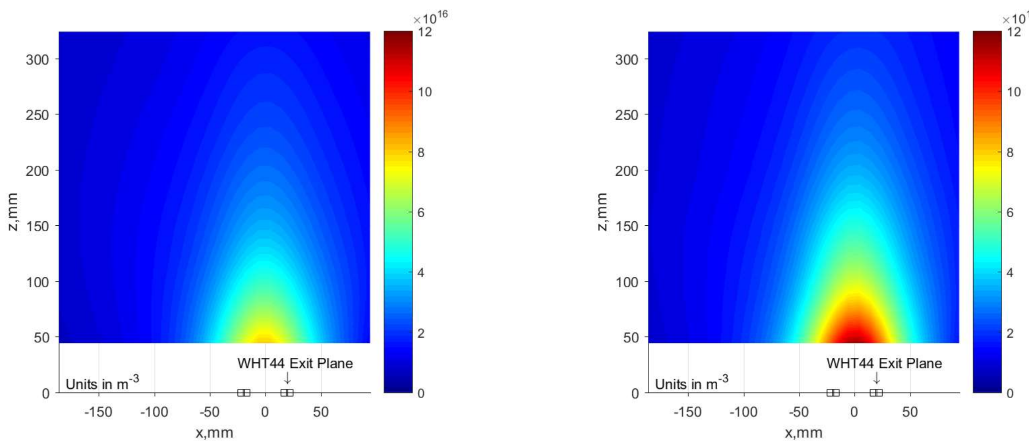

Figure 6. Ion number density. *130 W condition (left) and 200 W condition (right).*

D. Discussion

While the plume shows good plume symmetry about the annulus axis, there appears to be a divergence angle in the thruster plume. Results of the RPA data are near the anticipated levels of a thruster operating at a 200 V discharge. Ion number density, plasma potential, and floating potential are on the same order of magnitude as what was measured in the BHT-200.[6–8] Electron temperature showed different characteristics such as a more uniform downstream electron temperature rather than a higher temperature at the center of the plume. It should be restated that background pressure during probe data collection ranged between 5E-4 and 7E-4 Torr and heavy discharge oscillations were present that could have impacted the results.

IV. Conclusion

First plume measurements have been performed on a 200 W Hall effect thruster that was designed, fabricated, and tested at ALPE. Comparisons were made to a similarly sized HET, the BHT-200 and show good agreement. Thruster operation was not optimized, and background pressure was higher than desired and may have contributed to unexpected plume behavior. Better probe techniques, lower facility pressure, and optimized cathode coupling may resolve the discrepancies in plasma diagnostic results and create an environment that enables the thruster to operate with lower oscillations. Overall the project was a success, and plume properties were measured at two operating conditions for the WHT-44. Future work will include operation at facilities with lower pressure capabilities, careful cathode coupling studies, discharge and magnet parameter sweeping, the addition of correction geometric correction factors to FP data, multiple radii FP sweeps, high-speed plume diagnostics, and thrust stand measurements.

Appendix

This section contains all Langmuir probe data maps.

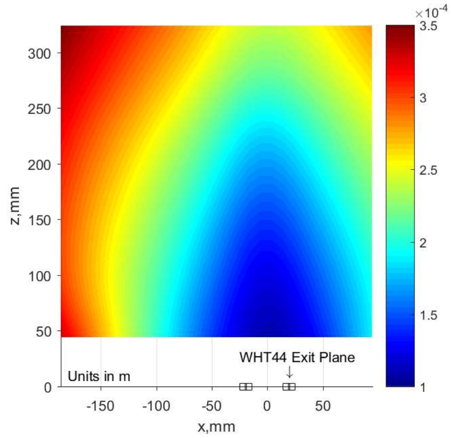

Figure A1. Debye Length at 140W.

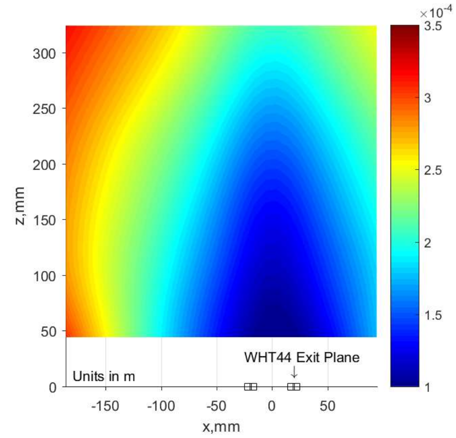

Figure A2. Debye Length at 200W.

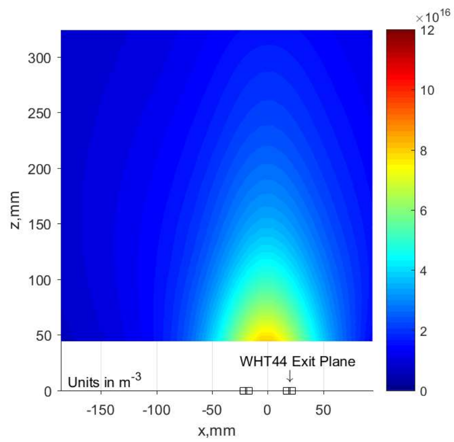

Figure A3. Ion number density at 140W.

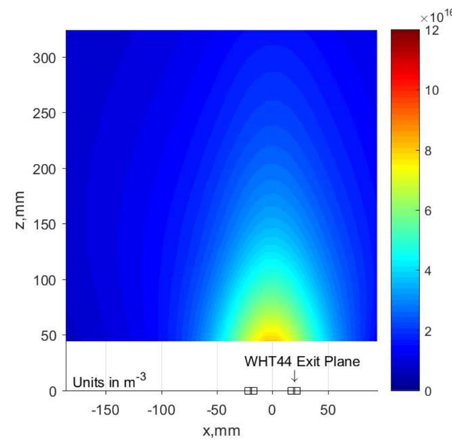

Figure A4. Ion number density at 200W.

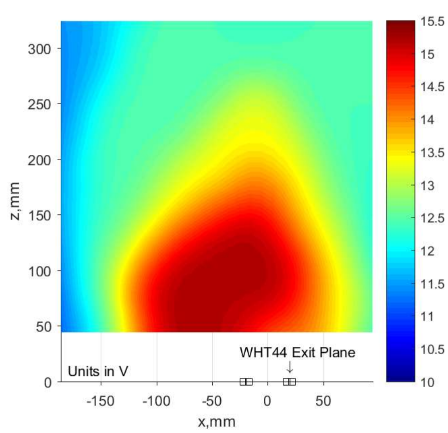

Figure A5. Plasma Potential at 140W.

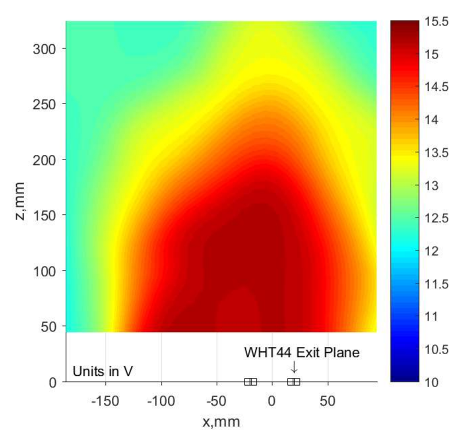

Figure A6. Plasma Potential at 200W.

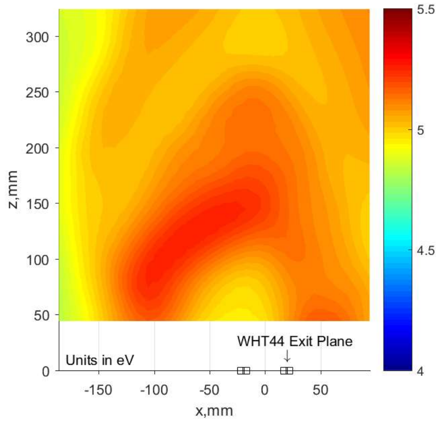

Figure A7. Electron Temperature at 140W.

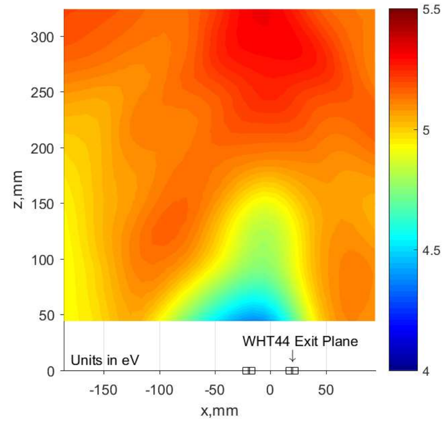

Figure A8. Electron Temperature at 200W.

Acknowledgments

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