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Technical Notes

Investigation of Channel Interactions in Nested Hall Thruster

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Nomenclature

d_{oc} = outer-channel mean diameter, m
g = gravitational constant, m/s^2
$I_{sp,a}$ = anode specific impulse, s
j = current density, mA/m^2
k = Boltzmann's constant, J/K
$\dot{m}_a$ = anode mass flow rate, kg/s
m_{Xe} = mass of xenon, kg
P_d = discharge power, W
r = radial location, m
T = thrust, mN
T_{gas} = gas temperature, K
u_e = exhaust velocity, m/s
v_{th} = thermal velocity, m/s
z = axial (downstream) location, m
β = divergence half-angle, deg
η_a = anode efficiency

I. Introduction

HIGH-POWER Hall thrusters are an enabling technology for deep space missions [1–4]. Nested Hall thrusters are a type of Hall thruster in which multiple discharge channels are nested concentrically together. These devices are an attractive option for scaling to high power since they are founded on a mature technology, expand the thruster's operational envelope, and lower the propulsion system's specific mass (kilograms/kilowatts) [5,6] as compared to single-channel thrusters of the same power level. To further this technology, the Plasmadynamics and Electric Propulsion Laboratory developed the X2, a 6 kW proof-of-concept nested Hall thruster [7–9].

Nested Hall thrusters offer expanded operating envelopes through their variable discharge area. Each channel of nested Hall thrusters can be fired independently or in any combination with other channels. Understanding the performance in these multichannel operational modes is critical. Previous work done on the X2 [7], a two-channel nested Hall thruster, has shown that the measured thrust when both channels are firing simultaneously (dual-channel mode) is greater than the superposition of each channel operating individually. Results showed that this anomalous performance was not simply due to the higher background pressure during higher power operation, as the study was done at constant backpressure and thrust still improved between 2 and 9%.

The goal of this work was to investigate the mechanism behind this anomalously high performance. Performance and Faraday probe measurements were taken for the X2 operating at a constant background pressure in all possible firing configurations. Neutral gas was injected into the chamber to maintain a constant chamber pressure during all conditions. Gas was injected either downstream of the thruster or via the nonoperating channel, which better simulates the local pressure during dual-channel operation. These three conditions (dual channel, single channel with downstream injection, and single channel with channel injection) were used to determine the source of the anomalous performance. The mechanism resulting in the higher than anticipated performance is expected to be either neutral ingestion from the adjacent channel or divergence angle decreases leading to increased collimation of the beam.

II. Experimental Setup

A. Thruster

The X2 is a two-channel nested Hall thruster designed for low-voltage operation [8]. As seen in Fig. 1, the thruster has two concentric discharge chambers that can be fired together or independently, leading to three different firing configurations. The thruster was operated with a single, centrally mounted LaB_6 cathode. The thruster has comparable design properties to state-of-the-art Hall thrusters and has an operational envelope from 0.5 to 10 kW. The nominal power for the thruster is 6 kW. A full description of the thruster design and general performance is provided by Liang [7]. The thruster was operated at 150 V anode potential relative to cathode for each condition, and each channel received power from an independent power supply. The cathode keeper and heater, as well as the electromagnets, were all powered with commercially available power supplies. The discharge chambers were provided high purity xenon via commercially available mass flow controllers. The applied magnetic field for each condition was kept constant. The flow to the outer channel was 21.8 mg/s. The flow to the inner channel was 8.7 mg/s. The cathode flow fraction, the fraction of the anode flow rate at which the cathode flow rate was set, was kept at a constant 10% of all firing channels. Pressure was controlled via neutral gas injection, which will be addressed later.

B. Thrust Stand

An inverted-pendulum thrust stand, as described by Walker and Gallimore [10], was used to make thrust measurements. The thrust stand was run in null mode, meaning electromagnets were provided sufficient current to hold the thruster at constant axial location. Known mass plumbobs were used to perform multiple calibrations after thruster firing was completed. A proportional-integral-derivative (PID) circuit was used to control the magnitude of the coil current, which keeps the thrust stand stationary. The PID had a 1 Hz oscillation, which was filtered out of the data in postprocessing. An uncertainty analysis was performed as described by Polk et al. [11]. Efficiencies were then calculated using thrust data as follows [12]:

$$\eta_a = \frac{T^2}{2\dot{m}_a P_d} \tag{1}$$

$$I_{sp,a} = \frac{T}{\dot{m}_a g} \tag{2}$$

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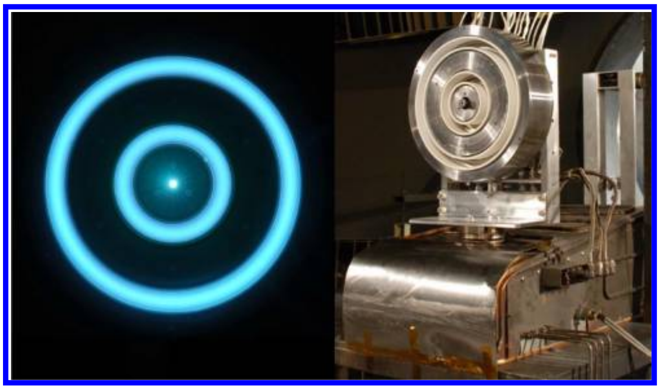

Fig. 1 A picture of the X2, a 6 kW nested Hall thruster [8].

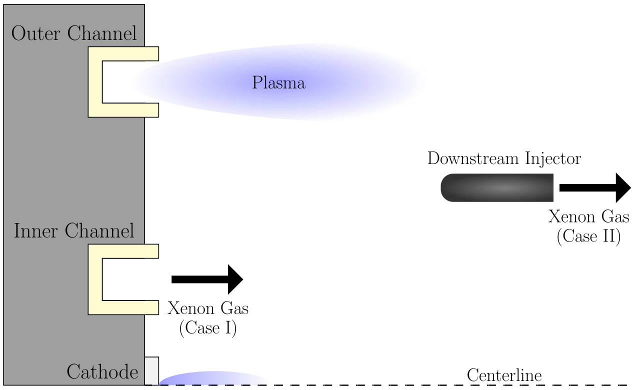

Fig. 2 Location of neutral gas injection for various cases (not to scale). The downstream injection was approximately 4 thruster diameters downstream of the thruster.

C. Near-Field Faraday Probe

A planar near-field Faraday probe was used to obtain current density measurements. The probe has a circular collector with diameter 3.2 mm and was biased to −40 V during operation to ensure ion saturation [13]. Current measurements were collected at 60 Hz using a Keithley 6485 picoammeter. The probe was swept from $0.07d_{\text{OC}}$ to $0.35d_{OC}$ in $0.035d_{\text{OC}}$ increments. The divergence half-angle was calculated as

$$\beta = \arctan\left(\frac{r_1 - r_{\text{max}}}{z}\right) \tag{3}$$

where r_1 is the dynamic integration limit as described by Reid and Gallimore [14]. The dynamic limits were calculated as the position where the current density was at 37% of the maximum, or the dropoff point. The dynamic integration limits allowed for evolving limits as a function of the axial position by being recalculated at each step. The divergence angle was calculated at two clock angles around the thruster and averaged for an overall divergence angle. Due to plume merging, it was not always possible to calculate divergence angle in far downstream locations of each individual channel. Therefore, the divergence angle was only calculated at axial positions where the plumes of the inner channel, outer channel, and cathode could be differentiated. Once this condition was no longer satisfied, the divergence angle was no longer calculated.

D. Pressure Control

Hall thrusters are naturally oscillatory [15]. Additionally, the strength of oscillations is known to affect thruster performance [16]. Since the background pressure in the chamber can affect oscillation strength [17–19], the facility can thus affect the performance of Hall thrusters. Furthermore, neutral ingestion changes with varying background pressure increasing the performance artifically [20,21]. Therefore, it is recommended that all measurements be collected with the same background chamber pressure [22]. To compensate for this, neutral xenon gas was flowed into the chamber to artificially increase the background chamber pressure during single-channel operation (up to the value of pressure that was observed during dual-channel operation). The chamber pressure during all firing configurations was 6.7×10^{-6} Xe, measured using a Varian Series UHV-564 ion gauge located 3 m radially from the thruster and 2 m axially downstream.

Neutral gas was injected in one of two locations during single-channel operation as seen in Fig. 2: downstream or through the channel not actively firing (indicated by the black arrows in the figure). These conditions were used to determine whether neutral ingestion from adjacent channel(s) was the source of the improved thrust seen in previous experiments. The total flow into the chamber for all operating conditions was equal.

III. Results and Discussion

Table 1 contains all test points for the experiment along with the anode efficiency, anode specific impulse, beam efficiency, and divergence efficiency results. For each test point, thrust and Faraday probe data were taken. Uncertainties on the power are 2%. To better understand performance differences, an effective dual-channel anode efficiency and specific impulse were calculated for the injection point by weighting each value by its mass flow fraction. The results are seen in Table 2. The results clearly show that dual-channel operation has higher performance than single-channel operation when background pressure is controlled with downstream injection. However, when pressure is controlled with channel injection, the performance of the thruster matches dual-channel performance. The matching of performance within uncertainty for the channel injection test point indicates that the increased neutral density near the thruster during dual-channel operation is resulting in increased performance.

Thrust results can be seen in Fig. 3. For points where flow was injected via the nonoperating channel, the thrust numbers were corrected for the thrust due to cold gas flow. The thrust due to cold gas was

$$T_{\text{coldgas}} = \dot{m}u_e \tag{4}$$

where the exhaust velocity was assumed to be the thermal velocity defined as

Table 2 Effective performance values for each operating conditions

Operating condition	η_a	$I_{\text{sp},a}$, s
Dual channel	0.47 ± 0.01	1196 ± 14
Channel injection	0.47 ± 0.03	1206 ± 36
Downstream injection	0.42 ± 0.02	1141 ± 33

Table 1 Results matrix for X2 testing

Test point	Inner power, kW	Outer power, kW	Total power, kW	Gas injection point	Thrust, mN	η_a	$I_{\text{sp},a}$, s
1	1.23	3.23	4.46	— —	357.8 ± 4.6	0.47 ± 0.01	1196 ± 15
2	1.26	— —	1.26	Downstream	248.5 ± 3.3	0.39 ± 0.02	1086 ± 32
3	1.25	— —	1.25	Channel	264.0 ± 2.7	0.42 ± 0.03	1132 ± 33
4	— —	3.26	3.26	Downstream	92.7 ± 2.7	0.44 ± 0.01	1163 ± 16
5	— —	3.24	3.24	Channel	95.0 ± 3.0	0.49 ± 0.02	1235 ± 16

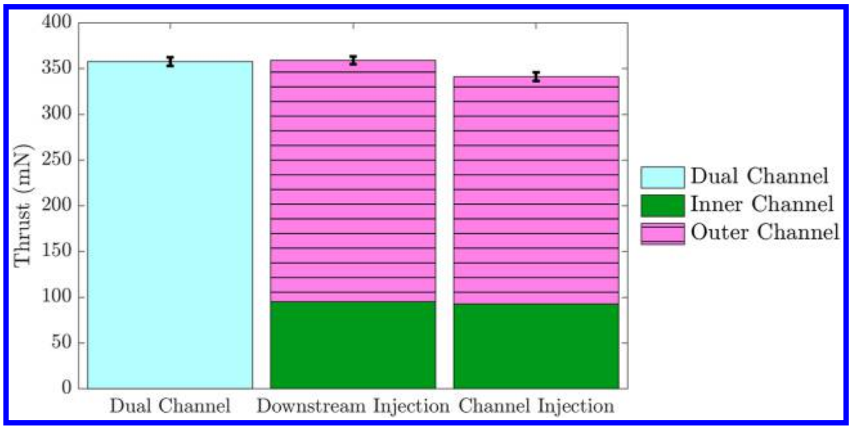

Fig. 3 Thrust results for all operating condtions of the X2.

$$v_{\text{th}} = \sqrt{\frac{8kT_{\text{gas}}}{\pi m_{\text{Xe}}}} \tag{5}$$

The temperature of the gas was assumed to be 523 K as this was the approximate steady state temperature of the thruster. The cold gas thrust when flowing through the outer channel was calculated to be 6.8 mN and for the inner channel was 2.7 mN. The major result is that in the dual-channel mode the thruster had a 4.9% increase in thrust over the superposition of each channel when the background pressure was controlled via downstream injection. This improvement is consistent with improvements seen by Liang [7] at different operating conditions. This anomalous thrust was recovered when the pressure local to the thruster was raised to match the background chamber pressure via channel injection. This result suggests that part of the anomalous performance seen in nested Hall thrusters was due to neutral ingestion from the adjacent channel.

Figure 4 shows the evolution of the divergence angle for both the inner and outer channels. Figure 4a shows the inner channel divergence angle remained constant for all axial locations for both neutral injection cases. For the dual-channel mode, the divergence half-angle started at 14 deg very close to the thruster exit plane and then quickly evolved to reach the value of the test point 3, the inner channel with channel injection. The value of divergence is taken as the final value that was calculated. The divergence angles of the outer channel, as seen in Fig. 4b, show that when gas was injected downstream the divergence remained higher than all other cases. This data indicate that local pressure influenced the divergence angle, decreasing it for the dual channel and single channel with channel injection modes as compared to single channel with downstream injection for the outer channel. The decrease in the divergence angle seen should theoretically have increased the thrust 3%. This result indicates that only part of the improved performance was due to a decrease in the divergence angle.

IV. Conclusions

The performance of a two-channel nested Hall thruster operating at 150 V anode potential was measured. Thrust increased 4.9% in the dual-channel mode vs the summation of single channels when pressure was controlled via downstream injection. This difference was eliminated when the pressure was controlled via injection through the nonoperating channel, which better simulated the local pressure of the thruster during operation. The outer-channel divergence angle decreased in dual-channel operation and single channel with channel injection leading to an increased thrust, anode efficiency, and anode specific impulse. The results indicate that part of the anomalous performance was due to neutral ingestion from the adjacent channel and the other part was due to a decrease in the divergence angle leading to more beam collimation. Further work will investigate nested Hall thruster performance and plume data over a variety of operating conditions and thrusters. Additionally, a neutral flow model will be developed to calculate neutral density paths near the thruster exit plane. Finally, the implications of this result suggest that channel spacing on nested Hall thrusters is critical for maximizing this effect. Plasma modeling of this effect is critical to informing that discussion.

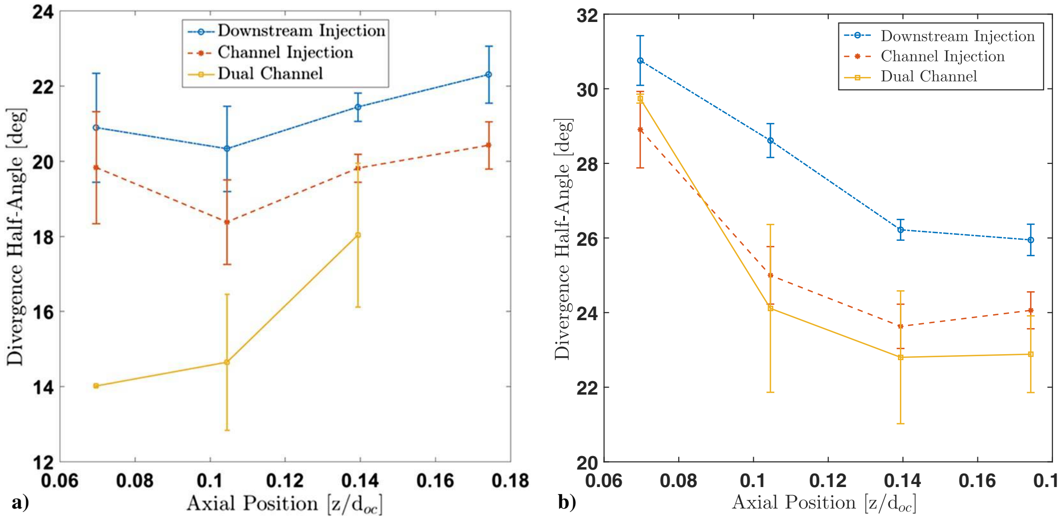

Fig. 4 a) Inner-channel divergence angle as a function of downstream position for all test cases. b) Outer-channel divergence angle as a function of downstream position for all test cases.

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References

[1] Jankovsky, R., Tverdokhlebov, S., and Manzella, D., "High Power Hall Thrusters," NASA, Glenn Research Center Rept. A99-31574, 1999. doi:10.2514/6.1999-2949

[2] Brophy, J. R., Gershman, R., Landau, D., Yeomans, D., Polk, J., Porter, C., Williams, W., Allen, C., and Asphaug, E., "Asteroid Return Mission Feasibility Study," AIAA Paper 2011-5665, July 2011. doi:10.2514/6.2011-5665

[3] Schmidt, T. D., Seboldt, W., and Auweter-Kurtz, M., "Flexible Piloted Mars Missions Using Continuous Electric Propulsion," *Journal of Spacecraft and Rockets*, Vol. 43, No. 6, 2006, pp. 1231–1238. doi:10.2514/1.17843

[4] Donahue, B., "Solar Electric and Nuclear Thermal Propulsion Architectures for Human Mars Missions Beginning in 2033," AIAA Paper 2010-6819, July 2010. doi:10.2514/6.2010-6819

[5] Brown, D. L., Beal, B. E., and Haas, J. M., "Air Force Research Laboratory High Power Electric Propulsion Technology Development," *IEEE Aerospace Conference*, Inst. of Electrical and Electronics Engineers, New York, 2010, pp. 1–9. doi:10.1109/AERO.2010.5447035

[6] Hofer, R. R., and Randolph, T. M., "Mass and Cost Model for Selecting Thruster Size in Electric Propulsion Systems," *Journal of Propulsion and Power*, Vol. 29, No. 1, 2013, pp. 166–177. doi:10.2514/1.B34525

[7] Liang, R., "The Combination of Two Concentric Discharge Channels into a Nested Hall-Effect Thruster," Ph.D. Thesis, Univ. of Michigan, Ann Arbor, MI, 2013.

[8] Liang, R., and Gallimore, A. D., "Constant-Power Performance and Plume Measurements of a Nested-Channel Hall-Effect Thruster," *32nd International Electric Propulsion Conference*, Electric Rocket Propulsion Soc. Paper IEPC-2011-049, Fairview Park, OH, Sept. 2011.

[9] Liang, R., and Gallimore, A. D., "Far-Field Plume Measurements of a Nested-Channel Hall-Effect Thruster," AIAA Paper 2011-1016, Jan. 2011. doi:10.2514/6.2011-1016

[10] Walker, M. L., and Gallimore, A. D., "Performance Characteristics of a Cluster of 5-kW Laboratory Hall Thrusters," *Journal of Propulsion and Power*, Vol. 23, No. 1, 2007, pp. 35–43. doi:10.2514/1.19752

[11] Polk, J. E., Pancotti, A., Haag, T., King, S., Walker, M., Blakely, J., and Ziemer, J., "Recommended Practices in Thrust Measurements," *33rd International Electric Propulsion Conference*, Paper IEPC-2013-440, Oct. 2013.

[12] Goebel, D. M., and Katz, I., *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*, 1st ed., Wiley, Hoboken, NJ, 2008.

[13] Hofer, R. R., Jankovsky, R. S., and Gallimore, A. D., "High-Specific Impulse Hall Thrusters, Part 1: Influence of Current Density and Magnetic Field," *Journal of Propulsion and Power*, Vol. 22, No. 4, 2006, pp. 721–731. doi:10.2514/1.15952

[14] Reid, B. M., and Gallimore, A. D., "Near-Field Ion Current Density Measurements of a 6-kW Hall Thruster," *31st International Electric Propulsion Conference*, Paper IEPC-2009-124, Sept. 2009.

[15] Choueiri, E., "Plasma Oscillations in Hall Thrusters," *Physics of Plasmas*, Vol. 8, No. 4, 2001, pp. 1411–1426. doi:10.1063/1.1354644

[16] Sekerak, M. J., Gallimore, A. D., Brown, D. L., Hofer, R. R., and Polk, J. E., "Mode Transitions in Hall-Effect Thrusters Induced by Variable Magnetic Field Strength," *Journal of Propulsion and Power*, Vol. 32, No. 4, 2016, pp. 903–917. doi:10.2514/1.B35709

[17] Randolph, T., Kim, V., Kaufman, H., Kozubsky, K., Zhurin, V. V., and Day, M., "Facility Effects on Stationary Plasma Thruster Testing," *23rd International Electric Propulsion Conference*, Paper IEPC-1993-93, Sept. 1993.

[18] Walker, M. L., Victor, A. L., Hofer, R. R., and Gallimore, A. D., "Effect of Backpressure on Ion Current Density Measurements in Hall Thruster Plumes," *Journal of Propulsion and Power*, Vol. 21, No. 3, 2005, pp. 408–415. doi:10.2514/1.7713

[19] Walker, M. L., "Effects of Facility Backpressure on the Performance and Plume of a Hall Thruster," Ph.D. Thesis, Univ. of Michigan, Ann Arbor, MI, 2005.

[20] Brown, D. L., Larson, C. W., Beal, B. E., and Gallimore, A. D., "Methodology and Historical Perspective of a Hall Thruster Efficiency Analysis," *Journal of Propulsion and Power*, Vol. 25, No. 6, 2009, pp. 1163–1177. doi:10.2514/1.38092

[21] Brown, D. L., and Gallimore, A. D., "Evaluation of Facility Effects on Ion Migration in a Hall Thruster Plume," *Journal of Propulsion and Power*, Vol. 27, No. 3, 2011, pp. 573–585. doi:10.2514/1.B34068

[22] Dankanich, J. W., Walker, M., Swiatek, M. W., and Yim, J. T., "Recommended Practice for Pressure Measurements and Calculation of Effective Pumping Speeds during Electric Propulsion Testing," *Journal of Propulsion and Power*, 2016, pp. 1–13. doi:10.2514/1.B35478

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