

Performance Measurements from a Cluster of Four Hall Thrusters

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A cluster of four 600 Watt Busek BHT-600 Hall thrusters has been evaluated in terms of performance characteristics including the measurement of thrust, anode efficiency, and anode specific impulse. Operation of Hall thrusters in a clustered configuration may conceivably lead to increased charge exchange ions, amplified discharge current instabilities, and direct increases in thrust (due to localized re-digestion and plume focusing effects). In an effort to quantify these speculations, analysis of 600 Watt fixed-power performance is conducted in various configurations including: single thruster, dual thruster, tri-thruster, and full cluster (4-thruster) operation. The total thrust generated by the clustered operation of the BHT-600 thrusters is observed to exceed, by 3.6%, the sum of thrusts from the same thrusters when operated singly (for a 200 V discharge voltage). Finally, an estimate of the facility effects on thrust is used to demonstrate the back-pressure independence of the Large Vacuum Testing Facility (LVTF) utilized for these tests involving the low power BHT-600 cluster. Results from the clustered configurations and from the single thruster configuration are presented with operational set points determined by tuning the magnetic circuit and mass flow rates for optimal thrust to power and optimal efficiency at discharge voltages 150-V to 600-V.

Nomenclature

T	=	thrust
I_{sp}	=	total specific impulse of Hall thruster
$I_{sp,a}$	=	anode specific impulse of Hall thruster
η	=	total efficiency of Hall thruster

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- η_a = anode efficiency of Hall thruster
- P_{ion^*} = Corrected ionization gauge chamber pressure
- η_a = anode efficiency
- \dot{m} = mass flow rate of xenon propellant

I. Introduction

THE study of closed drift Hall thrusters over the past few decades has led to the development of efficient (>50% total efficiency), specific impulse competitive ($I_{sp} > 2000$ s), and high thrust to power (>50 mN/kW) propulsive devices. Today, Hall thrusters garner a broad array of space-based applications ranging from: satellite orbit boosting to GEO satellite North-South station keeping. The recently narrowed I_{sp} gap between ion thrusters and Hall thruster has further motivated the use of Hall thrusters for future interplanetary missions.

A. Motivation

As worldwide telecommunication demands increase, so too do the satellites that support these growing networks. The development of comparably higher power Hall thrusters is following suit. The large solar arrays donned by

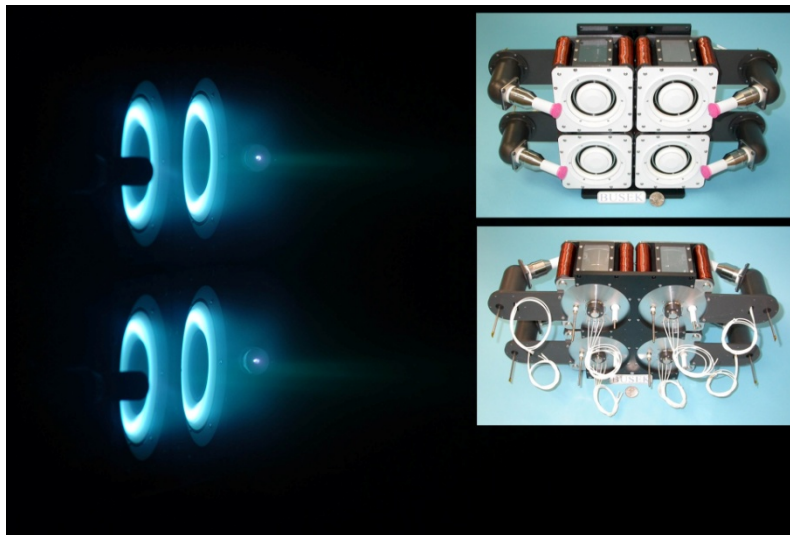


Figure 1. BHT-600 cluster running in LVTF at 600 Watts (300 V, 2.01 A) X 4 thrusters. Thrusters mounted on PEPL's milliNewton thrust stand. Inset photos, of Busek BHT-600 cluster front and rear prior to acceptance testing (U.S. quarter, 25 mm diameter, indicates scale).

modern telecommunication satellites, the high power-density thermoelectric power sources of future NASA missions [1], along with increased power demands from the Air Force [2], altogether represent the growing demand for an effective and efficient means of *electrically* propelling these large spacecraft. The aforementioned performance characteristics of modern Hall thrusters, places them as the leading electrical spacecraft propulsion candidate for the growing base of applications thus discussed. Yet, the ground based testing of high power Hall thrusters has limits imposed by the difficulty in maintaining a low vacuum (1×10^{-5} torr or lower) at the high mass-flowrates required to maintain the high power discharges [3]. Thus, interest has grown in the use of multiple Hall thrusters clustered together as a means of achieving greater overall thrust while still retaining the excellent performance characteristics of a single Hall thruster; one with moderate enough power to have undergone complete ground-based testing and development with coexisting vacuum chamber facilities.

B. Performance Measurements

In this paper, the performance effects from clustering multiple identical Hall thrusters are investigated. Thrust, specific impulse, and efficiency are among the various performance parameters that are measured. For the purposes

of data consistency all performance measurements are gathered at a fixed power level of 600 Watts, as this is the base power level of a single BHT-600 Hall thruster used in these experiments. To further the comparability of data in the differing clustered configurations, performance measurements will largely be expressed in a per thruster normalization basis – that is to say, for example, that the total thrust generated by operating the full cluster of four Hall thrusters simultaneously, is divided by four and reported as the effective single thruster thrust (or “per thruster thrust”). In this manner, trends due to any clustered configuration of Hall thrusters are directly observable by monitoring the trends in the measured performance parameters of thrust, I_{sp} , and efficiency.

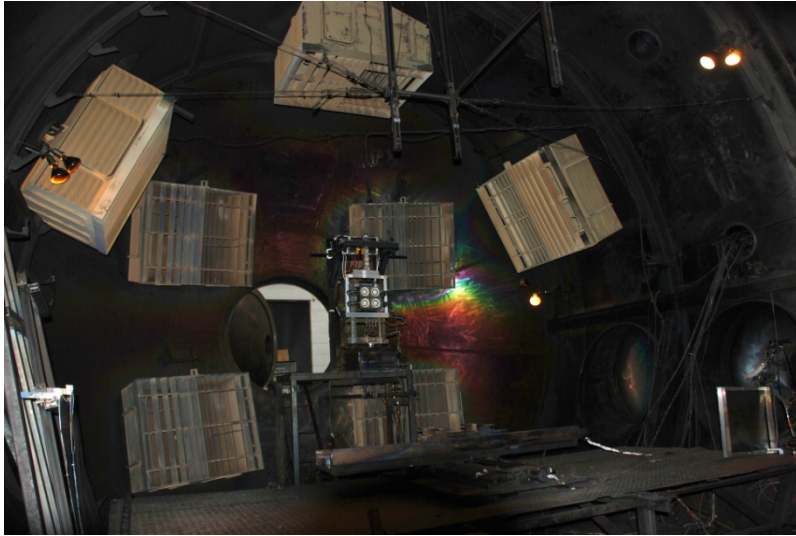


Figure 2. Internal view of Hall thruster cluster from within the LVTF. Cluster is mounted upon the NASA type inverted pendulum thrust stand, in the roughly radial center of the cylindrically shaped vacuum chamber. The seven cryogenic pumps are clearly visible. This photo was taken minutes before pumping down to vacuum conditions.

II. Experimental Setup

C. Busek BHT-600 Hall Thruster Cluster

A cluster of four identical BHT-600 Hall thrusters is utilized for these experiments. The cluster and the individual BHT-600s were designed by Busek Co. Inc., and were obtained by the University of Michigan’s Plasmadynamics and Electric Propulsion Laboratory (PEPL) in 2003 for testing the effects of operating clusters of Hall thrusters. Prior research performed at PEPL and the Air Force Research Lab (AFRL) [4-6] with an earlier cluster of four 200 W Busek BHT-200-X3 Hall thrusters provided a wealth of insight into the plume effects from clustering and led to the development of the BHT-600 cluster used in this research. Pervious measurements of the performance from a cluster of *four* Hall thrusters has yet to be published until now (at least as far as could be determined; however, sparse data does exist for dual- [7] and tri- [8] thruster clusters). The precise measurement of sub-milli-Newton resolution thrust levels from even a single thruster is a challenging task. Clustering four Hall thrusters together adds a great deal of complexity to the endeavor; since four times as many flow and electrical lines are required! Perhaps this explains the lack of prior research. Whatever the case, this research is crucial to quantifying and understanding the effects of clustering Hall thrusters - as such configurations will inevitably be required to propel future spacecraft – and ground-based testing facilities will not exist with the capacity to test fully clustered high-power Hall thruster configurations. The cluster used in this study is moderately low-power: at 600 Watts per thruster, the full cluster of four thrusters consumes a mere 2.4 kW of electrical power. Routinely, ground-based performance measurements from Hall thrusters powered in excess of 20kW are performed [9]. Therefore, this cluster is quite suitable for use in this performance study because it is unlikely to encounter vacuum pumping limitations.

Each BHT-600 has a discharge channel mean diameter of 5.6 cm and the thruster centerlines are separated 11 cm in both the vertical and horizontal arrangement within the cluster. Inner and outer electromagnets run at 2 Amps each for nominal conditions. Busek reports the following performance characteristics at 600 Watts ($V_D = 300$ V, $I_D = 2.05$ A, $\dot{m}_{total} = 2.6$ mg/sec) for a single BHT-600 Hall thruster: $T = 39.1$ mN, $I_{sp} = 1530$ sec, $\eta = 49\%$. These performance values have been confirmed within ± 1 mN agreement under matched conditions at PEPL during the

course of this research. Each thruster has its own 6.25 mm Busek BHC-5000 hollow cathode mounted at a 45° angle to the anode plane (Figure 1). The entire cluster unit is a flight qualified design, and appears to have a magnetic circuit and anode distributor optimized for a 2 Amp discharge current, as shall be seen in section H. This challenges thruster optimization at off-design discharge currents. The thrusters are numbered sequentially in a counter-clockwise manner beginning with the upper left thruster (T1) as viewed when looking into the discharge channel.

A dedicated set of five commercial Sorenson switching-based power supplies exists to operate each of the four thrusters (for a total of 20 power supplies): discharge (400 Volt 5 Amp, DHP400-5), heater (40 Volt 15 Amp, DLM40-15), keeper (600 Volt 1.7 Amp, DCS600-1.7E), inner magnet (60 Volt 10 Amp, DLM60-10), and outer magnet (60 Volt 10 Amp, DLM60-10). No current filtering is applied to the discharge supplies. Xenon flow is similarly controlled independently for each Hall thruster within the cluster, using commercial UNIT (UFC-7301) mass flow controllers (MFCs) calibrated for Xenon: 40 sccm-Xe max for anodes and 10 sccm-Xe max for cathodes. All eight MFCs are digitally controlled with a central LabView interface, and 10-channel UNIT MFC power supply. Digital control of the volumetric flowrate enables enhanced the accuracy of 1% of the *set-point* for most the MFC's specified range. A Humonics OptiFlow 570 Digital Flowmeter (bubble-meter) is used to calibrate each of the Anode MFCs prior to testing using both Nitrogen (with manufacturer supplied N₂ reference flowrates) as well as xenon. After applying the appropriate temperature correction to the bubble-meter flowrates (at ambient temperature of 25.5°C) to compute the effective standard flowrates (standard conditions: 101,325 Pa and 0°C) excellent agreement was observed throughout the full range of all four anode MFCs. All measured flowrates lay within the nominal error bars (1%) of manufacturer supplied MFCs' calibrations (with both N₂ and Xe); therefore the factory calibrations were left unchanged.

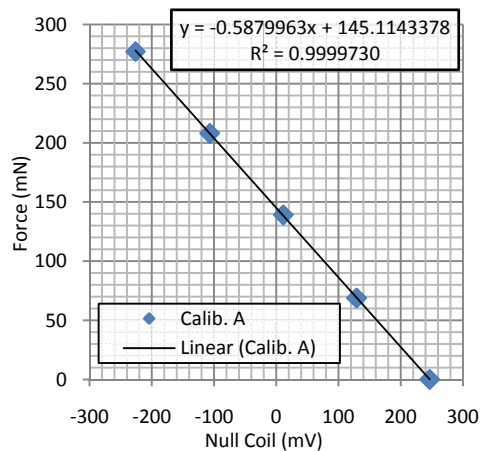


Figure 3. Sample calibration of thrust stand as measured for test#40. Linear fit parameters are listed. A total of 10 points are plotted but overlap quite well due to the excellent repeatability of the calibration.

measurements, six performance data points were acquired at a higher base pressure – resultant from only operating four of the available seven cryogenic pumps. With only four pumps in operation, the corrected, zero-flow, base pressure measured $P_{ion*4 pump} = 2.2 \times 10^{-6}$ torr. Unfortunately these were the first six data points collected; before various errors were removed from the performance measurement procedure; thus these higher pressure points shall not be fully examined.

D. Large Vacuum Testing Facility

PEPL's Large Vacuum Testing Facility (LVTF) is utilized to create the space simulating vacuum required for these tests. The LVTF is a stainless steel cylindrical vessel measuring 9 meters in length and 6 meters in diameter (see Figure 2). An array of seven cryogenic reentrant baffled vacuum panels are internally mounted around the thruster as positioned upon the thrust stand (center of cluster is aligned with the chamber's cylindrical centerline ± 30 cm). The aggregate pumping rate with seven pumps totals 240,000 liters/sec on xenon, the propellant used here. The chamber pressure is measured with an externally mounted hot filament ionization gauge. As the ionization gauge's calibration is made with air, a correction of the indicated pressure is required [10]. Nearly all of the performance data is collected while operating all seven pumps with a corrected base pressure of $P_{ion*} = 4.2 \times 10^{-7}$ torr (as measured with no thrusters in operation). The corrected chamber pressures vary with the total Xe flowrate used during a test and typical values for single thruster and clustered operation are 3.1×10^{-6} torr and 1.1×10^{-5} torr, respectively. In an effort confirm the chamber pressure independence of the presented thrust

E. Thrust Stand and Performance Measurements

The measurement of the force signal resulting from the thrust produced by the operation of the BHT-600 Hall thrusters is executed with a NASA-GRC type inverted pendulum Null balanced thrust stand [9]. A linear variable displacement transducer (LVDT) is used to measure the small displacement caused by the thrust force applied. This LVDT signal is the input to a commercial Stanford Research Systems closed-loop proportional, derivative, and integral (PID) feedback controller. The PID output is amplified with a linear power supply and applied to a Null balancing electromagnetic coil to restore the thruster platform to the initial set-point. This commercially available OTS (off the self) solution to control the Null coil was only recently implemented at PEPL [11] and improves the accuracy, repeatability, and ease with which thrust measurements are performed. The magnitude of this PID output (the Null signal), is proportional to the force applied to the thruster platform. Small weights strung along a two pulley system may be remotely lowered with a small DC motor, thereby applying a series of small forces to the thruster aligned parallel to the thrust force. In this manner, the proportionality constants between the Null signal (in milliVolts) and the thrust force (in milliNewtons) are ascertained from a linear regression. Calibrations of this type are performed for *each* measurement of thrust reported in this paper. While the average slope from all 47 tests performed exhibits a variance of only 0.43%, the zero point (with zero thrust production and no weights applied) shifts are significant due to thermal loading and other effects, thus are calibrations performed for every measurement of thrust. The mean correlation (Pearson) coefficient from all 47 calibrations is $R^2_{\text{ave}}=0.99993$ (minimum $R^2_{\text{min}}=0.99951$). The procedure followed for each measurement of thrust is as follows:

1. *start cathode keepers if not already running*
2. *initiate desired xenon flow to anode, wait two minutes*
3. *activate Hall thruster(s) and set all power supplies to appropriate settings, shutting off keepers*
4. *wait thirty minutes or more until discharge current and thrust signals level out (changes less than 1% per 5 minutes are considered "leveled out")*
5. *record the Null signal representing thrust – immediately afterwards extinguish discharges by shutting down discharge supplies and closing propellant flow lines but leaving magnets on (cathode keepers are turned on prior to thruster shutdown)*
6. *two minutes after shutdown record zero point of the Null signal*
7. *immediately perform an in situ calibration of the thrust stand using the small weights*

The Null signal is measured in three separate ways for redundancy: a Fluke 77 III digital multimeter, an analog strip chart, and a PC data acquisition system with digital LabView-based strip chart data-logging program. The multimeter specifications provide the best accuracy of the three measurements, and are therefore used as the primary measurement of the Null signal (thus used to compute thrust). Even so, the effective resolution of the multimeter is only 12-bits, and thus proves to be the dominant source of error in these experiments. Future work is already underway to add additional resolution to the Null signal measurement. The resolution of the Null signal, with this setup, is 0.1 mV (or 0.06 mN, in terms of thrust) as limited by the digits displayed on the multimeter. The error arising from the multimeter Null signal measurements tallies an average of about ± 1 mV. The error due to the "goodness" of the linear fit is determined as well, and averages about ± 0.7 mV. Together these errors give rise to an average accuracy of about ± 1 mN for the measurement of thrust. This represents the absolute error, whereas the repeatability of the measurement of thrust has a significantly improved precision. To quantify the repeatability, a few thruster cases were repeated to measure T under the same operational conditions but on separate days. The half-dozen repeated tests yield a standard deviation, $\sigma = \pm 0.22$ mN, for both single thruster and full clustered operation. Care has been taken in the computation of all accuracies of the performance measurements herein reported. Standard methods of error propagation are applied to each measurement of T, I_{sp} , and η . The respective errors are displayed as error bars on all plots and these errors fully represent the absolute accuracy propagated into the computation by including all known sources of error (MFCs, thrust stand, displays, power supplies, etc.).

F. Cathode Suspension

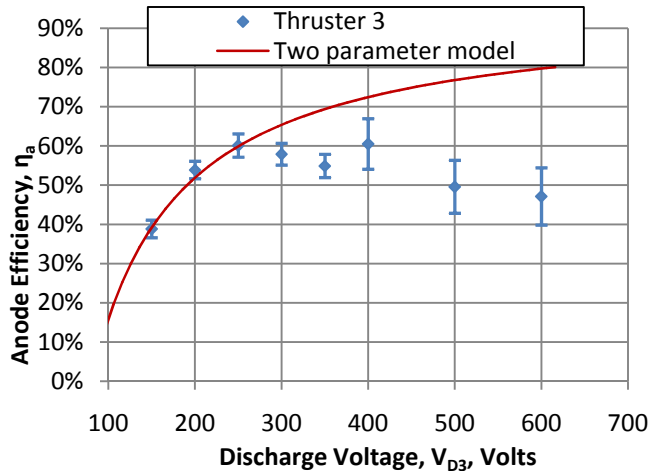


Figure 4. Fixed power 600 W single thruster anode efficiency at discharge voltages ranging from 150 V to 600 V. Model data is included for qualitative comparison.

Unique to this setup (but not unheard of), the cathodes were suspended away from the BHT-600 Hall thrusters, thereby isolating them from the thrust stand. This detachment of the cathodes was necessitated by the sheer number of eight xenon flow lines that are nominally required to operate the full cluster. The thrust stand does, however, have four flow lines integrated into its design and thus the four BHT-600 anodes were attached to these. By disjoining the cathodes from the thrust stand, the remaining four cathode flow lines could then be run externally to the cathodes. Other configurations involving split flows and electrically actuated valves were also considered, but ultimately abandoned, due to complexity issues and significant uncertainties in the per thruster xenon flow.

An aluminum frame rigidly supporting the cathodes was attached to the cluster – tightly routing all cathode flow lines and electrical lines to central distribution points. The complete cluster of BHT-600 thrusters was mounted to the thrust stand and the cathode support frame was externally supported with a rigid connection to an overhanging beam. Once this configuration was attained, the screws securing the cathodes to the Hall thrusters were removed. The cathode frame assembly was then shifted by 3.2 mm to create a safe non-contact gap between the cathodes and the thrusters. This shift also effectively pushed the cathode emission tips 3.2 mm closer to the anode exit plane of the cluster.

G. Cold Gas Thrust Correction

One unexpected observation during these experiments was the significance of the cold xenon thrust produced in the absence of a plasma discharge. Ideally, the measurement of thrust (Null signal) is followed by extinguishing the discharge and flow, then measuring the zero point of the Null signal, and finally performing a calibration. In order to mitigate the impact of the thermal drifting that occurs to the zero point of the Null signal, the preceding tasks should be carried out in quick succession. Unfortunately, the thrust produced by the thruster setup did not drop to zero immediately after extinguishing the discharge and flow. Indeed, a set of cold gas flow experiments were conducted at all flowrates operated to quantify the taper of cold gas thrust after closing the anode flow lines. In summary, it was concluded that the thrust due to the purging of the flow lines after closure dropped to zero (± 0.06 mN) within 120 seconds of line closure – for all anode flowrates. For this reason, the procedure listed in section 0, includes a 2 minute wait period to ensure the true zero point of the Null signal is achieved before recording. The flow lines that carry xenon from the outside of the LVTF traverse nearly 30 feet before reaching the thruster, so it is no wonder that they contribute to the thrust for a period of time after shutoff. The largest magnitude of cold gas thrust observed was under 1 mN (the thrust right before shutoff of the flow), and although this may seem like a small amount, it is imperative to remove as many sources of error as possible in order to attain a high level of repeatability. This way, the fine differences in thrust for the various clustered configurations can be meaningfully resolved.

III. Experimental Results:

H. Single Thruster Performance Measurements

In order to characterize the performance of a single thruster within the cluster of BHT-600 thrusters, the magnetic fields and anode flowrate must be optimized for each discharge voltage under investigation. Optimization occurs when the efficiency of the thruster is maximized. Total and anode efficiencies are defined for an electric thruster as:

$$\eta = \frac{T^2}{2\dot{m}P_T} \quad (1)$$

$$\eta_a = \frac{T^2}{2\dot{m}_a P_D} \quad (2)$$

P_T and P_D represent the total electrical power (including electromagnets) and the discharge power respectively. The flowrate in Eq.(1) is the total xenon mass flow to the thruster, including both the anode and cathode; whereas the anode efficiency only includes the anode mass flowrate. The efficiencies defined in Eq.(1) and Eq.(2) are thruster efficiencies only, and do not incorporate the losses associated with the power supplies (which have efficiencies near 80% at full load). Using the second equation, we can now present results obtained for the *quasi-optimization* performed with Thruster number 3 (T3). Figure 4 displays the variation of the anode efficiency, at the different discharge voltages examined. Typically, one expects the anode (or total) efficiency of a Hall thruster to increase monotonically with the discharge voltage. This trend is presented as the included “two parameter model” data also shown in Figure 4. The model, adapted from other Hall thruster “two parameter” models [12] is a rudimentary (but never-the-less useful) attempt to account for the *real world* efficiency behavior of a Hall thruster at different discharge voltages.

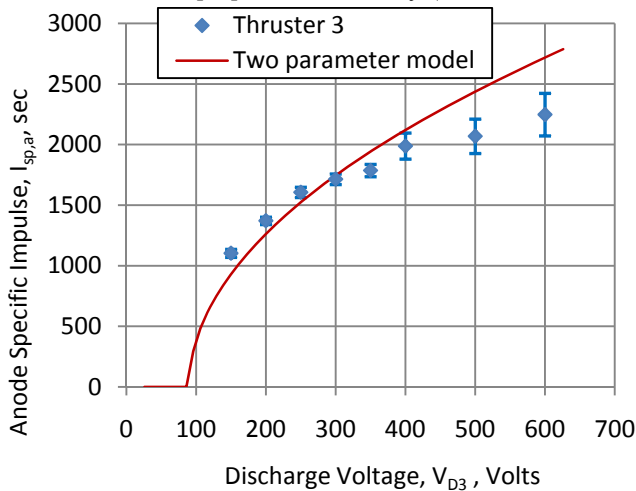


Figure 5. Fixed power anode specific impulse for quasi-optimized single thruster BHT-600. Sample model data included for qualitative trend comparison.

discharge current, and the cathode flow is nominally set to 8% of the anode flow. 2) The inner and outer electromagnet currents are varied slowly while watching the efficiency and thrust/power values in real-time (via a LabView data-logging interface). 3) After mapping a sufficient range of magnet settings, the point of maximum efficiency is returned to. 4) Finally the discharge current is set to the desired value by adjusting the anode flowrate in the appropriate direction (and cathode flow follows at 8% of the new anode flow). 5) Once the desired discharge current is attained and stabilized, the magnet settings are rechecked to confirm the optimization. This procedure is imperfect since the flowrates are not sufficiently tuned. As such, expected trends such as increasing efficiency with

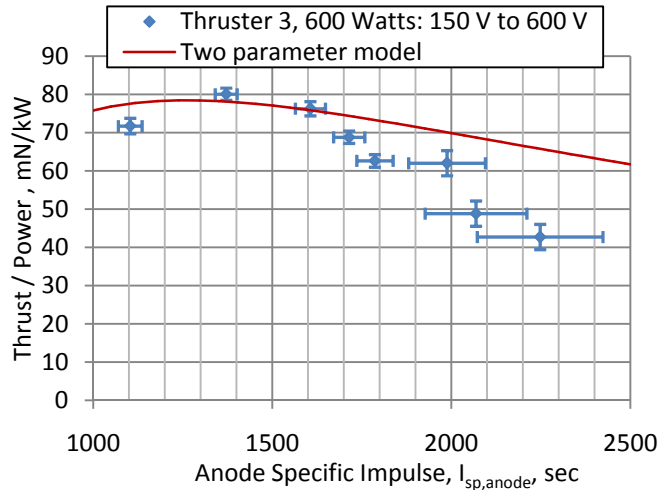


Figure 6. Fixed power Thrust to Power trend of quasi-optimized single thruster BHT-600 performance. Sample model data included for qualitative trend comparison.

discharge voltage. This trend is presented as the included “two parameter model” data also shown in Figure 4. The model, adapted from other Hall thruster “two parameter” models [12] is a rudimentary (but never-the-less useful) attempt to account for the *real world* efficiency behavior of a Hall thruster at different discharge voltages. The model data is only shown here to suggest the expected performance trend of the Hall thruster had the optimization procedure proved more fruitful. The presented experimental data diverge from the model, exhibiting an efficiency plateau at about 200 Volts and then, after 400 Volts, efficiency decay begins. This efficiency loss might be the result of poor propellant utilization at the lower flowrates used for 600 Watt discharges above 400 V. These settings are referred to as quasi-optimal because they may not represent the true optimal setting of the BHT-600 at the tested discharge voltages. For each discharge voltage a reasonable effort was applied in the tuning process to find the optimal magnet settings; but the anode flow and cathode flow are not adjusted significantly to enhance the attained optimization. The applied procedure of optimization roughly follows: 1) The anode flow is initially set by an estimate based on the desired

increasing discharge voltage may not be correctly captured. Additional experiments are certainly required to more fully optimize this thruster. For the purposes of the research herein presented, finding the true optimal settings is not necessary. Indeed, the main interest of this experiment is to see how the various performance parameters are affected by the operation of differing clustered configurations. So long as the same quasi-optimal settings are used with each of the thrusters, then the effects caused by clustering Hall thrusters are still accurately measured.

Next presented in Figure 6, is the Thrust to Power (discharge power) versus the anode specific impulse. The anode specific impulse is defined in units of seconds as: $I_{sp,a} = T/(\dot{m}_a g_0)$, with $g_0 = 9.81 \text{ m/s}^2$. The same thrust measurements used here were also used in Figure 4, but we can now explore the throttleability of the BHT-600 Hall thruster. Again, some model data is shown in conjunction with the experimentally measured data. A clear peak in the measured thrust to power of 80 mN/kW appears at an anode specific impulse of about 1370 sec. This maximized thrust to power performance corresponds to a 200 Volt 3 Amp discharge of the BHT-600. As seen earlier, the performance drops as the anode specific impulse (which scales with the discharge voltage as seen in Figure 5) continues to increase.

Having examined the bulk of the measured single thruster performance data, a clear loss of performance is consistently observed at discharge voltages above 300 Volts. There may be several reasons for this performance drop. As mentioned earlier, this could be the result of imprecise optimization. Another possibility is that the operational envelop of this thruster is narrow, and off-design settings, especially at higher discharge voltages, simply run inefficiently. Finally, the “flight qualified” nature of the BHT-600 likely leaves little room for increasing the peak discharge channel magnetic field due to a minimized use of heavy magnetic core materials. The iron alloy may begin saturating at electromagnetic currents just above the nominal current of 2 Amps used for the 300 Volt 2 Amp

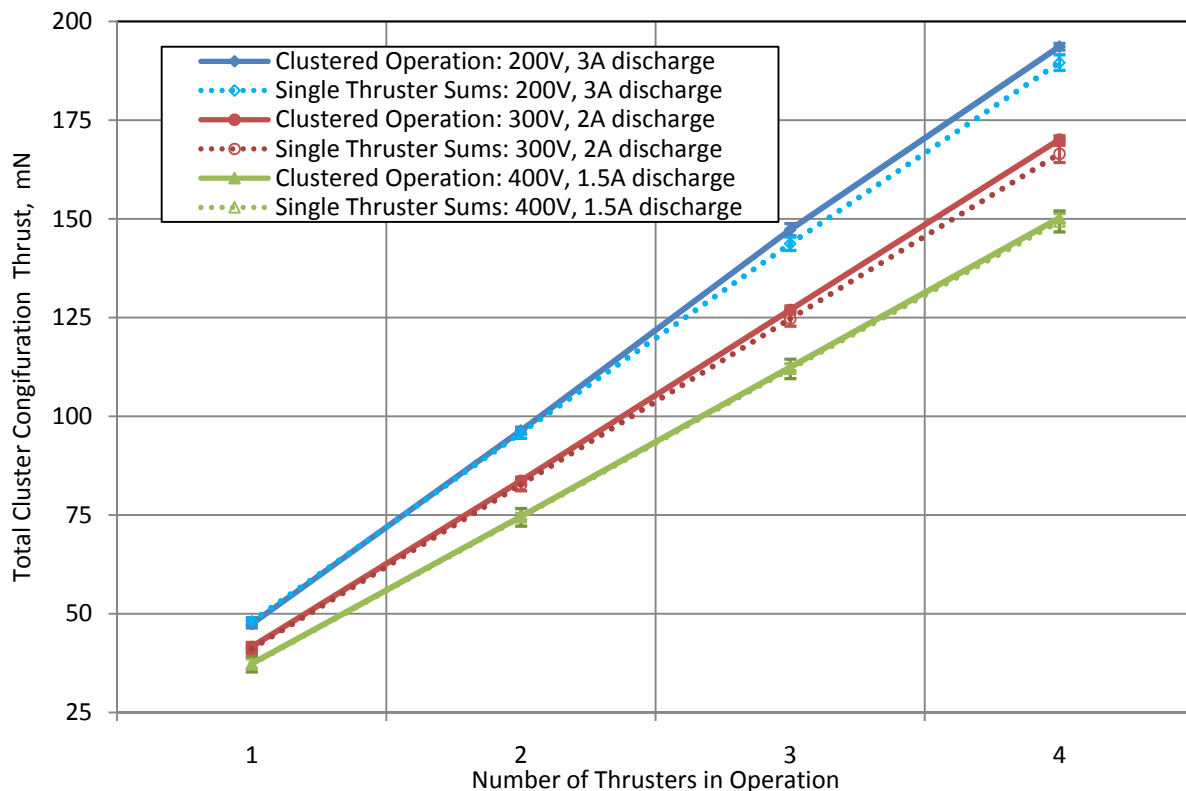


Figure 7. Total thrust produced by single (600 W), dual (2 x 600 W), tri (3 x 600 W), and quad (4 x 600 W) Hall thruster cluster operation. Also shown is the sum of the thrusts collected for each of the thruster when operating alone (un-clustered). The clustered total thrust exceeds the sum of the non-clustered individual thrusts for every point measured.

discharge settings. Additionally, this lack of extra iron lowers the thermal dissipation mass of the thruster and risk of nearing the Curie point temperature of the core materials is increased at higher electromagnet current settings (due to resistive heating of the coils). Indeed, while attempting to optimize the operation at discharge voltages above 300 Volts, unusual thrust trends were observed when attempting to run the electromagnets at currents in excess of 2.5 Amps. It is thought that the electromagnets might be overheating at such high settings, thereby lowering the saturation magnetic field strength – potentially causing saturation and distortion in the magnetic field lines. Lending to this hypothesis was the observation that the electromagnets could be operated at increased currents as high as (4 Amps) causing noticeable variations in performance – but only for a short period of time, since the discharge current would then drift in a peculiar and inconsistent manner if the electromagnetics remained at such current levels. Because of this characteristic, the highest magnet current used in the optimizing of the BHT-600 was 2.5 Amps. It is quite likely that better high discharge voltage performance optimization would have been achieved if the electromagnets could be reliably operated above 2.5 Amps.

I. Clustered Hall Thruster Performance Measurements

Now that a set of quasi-optimal throttle points have been mapped for a single thruster, various multi thruster configurations are examined using these same settings. In general, manufacturing tolerances could give rise to slightly shifted optimal settings for each thruster within the cluster. In this paper we shall ignore that possibility, and assume that the quasi-optimized settings determined for thruster 3 will apply as quasi-optimal settings for the remaining three thrusters. In practice, this assumption appeared quite valid, but even so, the variance in the thrust produced by the individual thrusters ranged from 1.0 mN or 2.2% (at a $V_D=200$ V) to 0.2 mN or 0.5% (at $V_D=400$ V). With measureable differences in thrusts among the different BHT-600 units, additional experiments were deemed necessary to measure the thrust of *each* BHT-600 thruster at *each* the three discharge voltages of 200 V, 300 V, and 400 V. While this squared the intended test matrix, it has yielded the impressive results in Figure 7. Here the linear trend of increased thrust is apparent as additional Hall thrusters are added to the clustered configuration. Now, in addition to these data, the sums of the thrusts from the individually (non-clustered) operated Hall thrusters are also shown in Figure 7. Remarkably, for each data point the clustered net thrust exceeds the sum of the individual thrusters – and at several points these differences exceed the all of the uncertainties involved in the measurements of thrust! Thus is it experimentally proved that when clustering together Hall thrusters: the thrusts of one plus one does not equal two. Indeed, we can quantify the clustering gained boost in thrust with the aid of the following Table 1:

V_D (Volts)	I_D (Amps)	Indiv. Thrust per Thruster (mN)	Clustered Thrust per Thruster (mN)	Boost in thrust from clustering (%)
200	3.0	47.2	49.0	3.62%
300	2.0	41.8	42.9	2.55%
400	1.5	37.4	37.6	0.65%

Table 1. Gain in Thrust due to clustering Hall thrusters at different discharge voltages.

To determine the listed “Thrust per Thruster” values a linear regression was applied to each of the six curves in Figure 7. The resulting slope possesses the units of mN/thruster and is thus used to populate Table 1. This method may underestimate the clustered per thruster thrust since all clustered configurations are weighted equally in a method of least squares fit. It is plausible that thrust boost is a non-linear function of the number of clustered Hall thrusters. Yet, with only four Hall thrusters to study in this research there is no way to be certain what might happen to the thrust boost as dozens of Hall thrusters are clustered together. The percent boosts in thrust shown in Table 1 are with respect to the non-clustered condition of operation. While a mere 0.65% gain in thrust is achieved at a 400 Volt discharge, a whopping 3.6% thrust boost occurs at 200 Volts! As has been suggested in prior Hall clustering research, localized propellant re-digestion may provide a physical mechanism to increase thrust. For our fixed-power data we notice that the propellant flowrate is highest at the lower voltage discharges: at 200 V 3A, the anode flow to a single BHT-600 registers 3.57 mg/sec-Xe (versus 2.47 mg/sec for a 300V 2A discharge and 1.91 mg/sec for a 400V 1.5A discharge). Interestingly, ratio of the 200 Volt thrust boost to the 300 Volt thrust boost works out

to be 1.42 while their flowrate ratios equate 1.50; certainly lending support the localized propellant re-digestion hypothesis.

1. Facility Effects on the Production of Thrust

One possible flaw in the propellant localized re-digestion hypothesis is the vacuum chamber facility effects, since the aggregate flowrate when running the full four thruster cluster is four times the flowrate incurred in running a single thruster. A deal of prior research has been applied to understanding and correcting for the facility effects in operating electric thrusters of this kind [3, 7]. Thankfully, the cluster utilized in this research is nominally low-power at 600W per BHT-600, and thus the seven employed cryogenic pumps do not struggle to maintain low-vacuum (1×10^{-5} torr) whilst pumping 240,000 liters of xenon per second. To put this back-pressure effect into perspective we can apply some basic gas kinetics laws regarding the random flux of particles into discharge channel to express the thrust increment $\Delta T_{\text{chamber}}$ due to this pressure [7]:

$$\Delta T_{\text{chamber}} = A_{\text{eff}} P_{\text{chamber}} P_{\text{ioniz}} \sqrt{\frac{eV_D}{kT_{\text{amb}}}} \quad (3)$$

Where, A_{eff} is the *effective area* of the discharge channel, P_{chamber} is the corrected chamber pressure, P_{ioniz} is the probability of ionization, e is the charge constant, V_D is the discharge voltage, k is Boltzmann's constant, and T_{amb} is the ambient room temperature in Kelvin (all SI units). This equation conservatively assumes that the ingested particles (xenon atoms here) would be accelerate to the full potential of the discharge voltage. Also, a 100% ionization probability is assumed. Using the combined discharge channel area of all four BHT-600 thruster discharge channels, $A_{\text{eff}} = 4 \times 12 \text{ cm}^2 = 48 \text{ cm}^2$ and $T_{\text{amb}} = 315 \text{ K}$ we construct the following table:

P_{chamber} (torr)	$\Delta T_{\text{chamber}}$ (mN)
1.00E-07	0.0038
1.00E-06	0.0380
1.00E-05	0.3798
1.50E-05	0.5698
2.00E-05	0.7597
1.00E-04	3.7984

Table 2. Estimation of facility effect thrust due to the imperfect (non-zero) vacuum pressures: assuming 100% ionization, and 100% acceleration (300 V, discharge) of the random particle flux into all four BHT-600 thrusters.

The highest measured corrected chamber pressure was 1.5×10^{-5} torr, occurring during the operation of the full four thruster cluster at a discharge of 200 V and 3 A. The total clustered thrust generated at this condition measured 193.6 mN, ± 0.85 mN. According to Table 2, we can see the facility contribution to total thrust estimate is only 0.6 mN or about 0.3% of the total thrust. While a better means than the provided kinetic estimate is required to truly quantify the facility effects of the BHT-600 cluster, it is at least clear that the magnitude of thrust due to facility caused propellant re-digestion is on the order of the overall error in the measurement of thrust. As such, the observed increases in thrust (in Table 1) can only be attributed to *localized* propellant re-digestion (an effect that would also occur in the true vacuum of space, due to the thruster to thruster proximities) or some other clustering phenomena such as beam focusing that have been observed in clustered Hall thruster beams [6].

2. Cluster Performance: Additional Results and Discussion

Next presented in Figure 9 and Figure 8 are the clustered anode efficiency versus discharge voltage, and the clustered thrust to power versus anode specific impulse, respectively:

While the overall clustering trend of improved performance is indeed observed in the preceding two figures, the

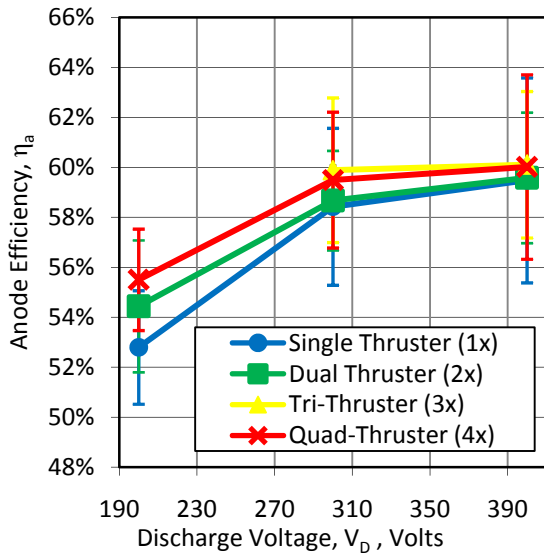


Figure 9. Anode efficiency from various clustered configurations. The single thruster data represents the mean anode efficiency computed from separate experiments with each of the four thrusters at the three discharge voltages shown.

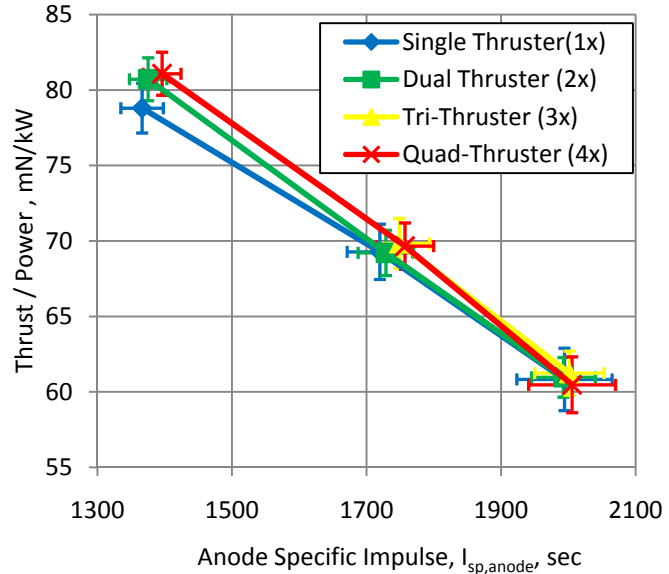


Figure 8. Thrust to Power ratios plotted against anode specific impulse for all clustered configurations. The single thruster data represents the mean T/P_D computed from separate experiments with each of the four thrusters.

absolute errors in propagated into the computations of anode efficiency and anode specific impulse overwhelm the certainty in these trends. To more accurately display the data, the single thruster data points are computed from the average values of these performance parameters (T/P_D , η_a , and $I_{sp,a}$) as measured separately with each of the four BHT-600 thrusters. As was seen in Figure 7, where the sum of the individually measured thrusts was less than the total clustered thrust, it is also observed here that the clustered values of T/P_D , η_a , and $I_{sp,a}$, exceed those same values measured during single thruster operation. Recalling that a maximal boost in thrust is observed at our lowest voltage 200 V discharge setting, we see that this corresponds to our least efficient point. This implies that the performance benefits from clustering are greater for lower efficiencies. Considering how anode efficiency is defined in Eq. (2), the clustering boost in thrust must be resulting from increased free propellant flux. The anode efficiency of our Hall thruster drops at low voltage likely because more xenon is being exhausted than can be effectively ionized and fully accelerated away from the anode. Thus, a larger fraction of neutrals and incompletely accelerated ions exit each Hall thruster discharge channel. In single thruster operation, these particles would stream or radiate away from the thruster and contribute little to the overall thrust. Now, when Hall thrusters are closely clustered together, many of these particles will stream across the faces of the neighboring thrusters. To these neighboring thrusters these overlapping plumes give rise to slight increases in the localized density near their discharge channels (compared to non-clustered operation where no plume overlap occurs). This additional flux of propellant can then be more fully ionized and accelerated by these neighboring thrusters thereby leading to increased overall performance of the cluster. In this way, clustered Hall thrusters cooperate with each other to improve performance beyond what is achieved alone and unclustered.

IV. Conclusions

Fixed power, 600 Watt per thruster, performance measurement have been performed with the BHT-600 four thruster cluster in all basic configurations including: single thruster, dual thruster, tri thruster, and quad cluster operation. Single thruster quasi-optimizations were carried out with one of the BHT-600 Hall thrusters at 8 different discharge voltages between 150 Volts and 600 Volts. Nominal accuracy in the absolute measurement of thrust was about 1 mN with an observed repeatability of 0.3 mN. Cold gas flow corrections were applied to the measurement technique, and vacuum facility effects were estimated to contribute negligible thrust (< 1 mN) at all operational conditions from quad clustered to single. Performance measurements from the clustered configurations exceeded the single thruster values for the three discharge voltages evaluated (200 V, 300 V, and 400 V). The total thrust from the running each of the clustered configurations always exceeded the sum of the thrusts produced by the same thrusters when operated alone. The direct gain in thrust due to clustering measured 1.8 mN per additional thruster (3.6%) at 200 V and 0.2 mN per additional thruster (0.7%) at 400V. Small increases are similarly observed in the clustered efficiencies and clustered specific impulses when compared to the non-clustered (single thruster) performance.

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