Developmental Status of a 100-kW Class Laboratory Nested channel Hall Thruster

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Abstract: Currently in the United States there is increasing commercial and governmental interest in Hall-effect thrusters for high power applications. Of the Hall-effect thrusters configurations available, it has been observed that Nested channel Hall thrusters (NHT) are well suited to high power applications. The proof of concept work of Liang on the X2 NHT has shown that such a configuration meets or exceeds the performance of conventional single-channel thrusters. In order to extend the NHT concept to higher operating powers with a wider throttling range, the Plasmadynamics and Electric Propulsion Laboratory at the University of Michigan, with the support of the United States Air Force Office of Scientific Research and NASA, is developing a 100-kW class laboratory-model NHT. The motivation and heritage of this thruster, along with the necessary preparations undertaken to test such a device are discussed in this paper.

Nomenclature

T = thrust
P = propulsive power
Isp = specific impulse
T/M = thrust/mass
η = thruster efficiency
T/M = thrust/mass
α = mass/power

I. Introduction

Of the Hall-effect thrusters configurations available, it has been observed that NHTs are well suited to high power applications.[1] The proof of concept work of Liang on the X2 10-kW class NHT has shown that such a configuration meets or exceeds the performance of conventional single-channel thrusters.[2,3] In order to extend the NHT concept to higher operating powers with a wider throttling range, the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan, with the support of the United States Air Force Office of Scientific Research (AFOSR) and NASA, is developing a 100-kW class laboratory-model NHT known as the X3.

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When considering high power operation, an NHT has many advantages over large single-channel Hall thrusters or clusters of small single-channel Hall thrusters. Among these are reduced footprint, increased thruster specific power, and improved operation over a wider throttling range.[1,4] The wide throttling range of a high power NHT gives it additional superiority in the realm of long range solar electric propulsion (SEP) missions. As an SEP craft travels further from the sun attenuating available system power, an NHT would still be able to operate as an efficient device; a significant attribute that a conventional state of the art (SOA) single channel Hall thruster designed to a narrow power range does not possess.

This second-generation NHT features three discharge channels and has seven distinct operating regimes comprised of the various combinations of channel operation, discharge voltage and current. These configurations allow for an unprecedented range of operation from low-voltage, high thrust-to-power, to high-voltage high-Isp operation, with a power throttling range spanning 1 kW to 200 kW. The thruster should be able to achieve up to 15 N of thrust at moderate specific impulse and 4,600 sec of Isp at high voltage with xenon and krypton propellants, respectively.

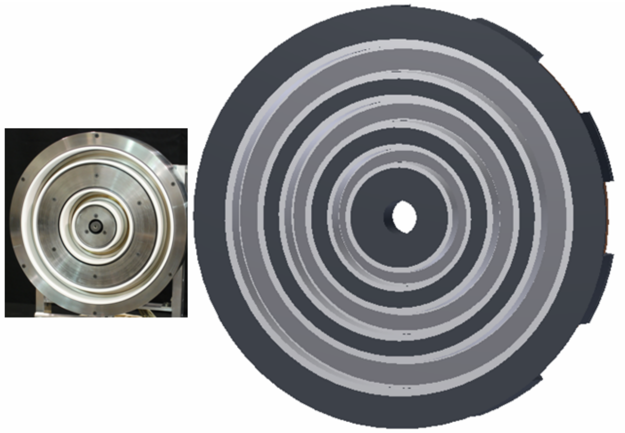


Figure 1. A rendering of the X3 100-kW class NHT (right) beside the X2 NHT (left).

Maximum Exit Area (Low ISP—High T/P operation)	ISP Range (1400s-3200s)	Medium Exit Area (Mid ISP operation)	ISP Range (2000s-3600s)	Minimum Exit Area (High ISP Operation)	ISP Range (2000s-4600s)
	Power Range		Power Range		Power Range
	30 kW-240 kW		20 kW–170 kW		10 kW-140 kW
			15 kW–120 kW		5 kW-90 kW
			10 kW-80kW		1 kW-50 kW

Figure 2. Illustration of seven possible channel configurations for the X3 100-kW class NHT. Channels utilized are highlighted in color (red- tri-channel mode, green- dual channel mode, blue- single channel mode). Power ranges showing the capability of each configuration are given, highlighting redundancy inherent in NHT concept via the overlapping power ranges.

The remainder of the paper is organized as follows. In Section II we will discus the background and heritage that this thruster is built on, and the motivation behind engaging in the development and fabrication of a high power NHT. Section III provides an overview for the selection process of a high power Hall thruster. In Section IV, some of the facility augmentation necessary for testing a thruster of this magnitude will be presented, as well as initial plans for testing. Finally, in Section V, we will summarize the status to date, and layout the near term plans for the thruster.

II. Background/Motivation

The University of Michigan/AFOSR Center of Excellence in Electric Propulsion (MACEEP) is a research entity comprised of a number of universities and a small business in the U.S., with the University of Michigan as the lead institution. The Center's avenues of scientific pursuit can be distilled to four distinct thrust areas: High-Power Plasma Propulsion, Electrospray Propulsion, Time-Resolved Plasma Diagnostics, and Modeling and Simulation.[5] Under the first category, the X2 proof of concept thruster was first conceived. The testing and evaluation of the X2 thruster has indeed shown that the NHT concept is feasible and can produce performance comparable or in excess of conventional single channel Hall thrusters which have produced thrust in the range of milli-Newtons and performed at efficiencies >60% .[2,3,6]

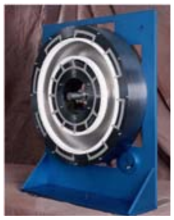


Figure 4. NASA 457M High power Hall thruster.[9]

Throughout the past decade, there has been a steadily building interest in developing high power EP devices for long range cargo missions and other taxing maneuvers.[7-12] Recently, the United State government has identified the importance of fast and efficient payload delivery to geosynchronous Earth orbit (GEO)[13] and the use of high-power electric propulsion (EP) for NASA's Game Changing Technology Development (GCTD), Innovative Advanced Concepts (NIAC), and Space Technology Research Grants. A recent NASA Solar Electric Propulsion (SEP) Demonstration Mission Concept Studies broad agency announcement (NNC11ZMA017K) asked for concept/mission studies of advancing key in-space propulsion concepts for a 300-kW SEP tug. Additionally, a high-power EP tug spacecraft has been examined for delivering cargo to the Moon and Mars.[14-15]

Figure 5. NASA 400M High Power Hall thruster[10]

The United State Air Force has also identified the importance of fast and efficient payload delivery to geosynchronous Earth orbit (GEO).[13]. The Air Force DoD SBIR 11.2 solicitation AF112-177 stated as a goal a new, high-power (50 – 100 kW), low thruster specific mass (<1.5 kg/kW), efficient (>60%), high thrust-to-power (*T/P*), and very long-life EP system for efficient and fast orbit transfers, station-keeping, and primary propulsion system for orbit raising. Additionally, as mentioned earlier, one of the AFOSR initiated Center's primary goals is the development of high-power (hundreds of kW) in-space propulsion devices.[5] Addressing the future needs that have been laid out through multiple solicitations from both NASA and DoD, total system power can reach tens to hundreds of kW, at specific impulses (I_{sp}) of ranging from 1,000 to 4,000 seconds, and high *T/P* ranging from 40 to >80mN/kW.

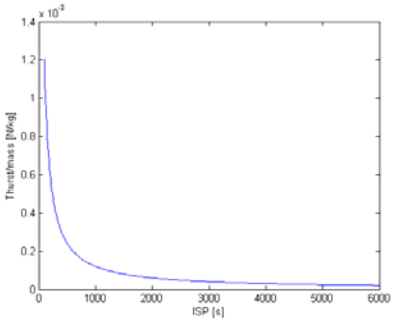


Figure. 3. Plot showing the reciprocal relationship between thrust/mass and ISP (see Eq.2).

Ready access to space imposes some difficult requirements on space propulsion and power systems, specifically short orbit transfer times, thruster mass, and cost efficiency. Propulsion systems requirements drive technologies to high-I_{sp}, high thrust (T), and relatively high thrust/mass (*T/M*). The first two requirements imply high propulsive power (P); the last requires high power densities and concurrent low masses for the propulsion system. All of these requirements can be expressed symbolically by the following relations:

$$P = (T g_0 * I\_sp)/2\eta \qquad (1)$$

$$T/M = T/\alpha P = 2\eta/(\alpha g_0 * I\_sp), \qquad (2)$$

where η equals the thruster efficiency in converting electrical power to directed kinetic power. The importance of these two equations is that while power can increase either from high I_{sp} or thrust, the thrust/mass of the propulsion system depends inversely upon specific impulse. These dependencies drive propulsion system requirements to an *optimum* I_{sp}, rather than a maximum I_{sp}, at which a system of a given α can deliver payload most efficiently.

It is with demonstrated need and interest in mind, particularly evidenced in recent U.S. solicitations, Ref. 1,7,12, coupled with the success of the X2 that has led MACEEP to initiate the investigation of the X2's natural next progression: a high-power, 100-kW class NHT. This second generation NHT has been scaled to address both AFOSR high thrust to power, expanded throttleability goals as well as NASA high power, high Isp operation. The ability to effectively operate over a range of voltages and flow rates coupled with the thruster's seven distinct channel configurations (Fig. 2) allows it to meet the breadth of goals presented by both agencies. With its 200:1 power throttling ratio, the thruster can operate efficiently in a wide range of scenarios, including: long-range SEP missions that start out with a large amount of system power (100's of kW) near Earth but diminishes as the craft reaches its objective further from the Sun, to nuclear electric propulsion missions, which consistently require the ability to process high power input, to a range of near Earth missions of fixed or variable power.

The expansive range of possibilities for such a high-power NHT were framed by the goals of the interested parties combined with the current capabilities of ground based facilities. A component of that framing was the conduction of a survey of all available vacuum test facilities and their pumping speeds worldwide in order to determine the maximum theoretical operating pressure for a given set of mass flow rates. Pairing that information with the power ranges of interest, a design was settled on that would be able to satisfy the interests of all parties while still being capable of actual ground-based evaluation throughout that range.

The development of the X3 100-kW class NHT has truly become a multi-agency, multi-entity effort, that draws on the expertise of the MACEEP, ElectroDynamic Applications (EDA), AFOSR, NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL). The design of this thruster has benefited from a multitude of lessons learned from the high-power Hall thruster development experience of the programs partners, particularly EDA and NASA GRC.

The X3 NHT will be a well suited partner to a variety of power sources. Many current mission designs[11,14, 16,17,] envisage using solar photovoltaic (PV) arrays,[18] such as Boeing's FAST Arrays[17,19] as the source of input power for a high-power EP mission. Solar concentrator power sources can also be used in place of PV arrays. Another option would be nuclear electric propulsion (NEP) where the X3 NHT would be powered by a smaller, more cost effective and efficient version of the reactor designed for the Jupiter Icy Moons Orbiter mission.[20] Both of these power sources are excellent choices, and each has its own advantages. High-power solar arrays are the most immediate choice for missions to Near Earth Objects and even Mars as they are far along in their development and capable of generating the power necessary for such missions.[16,21,22] The attraction of NEP architectures is that they are best suited to missions to the outer solar system where an SEP architecture may be unable to supply the necessary power level in the 100's of kW's to take full advantage of the SEP system.

III. High Power Hall Thruster Selection Process

The appeal of Hall thrusters systems as compared to other EP flight systems stems from its overall high efficiency (>50%), high *T/P*, long and successful flight heritage. Hall thrusters have been built and tested from power levels ranging from several hundred watts (BHT-200) to hundreds of kW (NASA-457M), as shown in Fig. 6. High-power Hall thruster technology has been demonstrated to power levels of 100 kW, 1,000 to 5,000 seconds I_{sp}, η>60%, and *T/P* reaching into the mid-90 mN/kW.[23-28].

Figure. 6. Photograph of Hall thrusters ranging from 200 W to 100 kW.

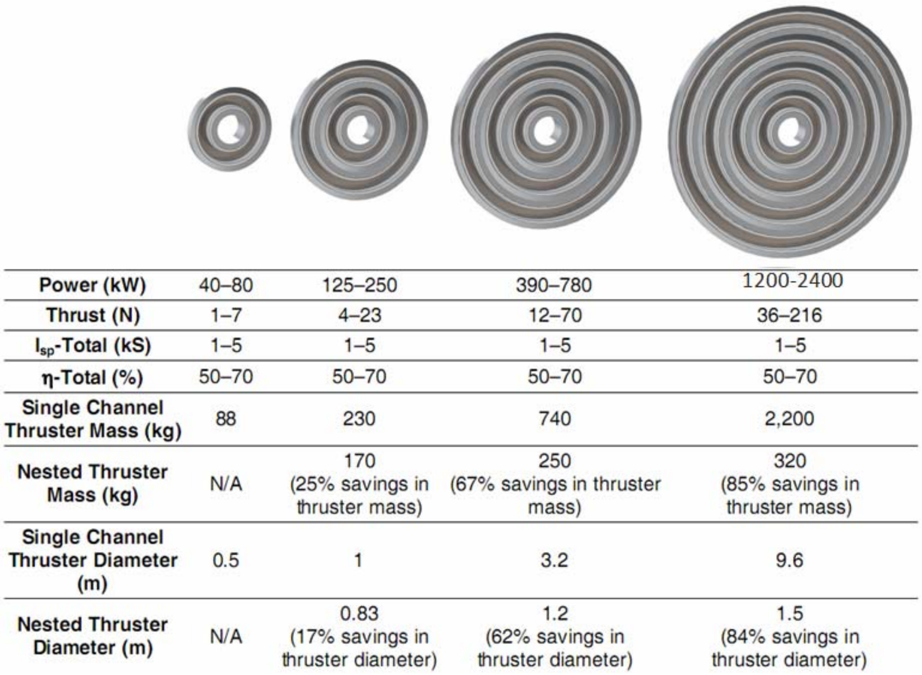
Hall thrusters, especially at high-power, have demonstrated large throttling ranges greater than 20 to1 for discharge power and greater than 5 to 1 for I_{sp} .[28-30] The X3 100 kW class NHT has a predicted throttling curve of 200 to 1 (Fig.7., first operation planed for the Fall of 2011 at PEPL).

Additionally, there have been great strides over the past decade, not to just understand the lifetime of SOA Hall thrusters but to develop new Hall thruster techniques that greatly improve the lifetime of the devices beyond the current SOA of 10,000+ hours.[26,28-29,31-32]

Figure 7. Solid Model of the X3 100 kW class Laboratory Nested Hall Thruster.

The key to scaling Hall thruster technologies to high power is selecting the key Hall thruster parameters correctly. As a Hall thruster increases in size with increasing power, the mass and footprint of the thruster increases. There are primarily three options when scaling a Hall thruster to higher power: 1) a monolithic single channel, 2) cluster a number of smaller thrusters, and 3) concentrically nesting two or more channels in a compact design. Table 1. illustrates the thruster specific mass and footprint savings for NHT device as it scales up in power.

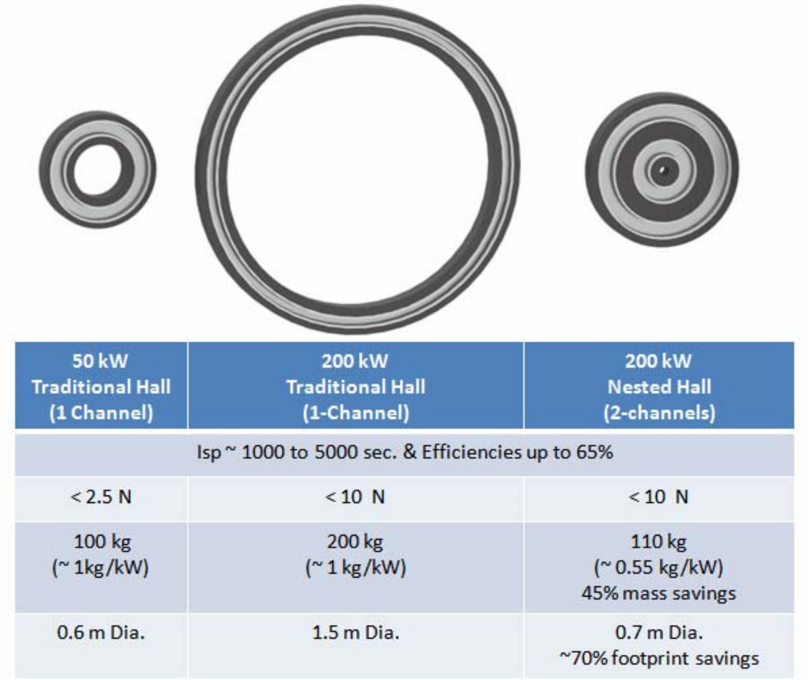
Table 1, Example of concentrically NHT specific mass and footprint savings.



Power (kW)	40–80	125–250	390–780	1200-2400
Thrust (N)	1–7	4–23	12–70	36–216
I_{sp}-Total (kS)	1–5	1–5	1–5	1–5
η-Total (%)	50–70	50–70	50–70	50–70
Single Channel Thruster Mass (kg)	88	230	740	2,200
Nested Thruster Mass (kg)	N/A	170 (25% savings in thruster mass)	250 (67% savings in thruster mass)	320 (85% savings in thruster mass)
Single Channel Thruster Diameter (m)	0.5	1	3.2	9.6
Nested Thruster Diameter (m)	N/A	0.83 (17% savings in thruster diameter)	1.2 (62% savings in thruster diameter)	1.5 (84% savings in thruster diameter)

It is important to note from Table 1 that a significant mass and footprint savings can be achieved with a NHT compared to a single-channel monolithic Hall thruster. To further emphasize this point, Table 2 illustrates the difference of several NHT configurations compared to a single channel Hall thruster for a 200 kW operating point. The NHT specific mass for the 200 kW example ranges from 0.5 to 1.6 kg/kW depending on the number of channels and the size of those channels. The optimal configuration for the 200-kW NHT in Table 2 is the 0.5 kg/kW three-channel option, which represents approximately a 60% decrease in the thruster specific mass and 52% decrease in thruster footprint.

Table 2, Several possible NHT configuration for a 200 kW Hall thruster.



50 kW Traditional Hall (1 Channel)	200 kW Traditional Hall (1-Channel)	200 kW Nested Hall (2-channels)
Isp ~ 1000 to 5000 sec. & Efficiencies up to 65%		
< 2.5 N	< 10 N	< 10 N
100 kg (~ 1kg/kW)	200 kg (~ 1 kg/kW)	110 kg (~ 0.55 kg/kW) 45% mass savings
0.6 m Dia.	1.5 m Dia.	0.7 m Dia. ~70% footprint savings

An NHT shows favorable specific mass and footprint characteristics as compared to a cluster of smaller powered individual Hall thrusters. A comparison of a 200-kW NHT, monolithic, and clustered configurations are illustrated below (Fig.8.).

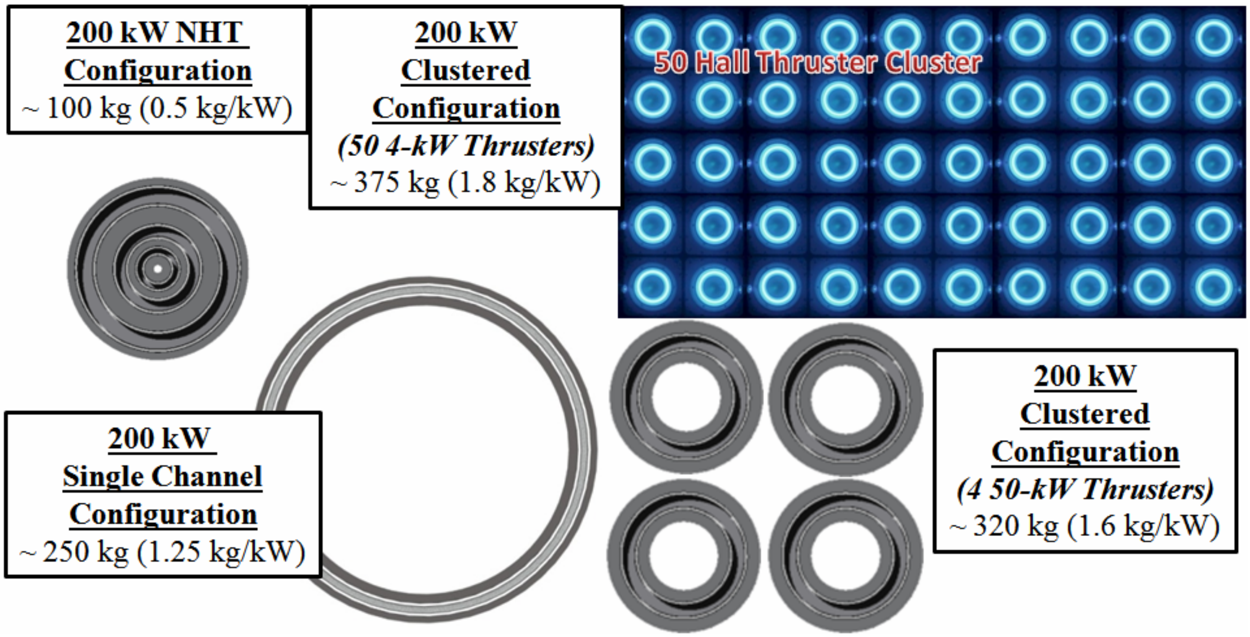


Figure 8. Comparison of a 200 kW NHT, a cluster of 50 4 kW SOA Hall thrusters, a cluster of 4 50 kW ASOA Hall thrusters, and monolithic 200 kW thrusters (thrusters in figure are for comparison purposes only).

Another benefit of the NHT concept is a greater throttling range with improved thruster efficiency over that range. As mentioned, SOA Hall thrusters have demonstrated throttling ranges up to 20 to 1. However, as a Hall thruster discharge power is decreased the efficiency of the device decreases as well. The improvement that a NHT provides is the ability to operate each of the discharge channels separately at improved thruster efficiency (Fig.2.).

The ability to operate each of the NHT channels separately will not increase complexity of the thruster system since propellant to each of the channels will be controlled by its own proportional flow controller while the power for the NHT is provided be a single power processing unit (PPU). Any of the seven possible configurations of the X3 (Fig.2) could be run off of a single PPU if desired, a key functionality of NHT's demonstrated in the work of Liang.[6] A further advantage of the NHT concept, from a spacecraft integration perspective, is that it only requires one gimbal, where an equivalent cluster configuration could require anywhere from 4-50 gimbals to accomplish the same propulsive goals (see Fig.8). Even though the NHT device is a relatively new concept for Hall thrusters, the basics of the NHT operation are derived from the long and successful flight heritage that Hall thrusters have enjoyed since the 1970's.

IV. Preparation/Testing

In the intervening time between the initial start of the project and thruster assembly, many steps have been undertaken to ensure the feasibility of testing the thruster to the extent of its stated goals. Identifying and amassing the necessary facility and supporting equipment ensures that the facility will be primed and ready for testing once the 100-kW class NHT is constructed.

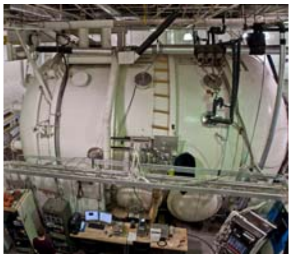


Figure 9. PEPL LVTF.

Starting with PEPL, significant infrastructure upgrades have been undertaken to be ready the facility for the arrival of the thruster. One such upgrade has been the addition of more than 200-kW of DC power supplies to the facility that will serve as the main supplies to discharge channels. These supplies run off of 480V three-phase AC power and represent a significant upgrade to the facility at PEPL in two ways: 1) they are able to be operated remotely via Ethernet/CAT5 connections, greatly streamlining the process of running experiments; and 2) the increase the range of thrusters that can be tested at PEPL, not limited to the 100-kW NHT.


Figure 10. NASA GRC vacuum facility.[10]

In addition, a number of appropriately sized DC magnet supplies and cathode supplies have been acquired. While currently part of a dedicated setup, they also benefit the lab as a whole, increasing the supplies available to run electromagnets on as well as facilitating any future testing of high-current cathodes at PEPL. Paired with the new power supplies is a host of appropriate measurement circuitry to ensure that the thruster will be able to be accurately characterized. While sufficient for the thrusters currently in use, an entire new breakout-box must be constructed to handle the high voltages (>800 VDC) and currents (>200 ADC) that will be encountered during the running of the thruster. In order to deliver the propellant to sustain a discharge at these higher operating conditions, a new "high-flow" mass flow controller system was constructed for LVTF. Additionally, the thrust stand in use at PEPL will be modified to accommodate the number of new electrical connections as well as the physical size of the thruster. This will include the assembly of new electrical wiring "waterfall," a new mount to accommodate the thruster, and flexures with increased buckling strength.

Table 4. X3 Test Plan

Facility	Power Range
PEPL LVTF	2-65 kW
GRC VF5	2-200 kW

Realizing that the pumping capacity of the large vacuum test facility (LVTF) of PEPL (Fig. 9) at 500,000 l/s on air makes it most suitable for initial checkout testing and characterization of the lower half of the 100-kW class NHT's operating envelope, another facility was located that would prove sufficient for high power evaluation of the thruster. NASA Glenn Research Center's possesses a vacuum facility number five (VF-5) (Fig. 10) with increased pumping speed, 3,500,000 l/s on air, experienced staff, and close physical proximity to PEPL that make it the logical site for the high power testing. VF-5 is well equipped to accommodate the testing of high-power Hall thrusters. In fact, the chamber has already seen the testing of several other high power thrusters, including the TM-50, T-220, NASA-457M, NASA-400M, and NASA-457Mv2.[23-24,27]

At the writing of this paper, the thruster is poised to enter production phase. Drawings are being produced so that parts can be manufactured. With the thruster under production, parallel efforts to ensure facility readiness will be completed. Initial shake-down testing of the X3 will take place at PEPL in the middle Fall of 2011, with performance validation and high power characterization to take place at NASA GRC in late Fall of 2011.

V. Conclusion

The literature[1,7] demonstrates a need for a new class of high power EP devices. At this very conference there is a confluence of several high-power EP projects, including Hall thrusters,[6,33] MPDT's,[34] etc.[35-36] It is with this desire and need for high-power EP that a team has been assembled and embarked on a concerted effort to design, build, and characterize a 100-kW class three-channel NHT. Building on the success of the X2, which clearly proved the feasibility of the NHT concept as well as its equality in performance to single-channel conventional HETs, the 100-kW class X3 will meet both USAF strategic goals as well as NASA's cargo and long range mission profiles.

In this paper, the operational envelope of the X3 with its seven different configurations has been shown, along with the facility preparations and other production phase steps that have been undertaken to make testing the thruster a reality. This information has been placed on a backdrop of calls for higher power EP devices and the ability to actually source them power, as well as the rationale behind selection of High power Hall thrusters.

VI. Acknowledgments

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