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14. ABSTRACT

Currently, there is great interest in the development of high-power electric propulsion (EP) devices that can be employed in missions requiring >100 kW levels of propulsive power. Of the candidates for such thrusters, the Nested-channel Hall thruster (NHT) has been shown to be particularly scalable to this mission requirement.[1] To this end, the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL), in conjunction with both the Air Force Research Laboratory (AFRL) and NASA, has developed a 100-kW-class NHT called the X3. While bringing the X3 to test-ready status, a number of developmental and facility-related challenges were encountered and overcome. This paper presents these challenges and the lessons learned associated with the X3's design, fabrication, and testing as a case study to inform other high-power EP development efforts.

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EP of a Different Class: The Challenges of Testing for MW Missions

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Currently, there is great interest in the development of high-power electric propulsion (EP) devices that can be employed in missions requiring >100 kW levels of propulsive power. Of the candidates for such thrusters, the Nested-channel Hall thruster (NHT) has been shown to be particularly scalable to this mission requirement.[1] To this end, the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL), in conjunction with both the Air Force Research Laboratory (AFRL) and NASA, has developed a 100-kW-class NHT called the X3. While bringing the X3 to test-ready status, a number of developmental and facility-related challenges were encountered and overcome. This paper presents these challenges and the lessons learned associated with the X3's design, fabrication, and testing as a case study to inform other high-power EP development efforts.

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Nomenclature

T	=	thrust
P	=	propulsive power
I_{sp}	=	specific impulse
T/P	=	thrust-to-power
η	=	thruster efficiency
g_0	=	acceleration due to gravity
VL	=	voltage of an inductor
L	=	inductance
$\frac{dI}{dt}$	=	time derivative of the current through an inductor

I. Introduction

Currently in the United States and Europe, there is increasing government and commercial interest in electric propulsion (EP) for high-power applications (i.e., from ~100kW to ~1MW). In order to meet this demand in the near term, there are a number of mature technologies that can be leveraged to design and build devices that can process the power levels required. One such configuration that is available is the Nested-channel Hall thruster (NHT). This technology, which has been observed to be suitable for high-power operation,[1] is based on the mature single-channel Hall-effect thruster and boasts increased thrust-to-power (T/P) with increased power and specific impulse (I_{sp}) throttling ranges.

With this in mind, the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan, in conjunction with both the Air Force Research Laboratory (AFRL) and NASA, has developed a 100kW class NHT. The challenges encountered in developing such a thruster and selecting a facility that can test it are relevant to the cases of other high-power EP devices such as magnetoplasmadynamic thrusters (MPDTs) pulsed inductive thrusters (PITs), and field reversed configuration thrusters (FRCs). The testing of high-power, low-I_{sp} thrusters introduces a unique set of problems ranging from coping with high propellant throughput to ensuring that sufficient electrical power is delivered to the thruster in a way that does not introduce extra operational concerns (e.g., voltage oscillations in the discharge due to the inductance of long feeder lines).

The remainder of this paper is organized as follows. In Section II, we motivate the design, fabrication, and ground testing of high-power EP devices. In Section III, we expound on the selection process for high-power Hall thrusters and the challenges associated with them. We discuss the facility issues associated with high-power thruster operation in Section IV, using the experiences gained from developing the facility capabilities necessary to operate the X3 100-kW-class NHT. Section V presents the testing of the X3 as a benchmark for future high-power thruster platforms. Finally, in Section VI we summarize the merits of high-power thrusters, the challenges that are likely to be encountered in their ground testing, and possible mitigation strategies.

II. Motivation

In recent years, there has been a steadily building interest in developing high-power EP devices.[2,3,4] Such systems (~100 kW to ~1 MW) have been flagged as a high-priority technology per the 2012 *NASA Space Technology Roadmaps and Priorities*[5]. Recently, a NASA Solar Electric Propulsion (SEP) Demonstration Mission Concept Studies broad agency announcement (NNC11ZMA017K) awarded contracts for teams to conduct concept and mission studies of advancing key in-space propulsion concepts for a 300-kW SEP transport vehicle.[6] The European Union, meanwhile, has been funding the HiPER (High-power Electric

propulsion: Roadmap for the future) project to lay the groundwork for Europe's future space transportation and exploration needs.[7]

Future space missions with large impulse needs favor the use of EP, whose larger specific impulses (I_{sp}) relative to chemical propulsion reduces required propellant mass for a given mission, thereby boosting payload mass or reducing launch costs. In an EP system, the I_{sp} and thrust T are related to the thruster's electrical power input P by

$$P = (g_0 I_{sp} T)/(2 \eta) \quad (1)$$

where g_0 is the gravitational constant at Earth's surface and η is the thruster efficiency in converting electrical power to directed kinetic power. Time-critical missions, such as manned spaceflight[8], require short flight times (i.e., high thrust) and thus drive EP requirements toward high-power.

Example missions enabled by high-power EP include the following:

- Cargo tugs cycling between Low Earth Orbit (LEO) and High Earth Orbit for on-station deployment of satellites[9] (e.g., in Geosynchronous Earth Orbit, GEO) or to support lunar and martian exploration missions[10]
- Heliocentric orbit transfer vehicles to Near Earth Objects (NEO)[11] and Mars[12131415]
- Solar system exploration missions, such as the Jupiter Icy Moons Orbiter[16] envisioned under Project Prometheus
- International Space Station orbit re-boost to provide drag makeup in LEO
- Orbital power beaming systems[18] that require drag makeup in LEO or transfer to higher-energy orbits

These missions in the hundreds of kW range are possible due to advancements in photovoltaic arrays[19] (e.g., Boeing's FAST arrays[20]) and solar concentrators. Missions requiring even higher power levels would likely need to make use of low specific power nuclear reactors.

These trends in space power for Earth-centric missions are also helping to drive U.S. Air Force interests in high-power EP. The on-board power for technologies including radar, lasers, and LIDAR could be exploited for high-power propulsion, thereby enhancing spacecraft maneuverability and payload capability. The U.S. Air Force has invested in high-power plasma propulsion research and development through the University of Michigan/Air Force Center of Excellence in Electric Propulsion (MACEEP)[22], through which the dual-channel X2 proof-of-concept Nested Hall Thruster[23] (NHT), the three-channel X3 NHT[24], and the Electrodeless Lorentz Force (ELF) thruster are being developed.

III. High-power Hall thruster selection and challenges

There are a number of EP thruster concepts that operate in the range of powers called for by MW class missions. The main contenders are MPDTs[26], PITs, FRCs, and high power Hall thrusters.[24]

Selection

The appeal of Hall thrusters as compared to other EP flight systems stems from its overall high efficiency (>50%), high *T/P*, and long and successful flight heritage. High-power Hall thruster technology has been demonstrated to power levels of 100 kW, specific impulses ranging from 1,000 to 5,000 s, $\eta > 60\%$, and *T/P* reaching into the mid-90 mN/kW.[293031323334] 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.[32,34-35,36-37] Indeed, system optimization studies have suggested that high-power single-channel (50-100 kW) and high-power (200-500 kW) NHTs appear sufficient to support 1-5 MW-class missions for the next several decades.[38] One of the many advantages of using high-power NHTs for such MW class missions is the

substantial footprint savings that can be had when compared to current flight model 4 kW hall thrusters or 50 kW single channel hall thrusters, as illustrated in **Figure** 1 below.

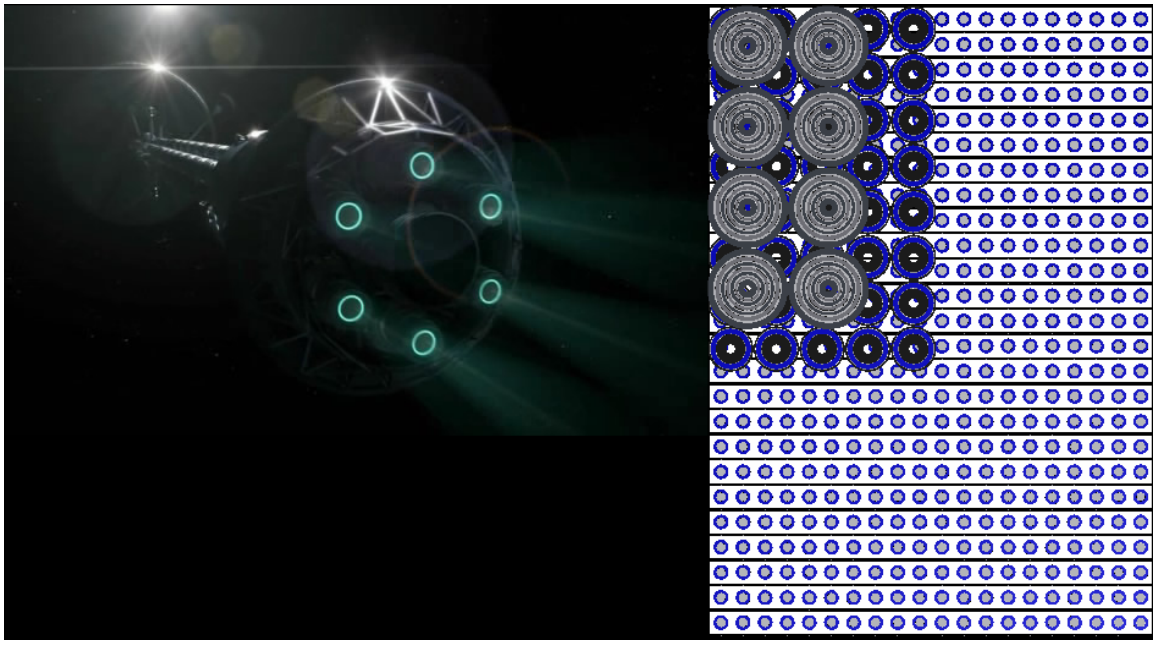


Figure 1. The Antares spacecraft from the television show Defying Gravity on the right, and the scaled versions of various thruster solutions for 2-MW of propulsion power: (8) 250-kW NHTs, (40) 50-kW HETs, (500) 4-kW HET's.

Another benefit of the NHT concept is a greater throttling range with improved thruster efficiency over that range. 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 (Figure 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 (Figure 2) could be run off of a single PPU if desired, a key functionality of NHT's demonstrated in the work of Liang.[39] 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 **Figure** 1).

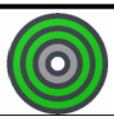
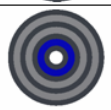
Maximum Exit Area (Low ISP—High T/P operation)	ISP Range (1400s-3200s)	Medium Exit Area (Mid ISP operation)	ISP Range (2000s-3600s)	Minimum Exit Area (High ISP Operation)	ISP Range (2000s-4600s)
	Power Range		Power Range		Power Range
	30 kW-240 kW		20 kW–170 kW		10 kW-140 kW
			15 kW–120 kW		5 kW-90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

Challenges

The development of a Hall thruster that can process several hundreds of kilowatts of discharge power presents a number of unique challenges that thrusters of a smaller scale simply do not encounter. Such challenges range from physical manufacturing restrictions to the modeling of phenomena that are normally taken for granted.

The sheer physical size of the X3 NHT makes fabrication a non-trivial task. The step from 50 kW to hundreds of kilowatts introduces nearly a factor of two increase in thruster diameter (i.e., on the order of 1 m), stressing the limits of affordable commercial manufacturing. In addition to procuring the appropriately sized stock materials, machine shops with the right pairing of skills and machinery to accomplish the fabrication of the thruster also had to be found. Despite being primarily fabricated in the industrial Midwestern United States, a number of specialty shops across the entire country had to be engaged to make the X3 project possible.

In most previous Hall thrusters, thermal modeling essentially consisted of using rule-of-thumb, back-of-the-envelope calculations to account for the heat loads present in the thruster. It is essential, however, when dealing with this entirely different scale of thruster that sufficient finite-element modeling be undertaken to ensure proper material selection and part spacing. A further benefit to undertaking thermal modeling is that it allows for *a priori* knowledge of the best locations to place thermocouples on and within the thruster. From a practical setup standpoint, this allows one to be as efficient as possible during the thruster's physical assembly while eliminating superfluous electrical connections.

For the X3, a 250 A cathode is required to span the full range of thruster operations. To give a sense of scale, a center-mounted 250 A cathode is akin to putting a BPT-4000[40] 4kW HET in a space that is half its size. For more details on the issues surrounding high current cathodes, the authors refer the reader to Dr. Dan Goebel's IEPC 2011 paper.[41]

IV. Facility Selection and Preparation

Facility Size and Pumping

High T/P thruster testing requires high propellant throughput. This reality necessitates the careful survey and selection of appropriate test facilities to ensure that they have 1) sufficient pumping speed to maintain desired operating pressures and 2) adequate size to mitigate facility effects and pressure gradients in the chamber. Table 1 below shows a survey of all the major vacuum chambers in the United States as well as two European chambers that fall into the same general class of large facilities.

Table 1. Listing of all large vacuum test facilities in the US and two comparable European facilities, including size and pumping information.

Facility	Dimensions	Air Pumping* Speed [l/s]	Operating Pressure** [torr]	Pump Type
Domestic				
PEPL LVTF[42]	20 ft diameter, 30 ft long	520,000	2.68E-04	Nude cryopumps
GTech, VF1 [43]	14 ft diameter, 22 ft long	600,000	2.33E-04	ODPs w/ baffles ***
GTech, VF2 [43]	16 ft diameter, 30 ft long	740,000	1.90E-04	Nude cryopumps
GRC VF5[44]	15 ft diameter, 60 ft long	3,500,000	3.99E-05	Cryopanels
		250,000	5.58E-04	ODPs
Plum Brook-SPF[45]	100 ft diameter, 122 ft high	1,300,000	1.07E-04	Cryopumps
Plum Brook-B2 [45]	35 ft diameter, 55 ft high	350,000	3.99E-04	ODPs
AEDC V12 [46]	12 ft diameter, 35 feet high	4,200,000	3.32E-05	Cryopanels and cryopumps
AFRL, SPEF	30 ft diameter	690,000	2.01E-04	ODPs and cold traps
Boeing, XIPS Qualification Facility [47]	20 ft diameter, 40 ft long	1,800,000	7.75E-05	Cryotubs
International				
ALTA, Italy, IV10[48]	20 ft diameter, 33 ft long	710,000	1.96E-04	Dry, oil free: scroll, turbo and cryopumps
JUMBO, Giessen, Germany[49]	10 ft diameter, 20 ft long	210,000	6.64E-04	Cryopumps

-*Conversion factor from pumping speed on air to pumping speed on xenon is ≈0.47, as reported values for pumping speed.
** Operating pressure at flow rate for air of 10,000 sccm
***ODP= oil diffusion pump

As can be seen from the table above, the vast majority of existing facilities are simply inadequate when it comes to testing a high-power thruster. This does not only apply to high power Hall devices. For the 250 kW power class of thruster, MPDTs are likely to be steady-state, applied field thrusters, suggesting that they would encounter the same testing complications as NHTs of the same power rating. Furthermore, even devices that achieve higher powers by use of a pulse-train discharge, such as FRCs, encounter this high throughput issue after the first few pulses following thruster ignition when they reach an operational mode akin to steady state.

Realizing that the pumping capacity of the Large Vacuum Test Facility (LVTF) at PEPL (Figure 3) at 520,000 l/s on air makes it most suitable for initial checkout testing and characterization of the lower half of the X3's operating envelope, it was determined that another facility was needed for high-power evaluation of the thruster. NASA Glenn Research Center's Vacuum Facility 5 (VF5) (Figure 4), with its increased pumping speed of 3,500,000 l/s on air, experienced staff, and close physical proximity to PEPL,

make it the logical site for the high-power testing campaign. VF5 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.[29-30,32] In truth, the only other facility in the nation that would be able to accommodate the high-power testing of the X3 is AEDC's V12.

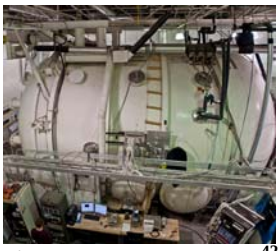


Figure 3. PEPL LVTF.[42]

Figure 4. NASA GRC vacuum facility.[4]

Electrical Infrastructure Considerations and Upgrades

Preparing for the testing of a multi-hundred kilowatt thruster requires more than simply selecting a large enough facility with adequate pumping speed. It has been found that in the process of preparing the facilities for the testing of the X3, a number of upgrades to the electrical infrastructure was required.

A critical upgrade at PEPL has been the addition of >300A of 480VAC 3-phase mains power to accommodate two additional main DC output supplies. Any facility that would be selected for high-power testing would need to have this infrastructure element carefully evaluated. It has been found that while enough power may exist in aggregate, the existence of several hundred amps of 480VAC at a single power outlet is rare.

The high throughput required by these thrusters indicates a high discharge current on the order of hundreds of amps. The lines that will be used for the X3 have been specifically selected for operation at high current and voltage. By using wires of a large enough gauge that can also tolerate temperatures higher than the average wire (i.e., normally only 150 °C), we are able to limit the number of wires used to a physically practical number.

The fact that many Hall thrusters have shown breathing mode oscillations in the ~10 kHz range with amplitudes as high as the steady DC value of the discharge current has required further examination of the discharge lines beyond gauge and temperature considerations.[52] When high currents are being delivered over long line lengths (e.g., >60A over ~30m), the voltage oscillations seen at the thruster become appreciable. Using the basic equation for the voltage across an inductor as related to the current through it (EQ 2),

$$V_L = L\left(\frac{dI}{dt}\right) \qquad \textbf{(2)}$$

and with the knowledge that inductance increases with line length (reaching values in the uH range), one can see that as more current is delivered over longer line lengths, these voltage oscillations do indeed get larger. In order to combat this line inductance problem, all discharge lines have been placed in grounded steel conduit. The use of this grounded conduit has duality of purpose: it 1) shields the discharge lines from background electromagnetic interference (EMI) and 2) reduces the inductance of the line by bringing the ground plane closer to the wire. Further, twisted pairs have been used wherever possible to further reduce

inductance of the line (i.e., in this case, mutual inductance between the wires is the source of the line inductance).

Structural Considerations

Due to the weight of the X3 thruster and ancillary connections, specialized fixtures for assembly and transportation are required. Table-top manipulation and installation relying solely on man-power are simply not practical nor safe. Fixtures rated to hold minimum loads of at least 700 lbs were selected to permit assembly and installation of the thruster while maintaining sufficient margin of safety.

Gas/Thermal Load Considerations

Most high pumping speeds are achieved through the use of some form of cryogenic pumping, as evidenced in Table 1 above. Operating at high throughputs introduces the concern of cryo-loading—the scenario where too much gas has accumulated on the cryogenic surface to allow it to effectively pump the chamber. Differential pumping coupled with flow diversion should be considered to help pumping restrictions, at least to the extent that it can reduce the pressure in the vicinity of the thruster.

From the perspective of thermal loading, with a thruster operating at several hundred kilowatts one can see greater than tens of kW of heat rejection from the thruster to the surroundings. This necessitates the question: how does one protect the sensitive electronics of the thrust stand from this heat load? Depending on the facility, this may necessitate the upgrading of the re-circulating chiller to be able to handle the higher heat loads. For example, a 5 kW capacity chiller is considered sufficient for the majority of NASA Glenn-style thrust stands that routinely test thrusters in the tens of kW range, but such a chiller would likely need to be swapped out for a higher capacity model in order to enable testing at and beyond the 100 kW operating point.

V. Testing the X3 as a benchmark for high-power thrusters

As indicated above, the testing of the X3 100 kW class NHT will be split into two main phases: 1) a shakedown and low power testing phase at PEPL's LVTF and 2) a high-power testing phase at NASA GRC's VF5. Table 2 below summarizes the power ranges for each of the test campaigns:

Table 2. X3 Test Plan

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

The logic underlying the test plan is based on a stepped approach to testing the highest power Hall thruster known to date. First, a shakedown period will be undertaken using krypton as the propellant. The use of a cheaper propellant (i.e., krypton compared to xenon) to initially "burn in" the thruster and to determine possible failure modes is a method that is generally applicable to high-power thruster. The next step is to undertake low power (i.e., up to ~65 kW) testing on xenon. The purpose of this test phast is to obtain an understanding of how the thruster works (e.g., what magnet settings work best). The riskier high-power testing comes last after a basic understanding of how all three channels operate is obtained in the preceding low-power test phase.

In order to frame the testing of a new class of thruster, it is useful to have a projection of performance. The two plots below (Figure 5,Figure 6) showcase expected performance of a 250 kW NHT base upon the performance of the well characterized thrusters.

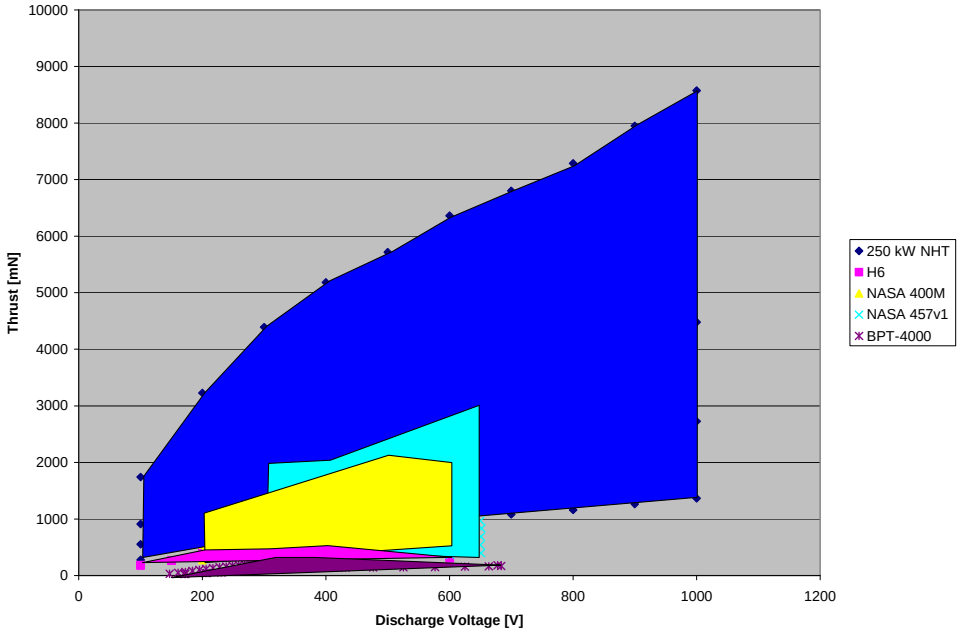


Figure 5. Projected Thrust vs discharge voltage for a 250 kW NHT alongside a number of known Hall thrusters

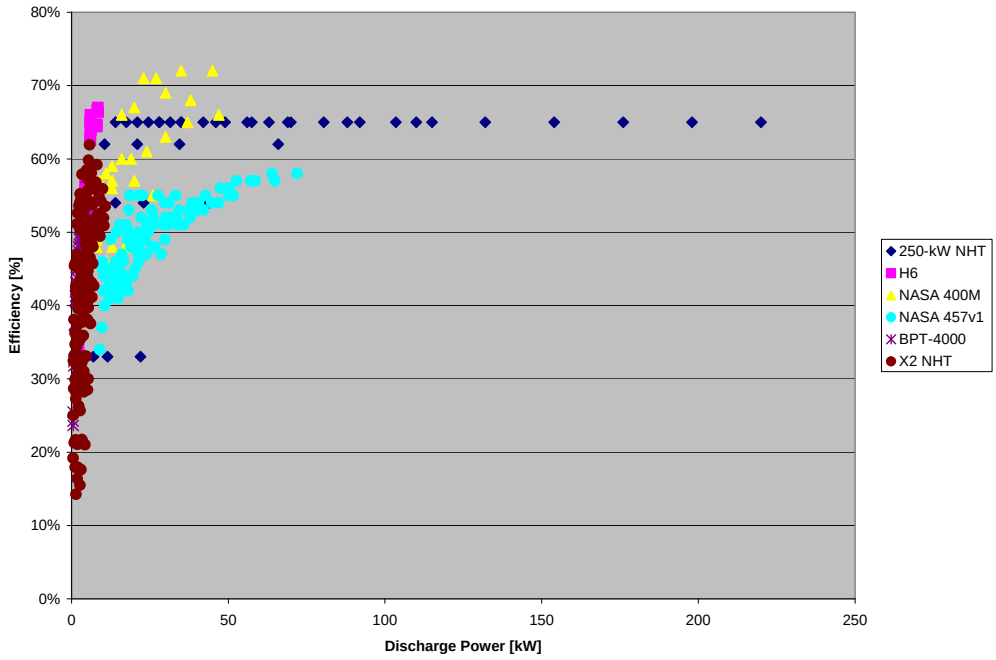


Figure 6. Projected efficiency vs discharge power of a 250 kW NHT alongside those values for a number of known Hall thrusters.

VI. Conclusion

There is a clear and demonstrated desire for the development of propulsion devices of an entirely new class that can process hundreds of kWs of power, both for missions in the nearer term at those power level as

well as a building block for future MW-level missions. The many unique challenges that have been encountered and overcome in the development of the X3 will pave the way for the further development of future thrusters.

Mitigation strategies have been developed to address testing limitations, some of which have already been implemented for the X3. Such strategies encompass the following:

-building and upgrading high-power facility infrastructure
-developing innovative pumping schemes (e.g., differential pumping or flow diversion) to address limited testing at elevated facility pressures or reduced duty cycles for pulsed systems
-propellant variation for higher pumping rates,
-advanced facility modeling and simulation to strategically locate pumps
-on-orbit testing platforms (i.e. no facility effects and flight qualification)

Benchmark thruster technology has been developed to enable missions that not only can reach hundreds of kWs but also MWs. In tandem with this thruster development, facility upgrades and test strategies must be employed in order to ensure the useful testing of this new class of electric propulsion.

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EP of a Different Class: The Challenges of Testing for MW Missions

48th AIAA/ASME/SAE/ASEE JPC
Atlanta, Georgia
AIAA 1309769

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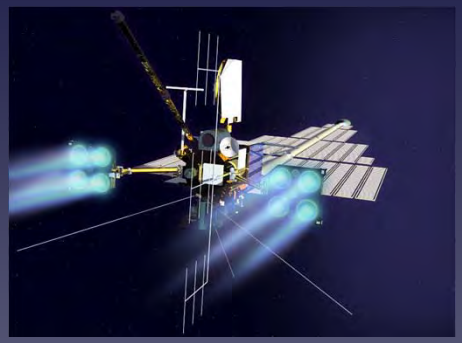
Overview

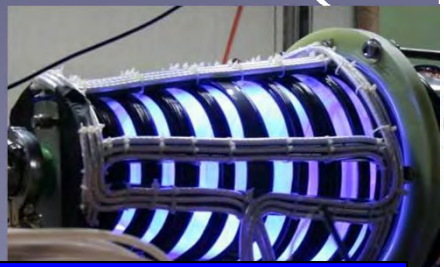
- Why high-power EP?
- Challenges associated with high-power EP
- Facility selection and preparation
- X3 NHT testing as a benchmark
- Summary

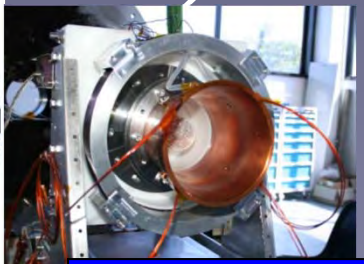
Why High-Power EP? (I)



NASA-Space Tugs

USAF-High T/P, expanded throttling





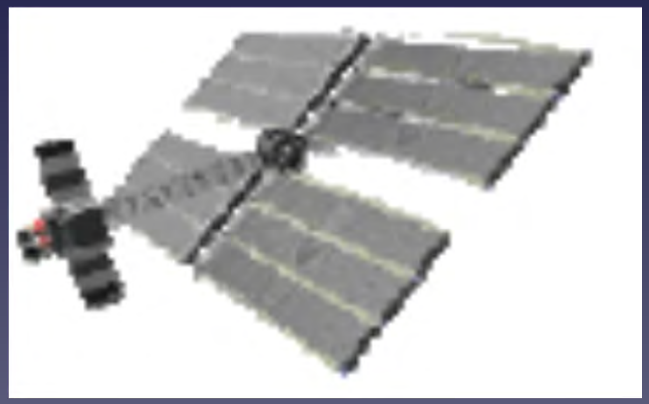
The ELF Thruster [1]

250-kW Class NHT

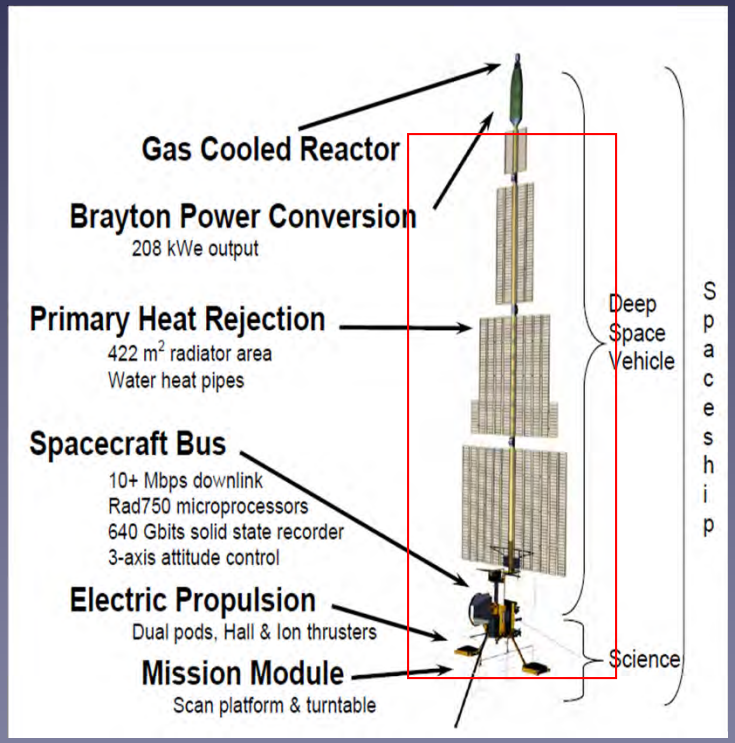
100 kW Class AFMPDT [2]

Multiple Missions

Why High-Power EP? (II)



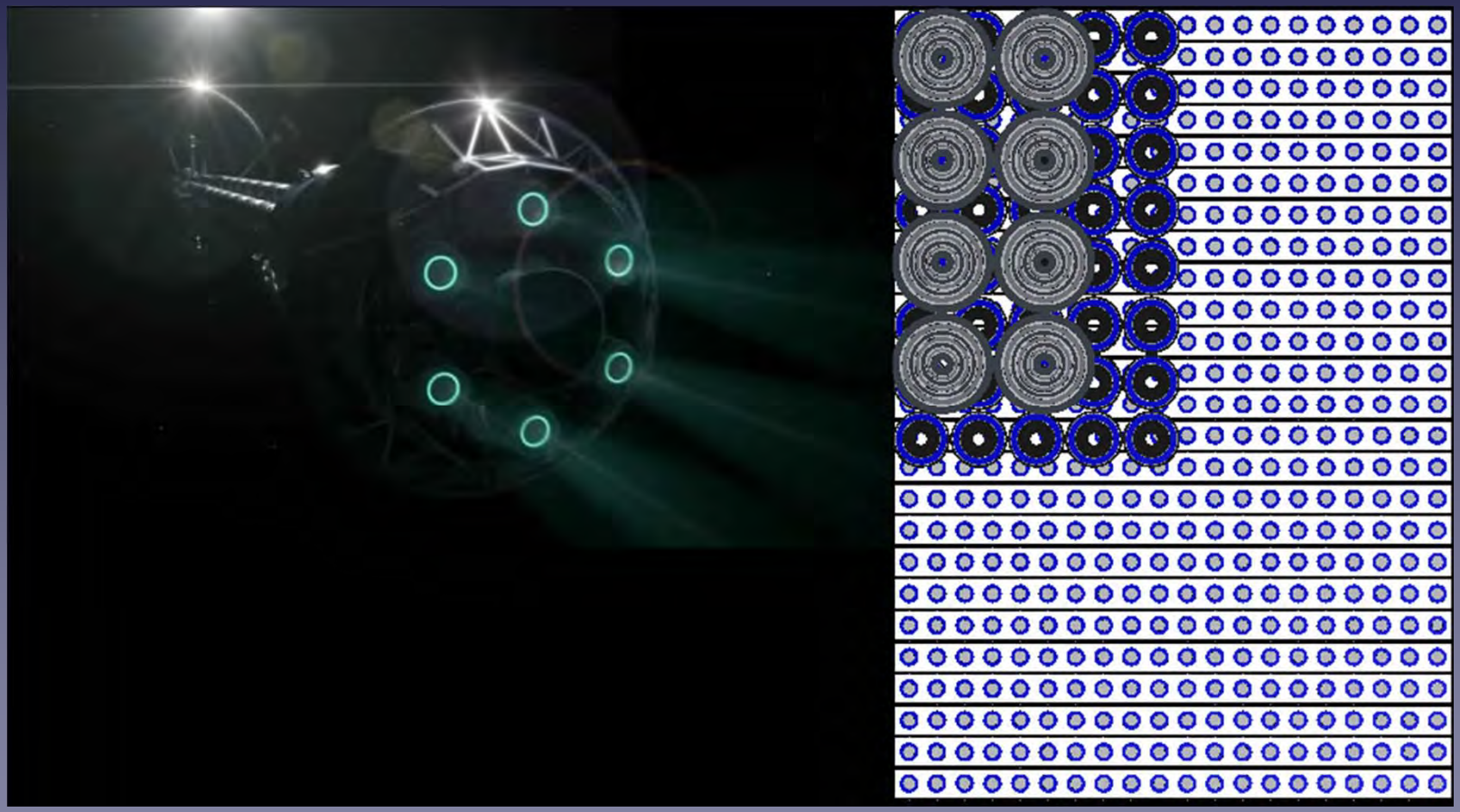
High Power Solar Arrays (SEP) [2]



Proposed JIMO Spacecraft (NEP) [3]

Increased In-Space Power Capacity

Advantages of NHTs (I)



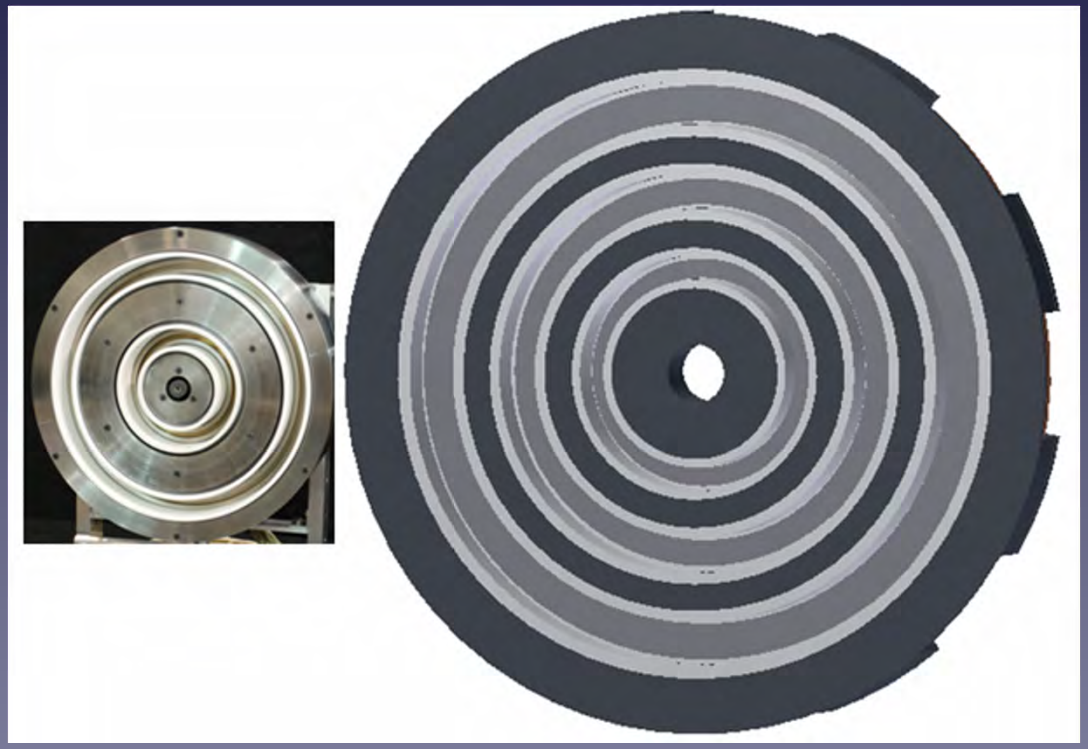
Smaller Footprint

Advantages of NHTs (II)

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

Enhanced Throttling Range

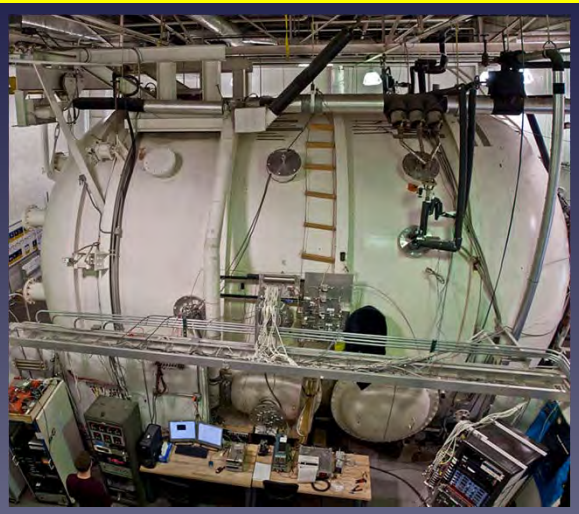
Challenges Associated with High-power EP (I)



Rendering of the X3 NHT next to X2 NHT [5]

Sheer Physical Size Introduces Fab Issues

Facility Selection and Preparation

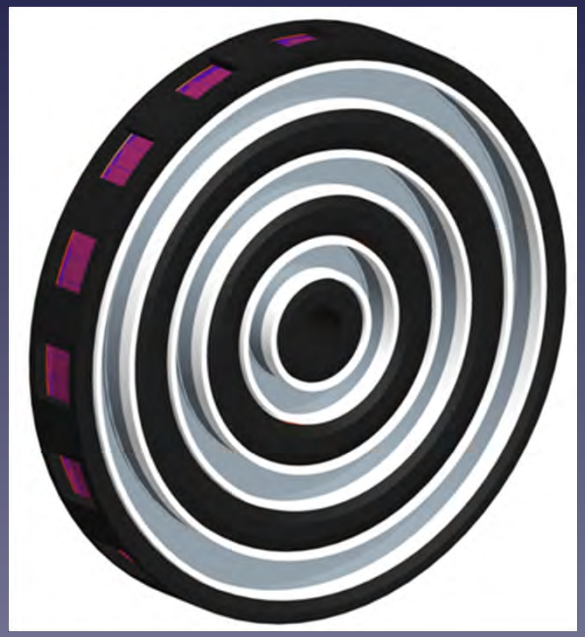


LVTF, PEPL

VF 5, NASA GRC

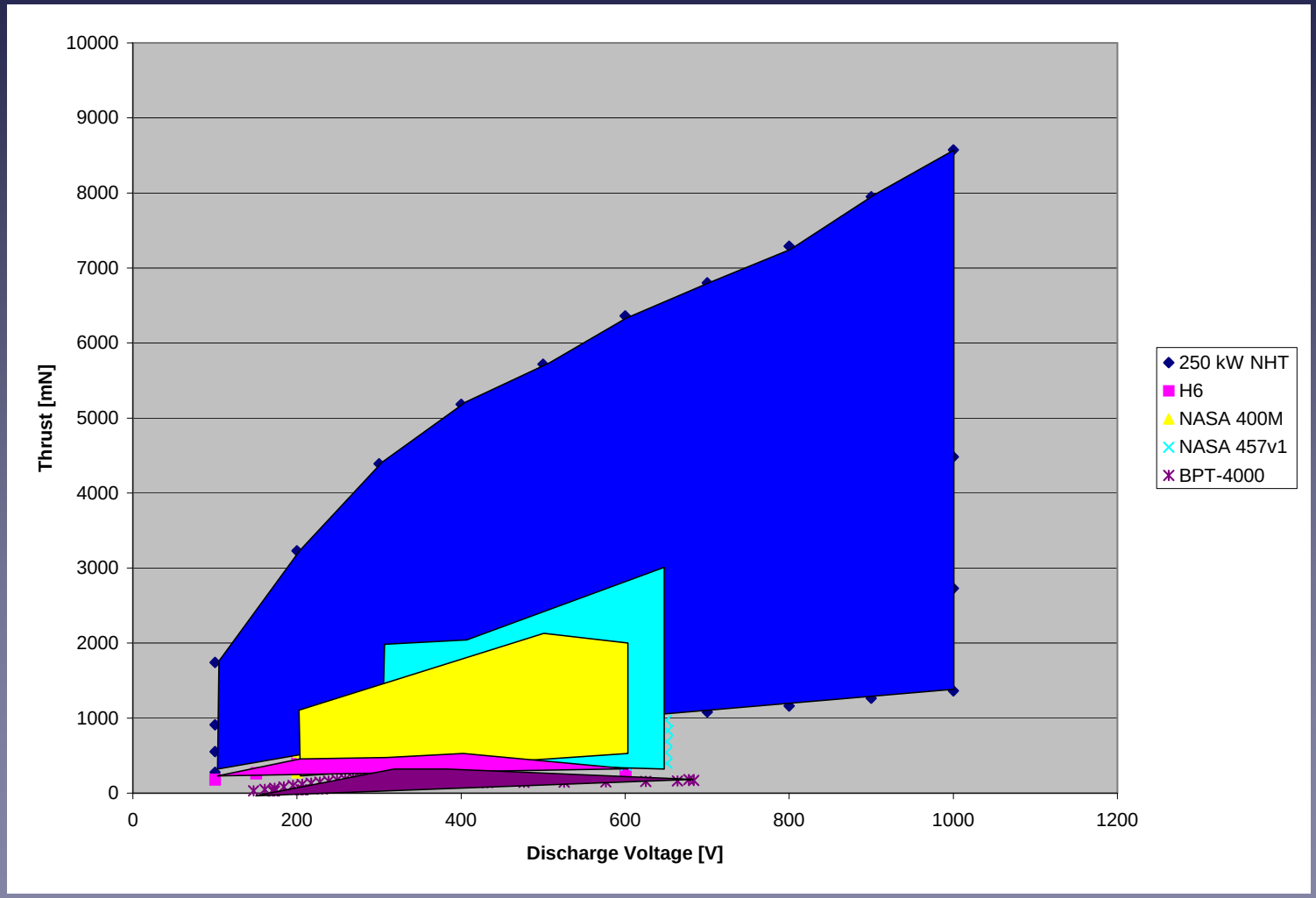
POWER SUPPLIES

X3 NHT Testing as a Benchmark (I)



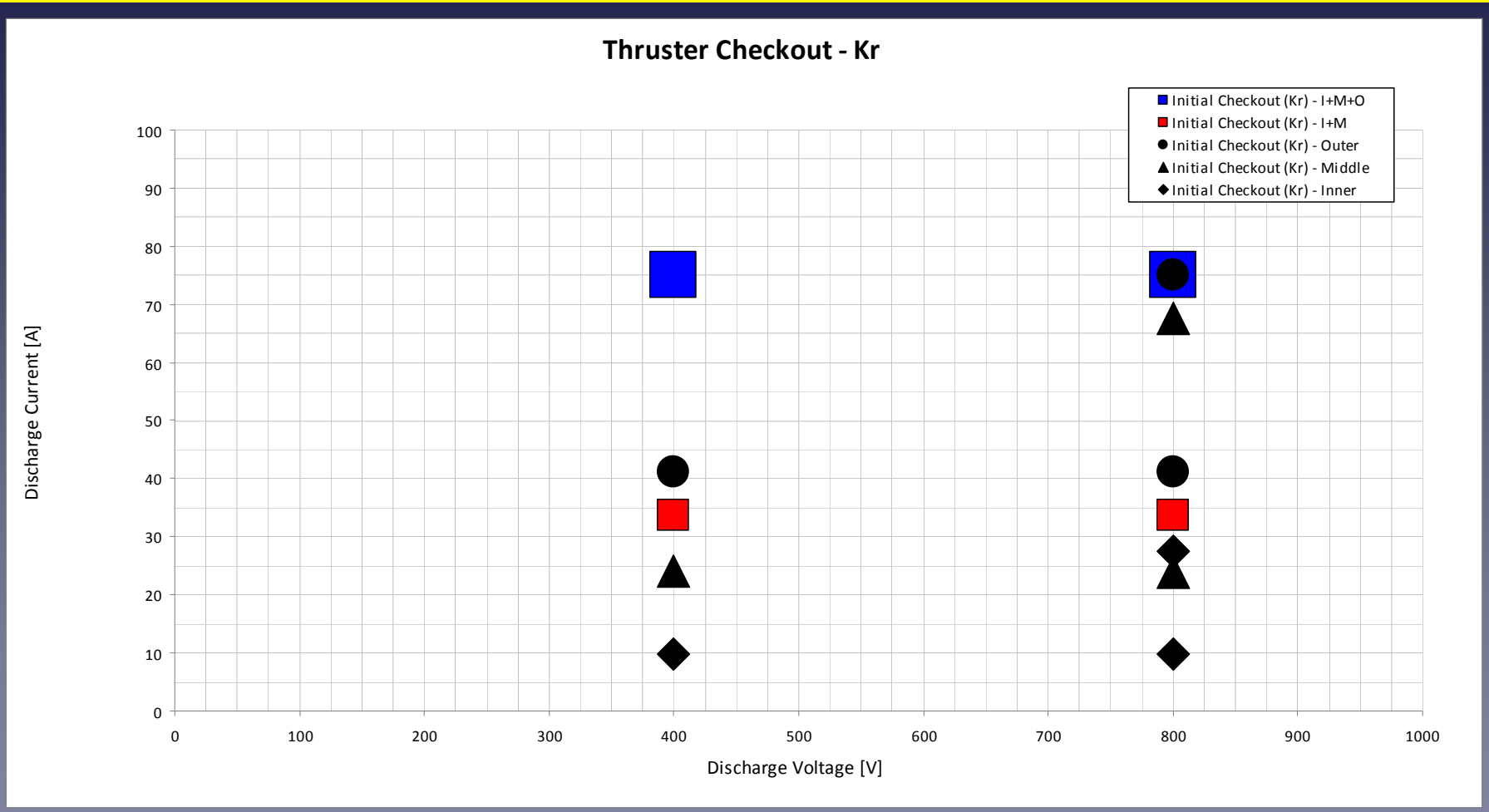
Test	Facility	Power Range
Shakedown	PEPL LVTF	2-65 kW
Validation/High Power	GRC VF5	2-200 kW

X3 NHT Testing as a Benchmark (II)



Projected Thrust of a 250 kW NHT based on and compared to existing Hall thrusters

X3 NHT Testing as a Benchmark (III)



- Prior to main low power test, Kr points to test assembly/connections
- Points NOT optimized, rough thruster settings only

Summary-Mitigation Strategies

- building and upgrading high-power facility infrastructure
- developing innovative pumping schemes (e.g., differential pumping or flow diversion)
- propellant variation for higher pumping rates,
- advanced facility modeling and simulation to strategically locate pumps
- on-orbit testing platforms

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