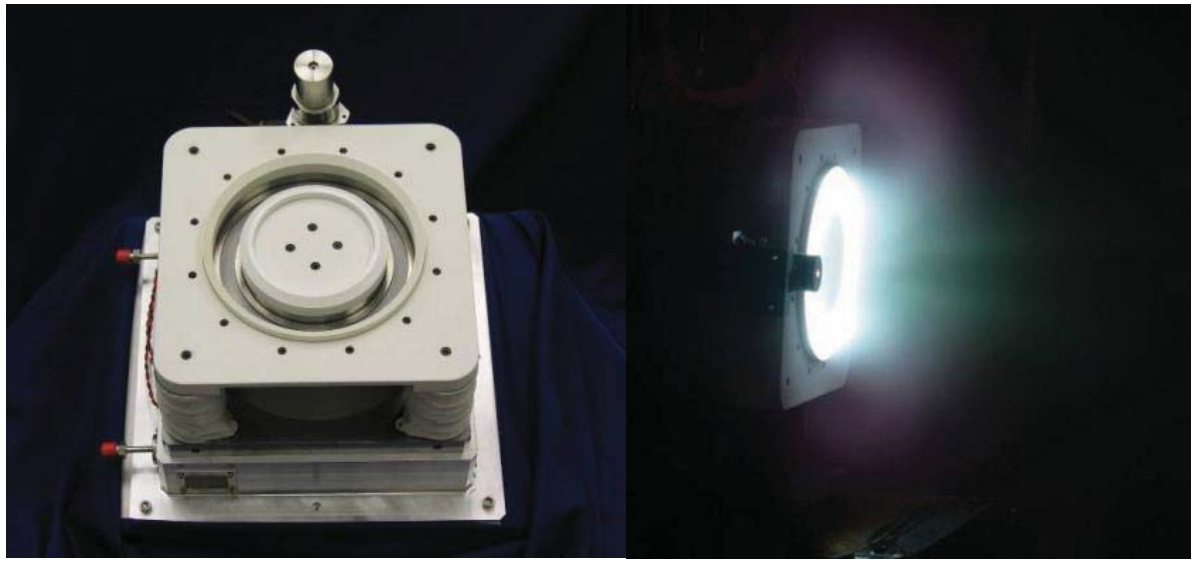
Performance Characterization of the Air Force Transformational Satellite 12 kW Hall Thruster

Hani Kamhawi, Thomas Haag, Timothy Smith , Daniel Herman,
Wensheng Huang, Rohit Shastry
NASA Glenn Research Center
&
Peter Peterson and Alex Mathers
Aerojet, Redmond



NASA HEOMD/STMD Investment in High Power Electric Propulsion

NASA STMD Game Changing Division In-Space Propulsion Project- STMD GCD ISP

- The STMD GCD ISP project is tasked with ***developing***, ***maturing***, and ***testing*** enabling human exploration propulsion technology

- The STMD GCD ISP project NASA Glenn is conducting foundational research and study of the requirements and potential designs for advanced high-energy, in-space propulsion systems. The project objective is to support deep-space human exploration and reduce travel time between Earth's orbit and future destinations for human activity

- High-power Hall propulsion systems have been indentified as enabling technologies and have been the focus of the activities
    - In-house effort to evaluate performance and interrogate operation of NASA designed and manufactured Hall thrusters
    - Evaluate existing high TRL EP devices that may be suitable for implementation in SEP TDM
        - Busek's BHT-20K- Performance evaluation was performed in 2010 and was reported in AIAA-2011-6152
        - Lockheed Martin/Aerojet XR-12

NASA HEOMD/STMD Investment in High Power Electric Propulsion

Solar Electric Propulsion Technical Demonstration Mission- SEP TDM

- NASA has identified high-power SEP as an enabling technology for human-crewed exploration beyond LEO
- SEP TDM formulation has focused on defining mission objectives and concepts to address NASA's SEP TDM technology, extensibility, integrated system, and capability mission objectives

Technology Mission Objective:	***Integrated System Mission Objective:***
Perform an in-space demonstration that advances the maturity of high-power electric propulsion technology and high-power solar array power system technology in relevant space environments and operational regimes.	*Demonstrate integrated SEP spacecraft design, fabrication and test as well as operational modes associated with orbit transfer.*
Extensibility Mission Objective:	***Capability Mission Objective:***
Demonstrate extensible high-power electric propulsion and solar array power system technologies and integrated SEP spacecraft operational modes that can be adapted for use in next-generation, higher power SEP systems.	*Provide a SEP-based transportation capability with performance advancements over those previously demonstrated.*

*

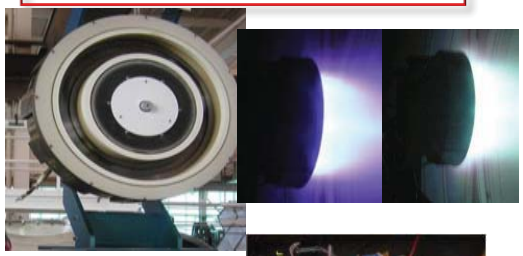
- The SEP TDM project has developed a series of seven mission concepts through contracts and Space Act Agreements (SAAs) with industry
- Additional mission concepts based on potential partnership applications are being developed
- The current SEP TDM activities are anticipated to transition to a flight project in 2015

* IAC-12-C4.4.2, Smith, b, Nazario, M, and Manzella, D.

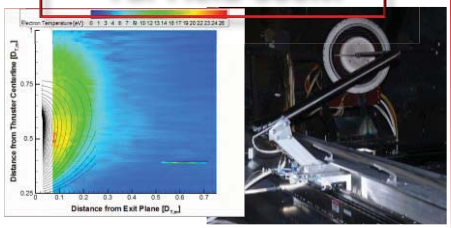
NASA Space Technology Mission Directorate Game Changing Division In Space Propulsion Project at NASA Glenn

NASA Glenn
STMD GCD ISP

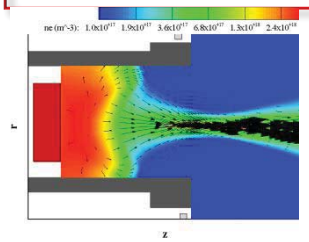
High-Power Hall Thruster Performance Characterization
- 300M-20 kW
- 457Mv2-50 kW
- Busek BHT-20K
- LM/Aerojet XR-12 12 kW



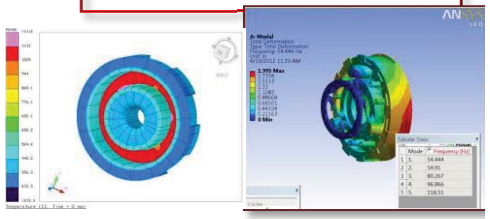
High-Power Hall Thruster Plasma Characterization
- Internal-300M
- Near Field-300M & 457Mv2
- Far Field-300M

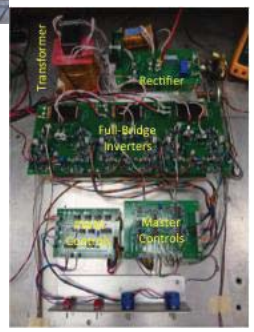


High-Power Hall Thruster Physics Based Modeling JPL HALL2De code
- 300M



High-Power Hall Thruster Thermal & Structural Modeling and Testing
- 300M
- 457Mv2

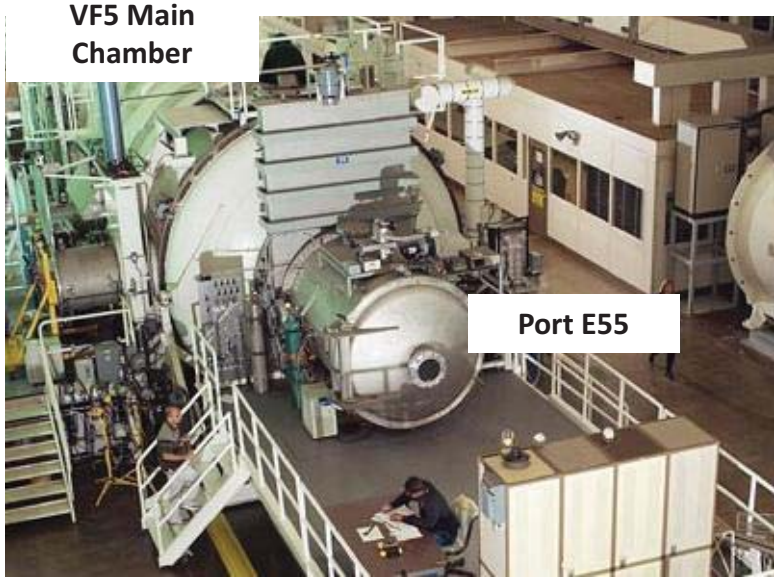




High-Power Hall Thruster Discharge Module Development

High Current Hollow Cathode Development and Testing

High Power Hall Thruster Testing at NASA Glenn is Performed in Vacuum Facility 5 (VF5)



NASA-300M mounted inside port E55

NASA-457Mv2 mounted inside VF5 main chamber

- The 300M 20 (kW), 457Mv2 (50 kW), Busek BHT-20K, and Lockheed Martin/AerojetXR-12 Hall thrusters were tested in VF5 at NASA Glenn.
- VF5 is the highest pumping speed vacuum facility in the US for electric propulsion.
- VF5 has a diameter of 4.6m,is 18.3m long and is evacuated with cryopanels and oil diffusion pumps
- VF5 has a peak pumping speed capability of 3,500,000 L/sec (air).
- The thrusters test configurations included placing thrusters in port E55 and in VF5 main chamber.

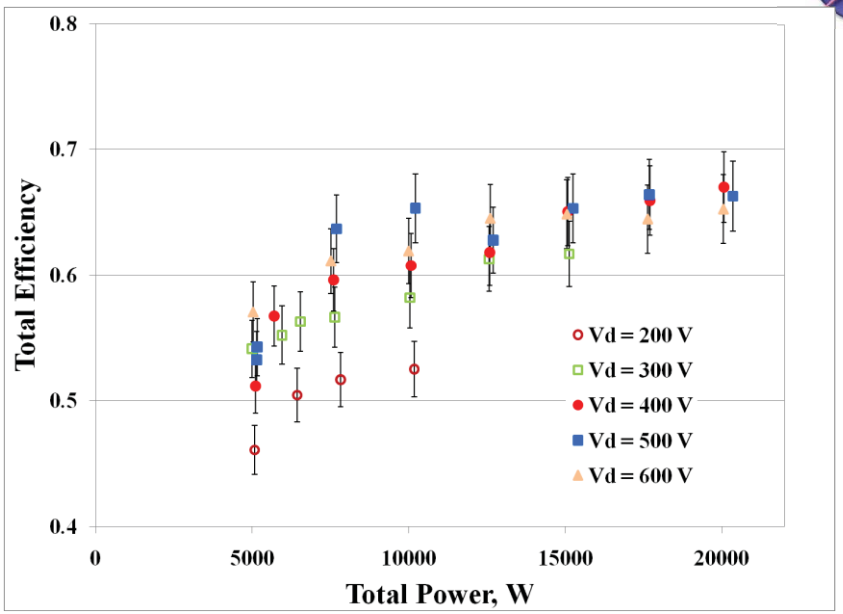
NASA Glenn VF5 is the highest pumping speed vacuum facility for electric propulsion testing in US

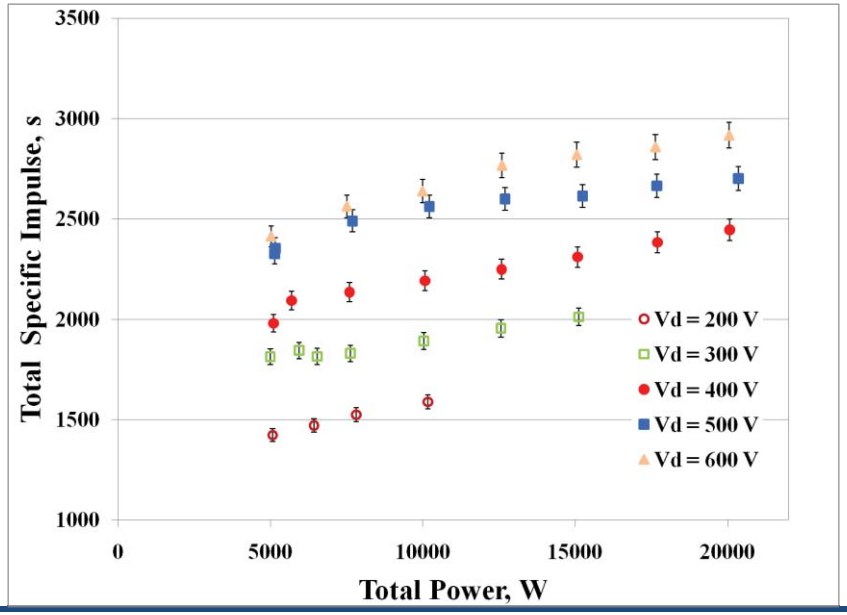
NASA-300M Overall Performance with Xenon

P_d, kW	V_d, V	η	I_{sp}, s
10	200	52	1,590
15	300	62	2,011
20	400	67	2,445
20	500	66	2,701
20	600	65	2,916

- Peak thrust efficiency of ~67% was achieved at a discharge voltage of 500 V.
- Peak total specific impulse of ~2,920 s was achieved at a discharge voltage of 600 V.

The NASA-300M performance characterization tests demonstrated performance levels that can meet and exceed SEP TDM requirements

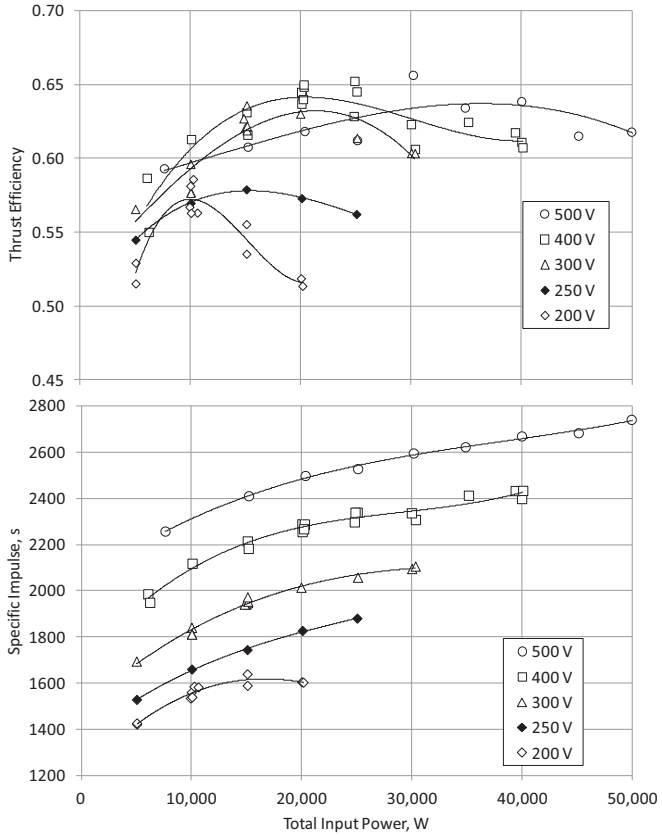




NASA-457Mv2 50 kW Hall Thruster Performance

- NASA-457M v2 development goal was TRL 4-5
- Thruster characteristics
  - 457 mm outer diameter
  - Solid boron nitride discharge channel
  - Centrally-mounted cathode
    - Laboratory model cathode utilized for performance test
  - Magnetic field utilizes plasma lens topology
- Peak thrust at 50 kW was 2.3 N.
- Thrust-to-power ranged from 46.1 mN/kW at full power to 76.4 mN/kW at low power.
- Thrust efficiencies varied from 0.51 at low power to 0.66 at (500 V)- 0.57 to 0.63 at 300 V
- Specific impulse range of 1420-2740 s
  - ~2000 s at 300 V discharge voltage

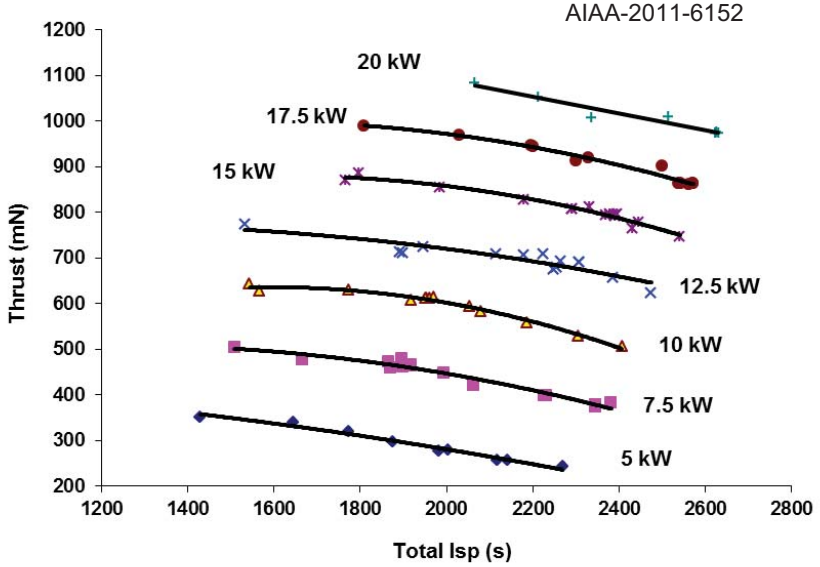
The NASA-457Mv2 performance characterization tests demonstrated performance levels comparable to NASA-300M



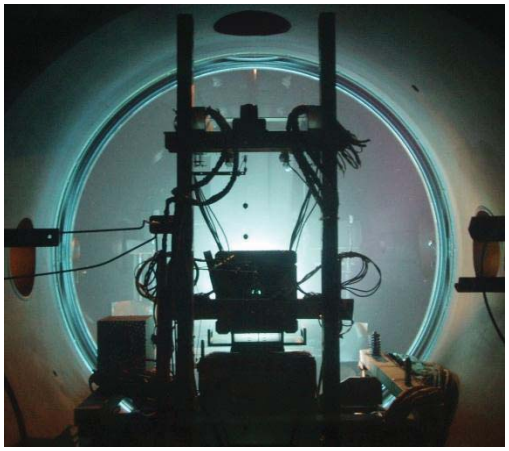
Busek BHT-20K kW Hall Thruster Performance

- Commercial/DoD Hall Thruster
  - Designed and built by Busek Co. Inc.
- Performance mapped in GRC VF5
  - Summer of 2010
- Test conditions:
  - Discharge power: 5 to 20 kW
  - Discharge potential: 200 to 500 V
  - Discharge current: up to 70 A
- Results
  - Peak anode efficiency ~ 69%
  - Peak total specific impulse ~ 2600 s
  - Peak thrust ~ 1.1 N

AIAA-2011-6152



Discharge Potential (V)	Anode Efficiency (%) at Discharge Power (kW)						
	5 kW	7.5 kW	10 kW	12.5 kW	15 kW	17.5 kW	20 kW
200	*54*	*54*	*52*	*51*			
250	*60*	*57*	*60*		*57*	*51*	
300	*61*	*62*	*64*	*60*	*61*	*61*	*60*
350	*59*	*63*	*65*	*64*	*65*	*64*	*63*
400	*58*	*61*	*65*	*67*	*67*	*65*	*63*
450	*58*	*63*	*65*	*66*	*68*	*69*	*68*
500	*58*	*63*	*65*	*66*	*67*	*68*	*68*



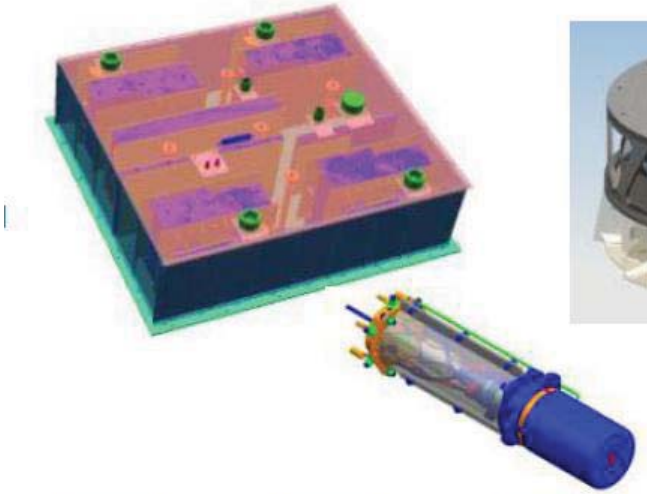
Aerojet's High Power Hall Thruster Propulsion System Background

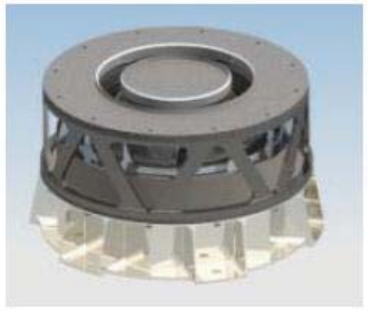
- Under the guide of the Tranformational Satellite (TSAT) program between 2005 and 2009, Lockheed Martin funded Aerojet to develop a 12 kW class Hall thruster system
- Program included the development of a Hall thruster, cathode, power processor, and xenon flow controller
- Single string system architecture was identical to the BPT-4000 system developed for Advanced Extremely High Frequency (AEHF) with a single power processor controlling one Hall thruster and one xenon flow controller
- With the cancellation of this program, all design and test data as well as hardware is available for use on other programs
- Under an existing Space Act Agreement with the Air Force the XR-12 thruster was loaned to NASA Glenn for performance evaluation

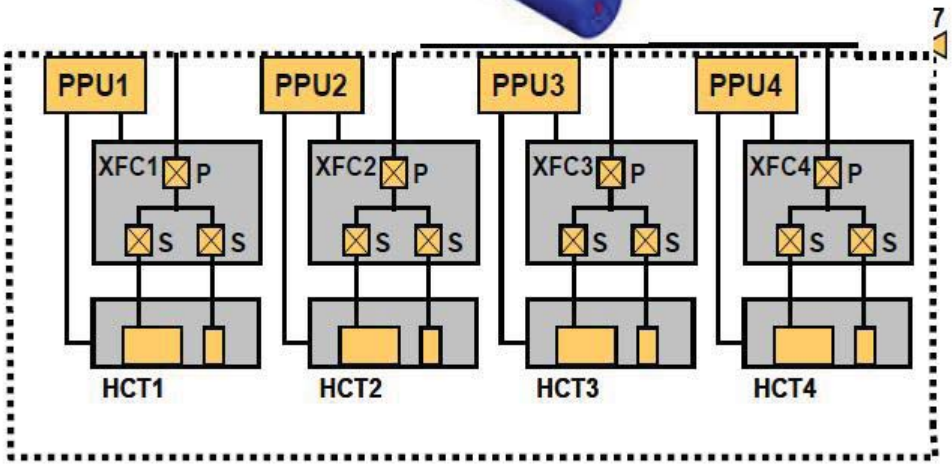
Aerojet's HPHTPS Hall Thruster System Background
12 kW Hall Thruster System Description

Key Design Features

- System design leverages heavily from the 4.5 kW HTPS program
  - Multi-mode Hall thruster system Supports orbit insertion, Station keeping, Repositioning and Decommissioning maneuvers.
- Architecture optimized for reliability, performance and scalability
  - Thrusters are gimbal mounted for thrust vector optimization
  - Single string power processing unit (PPU)/Hall Current Thruster (HCT)/XFC architecture
- Wide range of operating power
  - 2 HCTs at 12kW each for orbit topping
  - 2 Thrusters at 4.5 kW each for station keeping, Relocation, and end of life Disposal
- 4 for 3 redundancy
- Designed to military survivability requirements



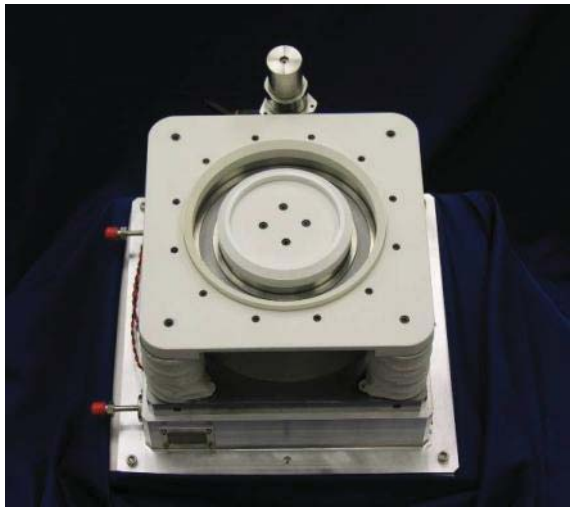




12 kW Hall Thruster System Description
XR-12 Rev 0 Hall Thruster

Thruster & Cathode (HCT)

- Thruster performance characterized from 2 to 12 kW in the Rev 0 configuration
  - Specific impulse capability from 1,400 to 2,000 sec demonstrated
- 2,600 hour cathode risk mitigation life test successfully completed
- 400 hr thruster life test completed on Rev A thruster
  - Ring erosion showed excellent agreement to analytical erosion model validated on the BPT-4000
  - Model predicts >15,000 hour life
  - Rev 0 shares similar characteristics with Rev A and BPT-4000



12 kW Hall Thruster System Description
PPU and XFC

Power Processor (PPU)

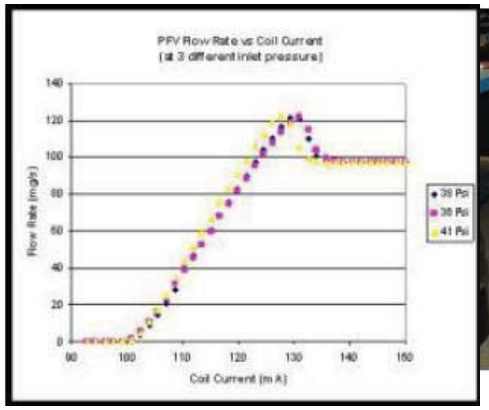
- Designed and built 12 kW breadboard power processor
  - Fully characterized each module individually
  - Demonstrated Integrated PPU operation over full power range – up to 13 kW
  - Initiated engineering model design effort

Control and DAq

Breadboard PPU

Xenon Flow Controller (XFC)

- Designed and built lab model XFC
  - Bench level testing and characterization of all key performance parameters



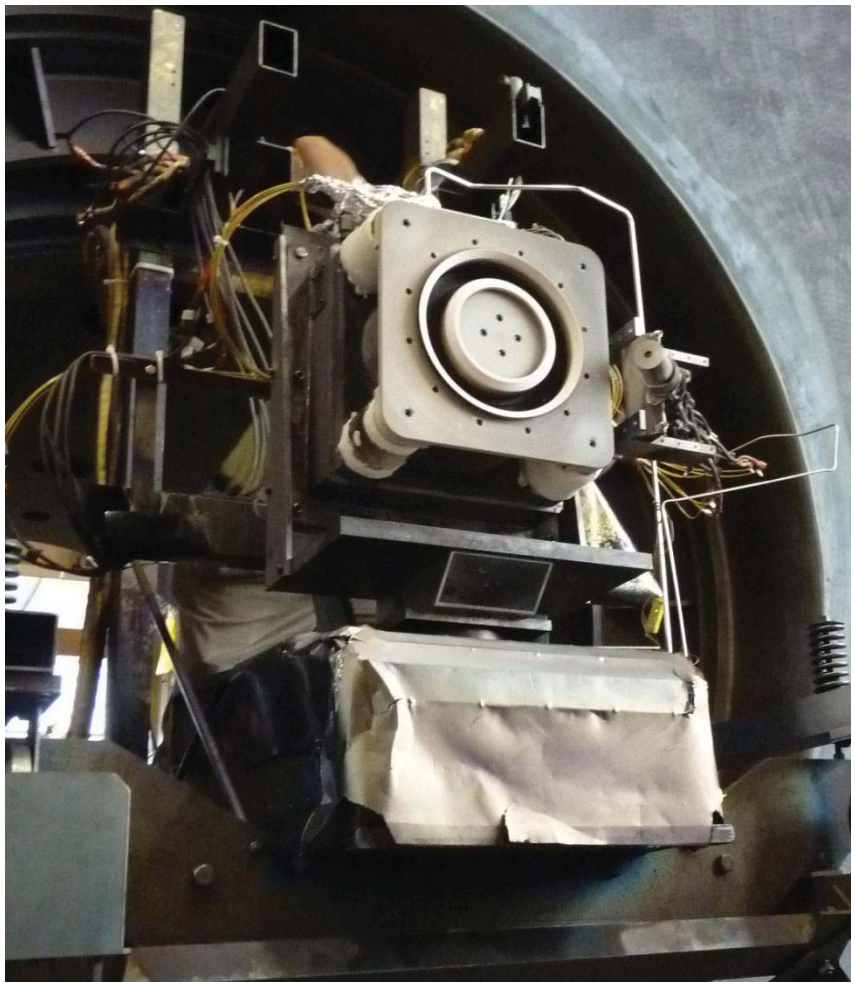
Load and Input Supply

Test Objectives

- **Under STMD GCD ISP program NASA GRC evaluated the performance of the Aerojet XR-12 Rev 0 Hall thruster for SEP TDM**
  - **Perform functional and performance testing of the TSAT XR-12 12 kW Hall thruster @ power conditions between 2 & 12 kW at discharge voltages between 175 & 450 V**
  - **Perform impedance mapping of the TSAT XR-12 thruster at 3 propellant flow rates**

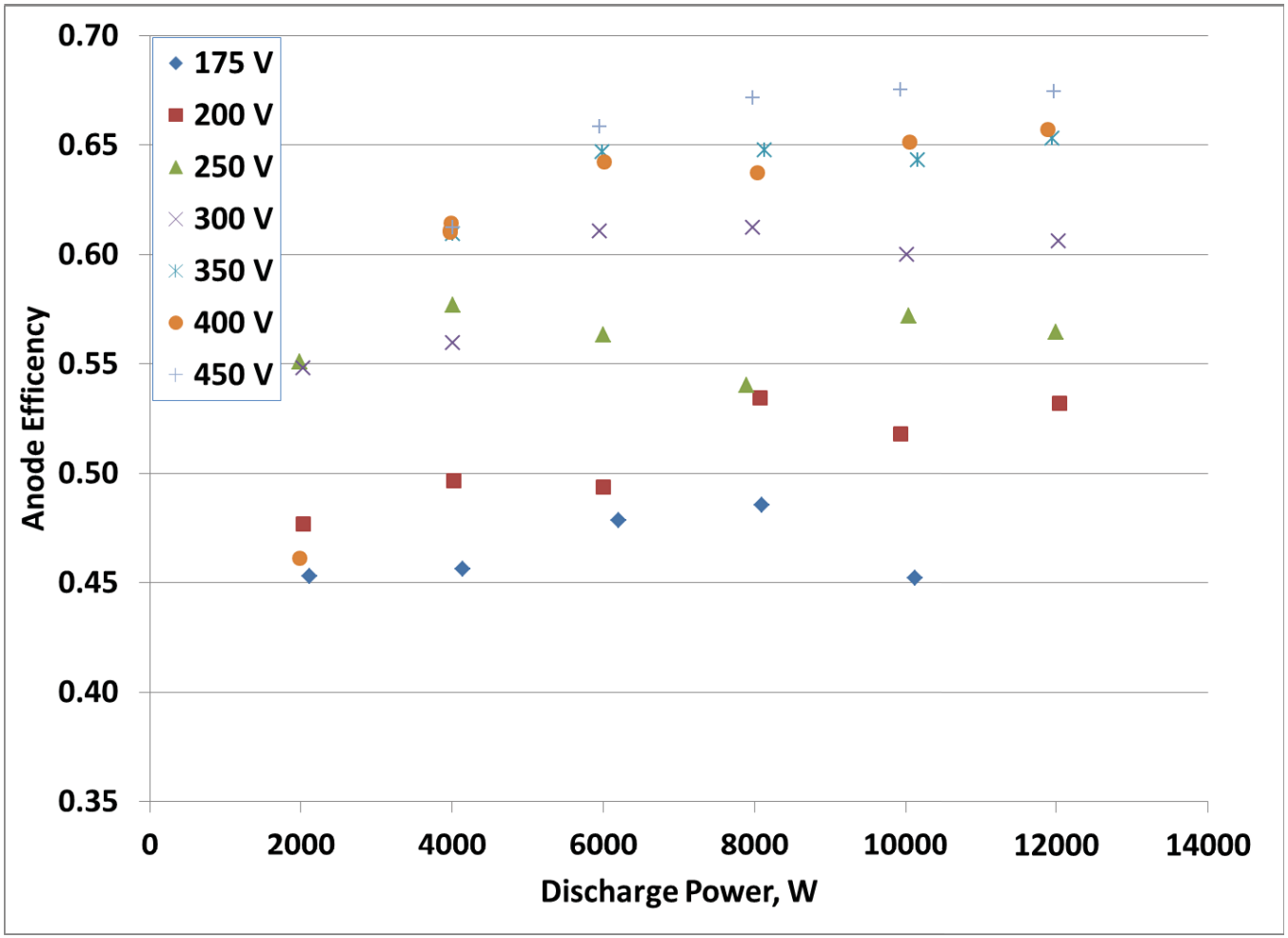
XR-12 Test Setup

- Test was performed in VF5 at NASA GRC
- XR-12 thruster was placed on the high power thrust stand in VF5 main volume
- XR-12 was powered by NASA GRC high voltage supply (2000V, 100A)
- A laboratory xenon feedsystem (not baked out) supplied 99.999% xenon to cathode and anode assemblies
  - Cathode MFC 200 sccm
  - Anode 1 SLM
- Thrust was measured with an inverted Pendulum thrust stand Thruster telemetry was recorded with an Agilent data logger
- Readings from the thruster sense wires were recorded
- Current and high voltage probes recorded the thruster's discharge and voltage waveforms



XR-12 Performance: Anode Efficiency

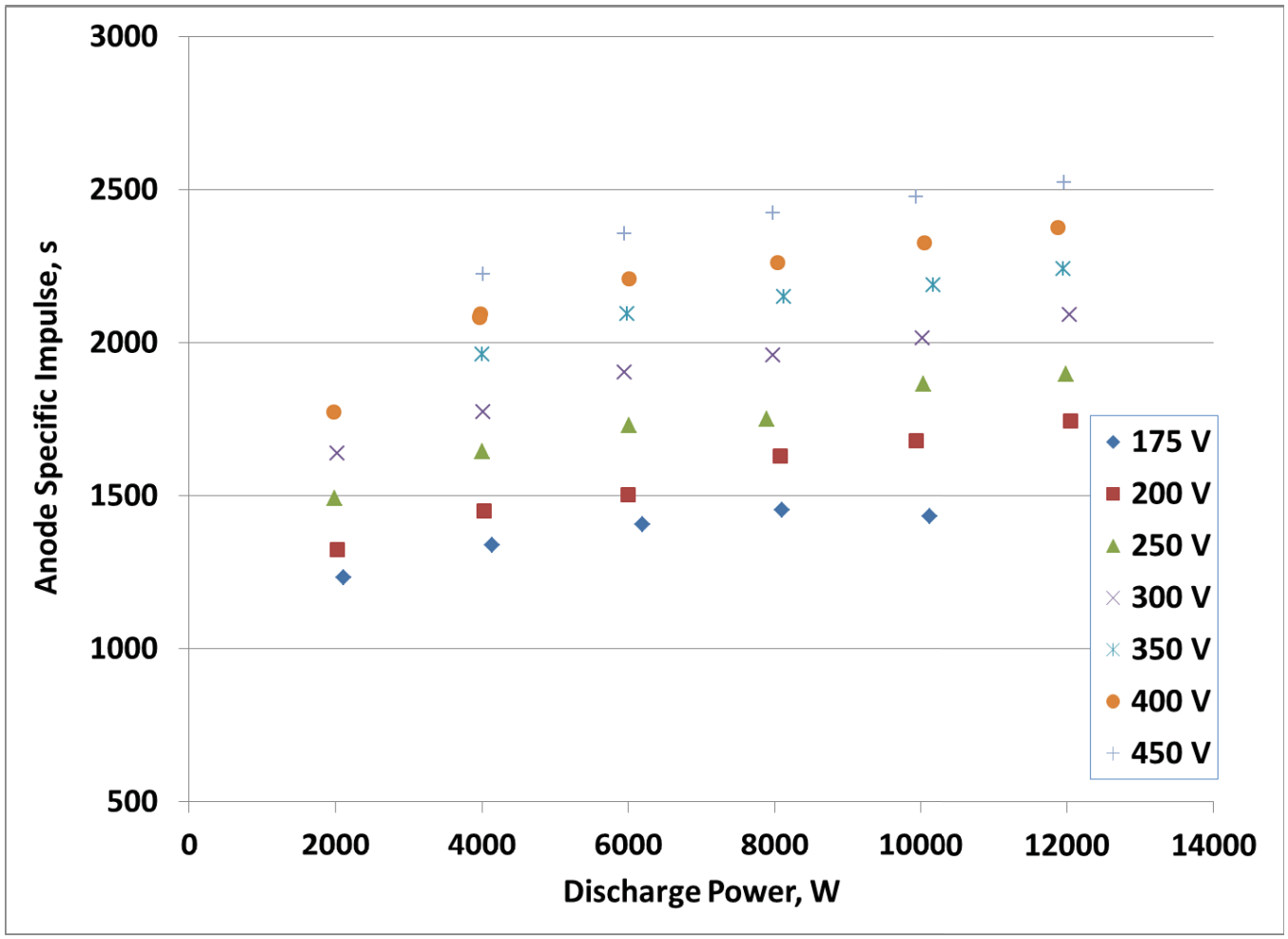
Peak anode efficiency of 68% was achieved @ 450 V and 12 kW



Additional Performance data can be found in paper IEPC-2013-451

XR-12 Performance: Anode Specific Impulse

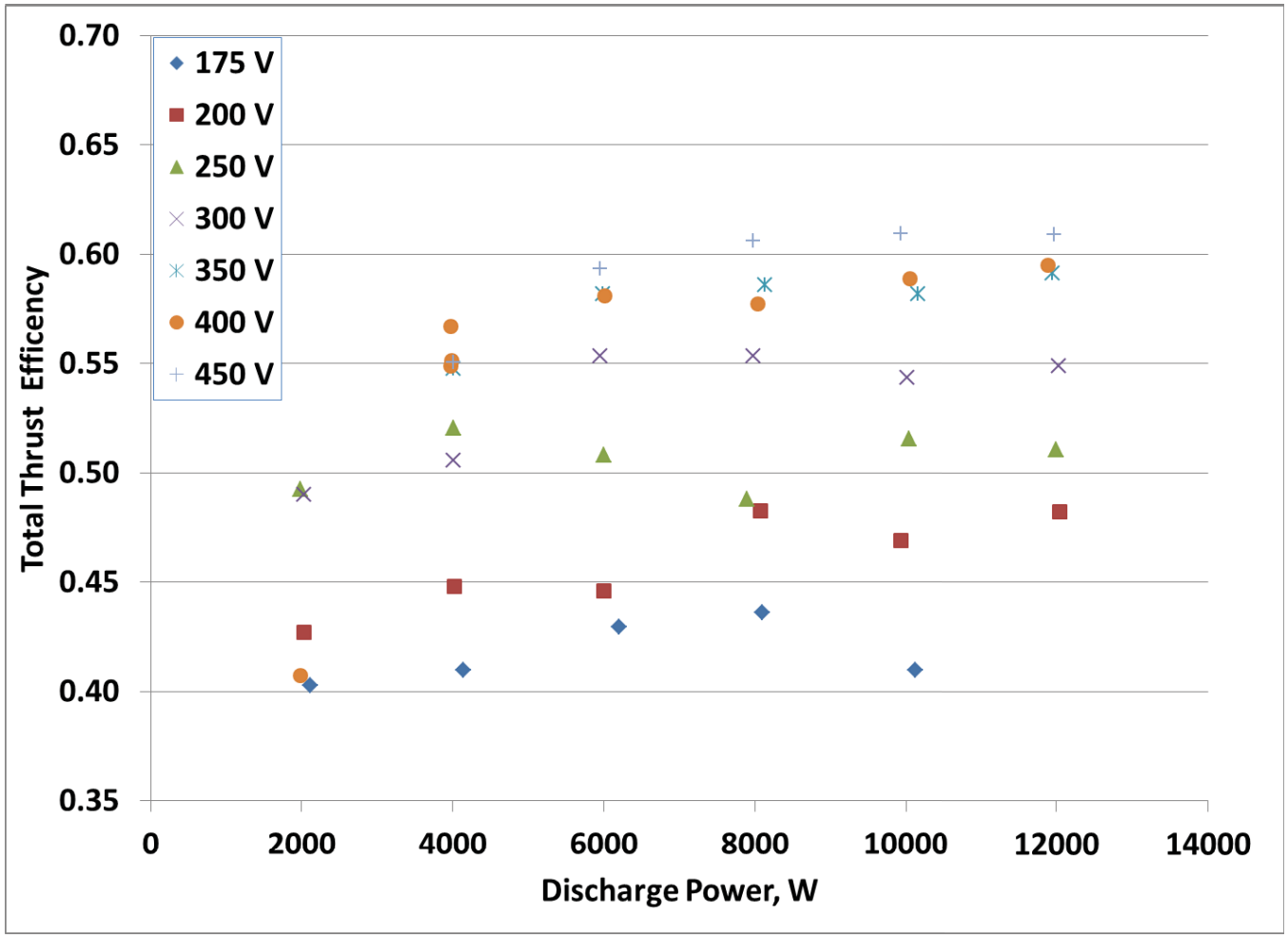
Peak anode specific impulse of 2,550 sec was achieved @ 450 V and 12 kW



Additional Performance data can be found in paper IEPC-2013-451

XR-12 Performance: Total Thrust Efficiency

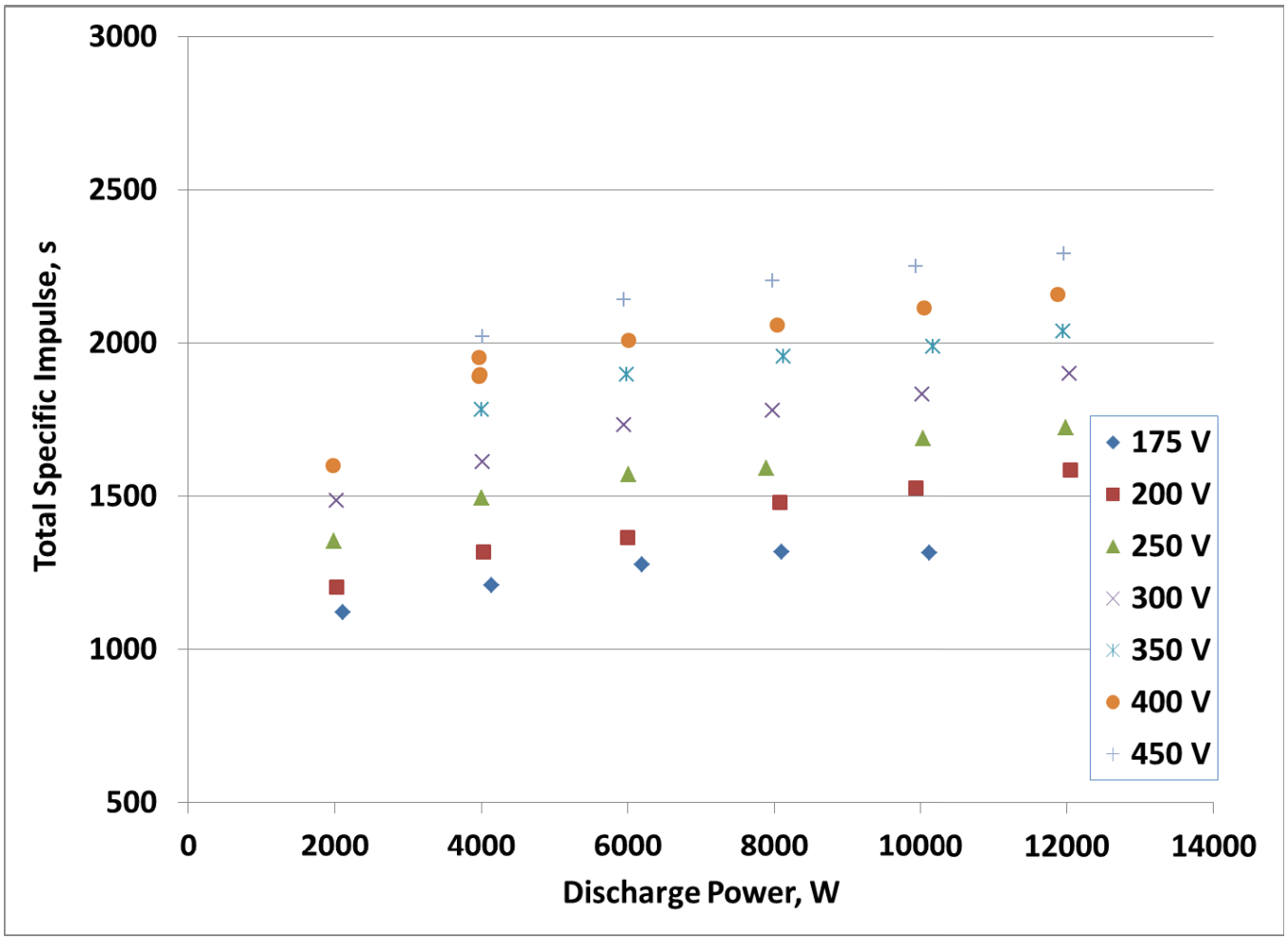
Peak total thrust efficiency of 61% was achieved @ 450 V and 12 kW



Additional Performance data can be found in paper IEPC-2013-451

XR-12 Performance: Total Specific Impulse

Peak total specific impulse of 2,300 sec was achieved @ 450 V and 12 kW



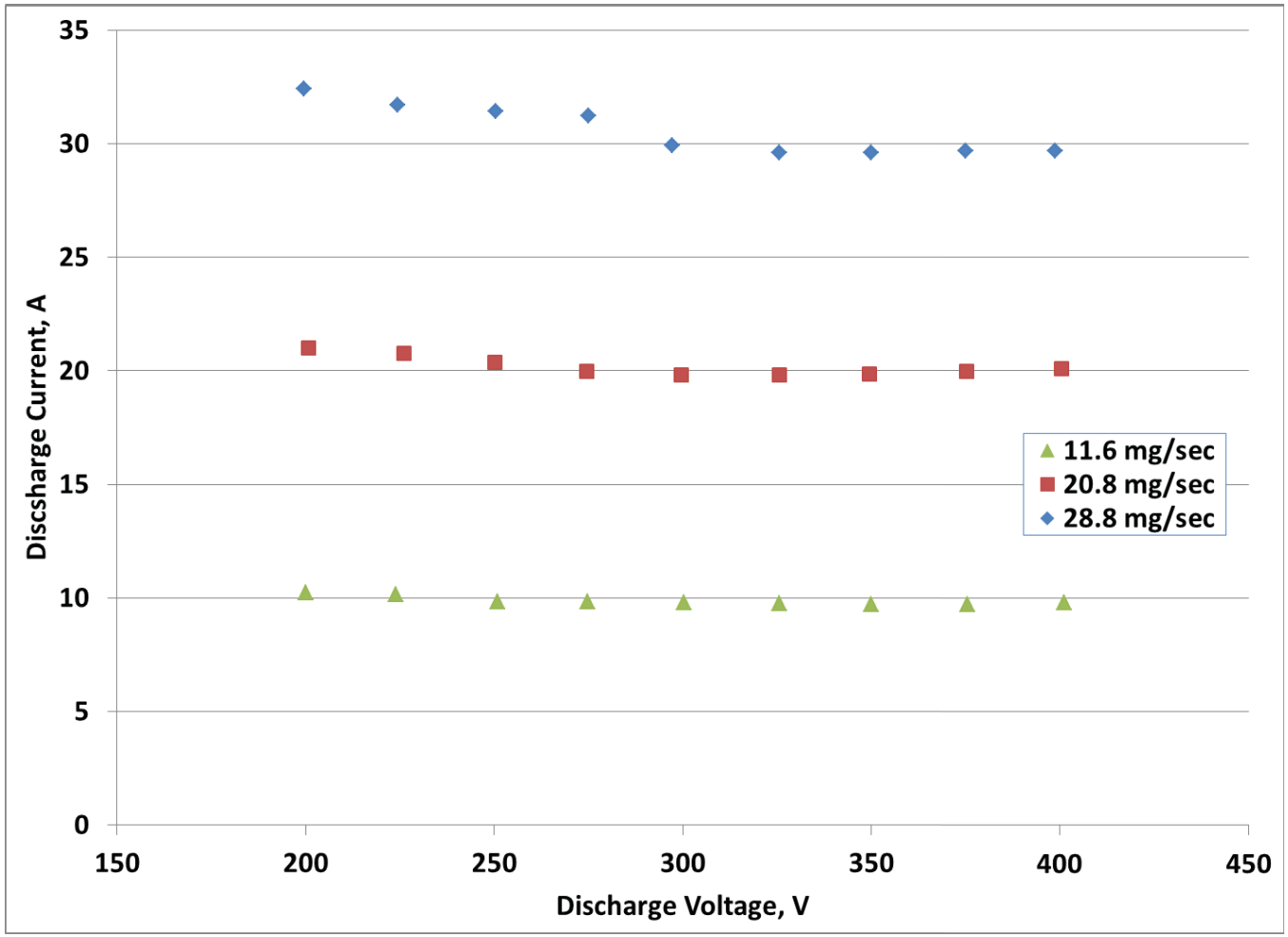
Additional Performance data can be found in paper IEPC-2013-451

Impedance Map

- At a fixed magnet current and propellant flow rate the discharge voltage was varied from 100 to 400 V in 25 V increments during which time the discharge current and thrust were recorded
- The thruster voltage and current (VI) characteristics were obtained for the following flow rates
  - 11.8 mg/s
  - 20.8 mg/s
  - 28.8 mg/s

XR-12 Performance: Impedance Map

VI map of the XR-12 thruster indicates a wide range of stable thruster operation



Summary and Conclusions

- **Performance characterization of the Lockheed Martin/Aerojet XR-12 brassboard thruster was performed at NASA Glenn VF5 vacuum facility (previous test results at UoM are published in IEPC-2013-451)**
- **XR-12 thruster performance was characterized for power levels from 2 to 12 kW at discharge voltages between 175 and 450 V**
- **Test results indicate that the thruster operation was nominal and stable across the entire operating design power range**
- **Peak total thrust efficiency of 61% was attained at 12 kW and 450 V**
- **Peak total specific impulse of 2,300 sec was attained at 12 kW and 450 V**
- **XR-12 performance is consistent with thruster performance levels used in the various SEP TDM mission studies**