Integration Tests of the 4 kW-class High Voltage Hall Accelerator Power Procesing Unit with the HiVHAc and the SPT-140 Hall Effect Thrusters

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Outline

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  - CPE EM PPU
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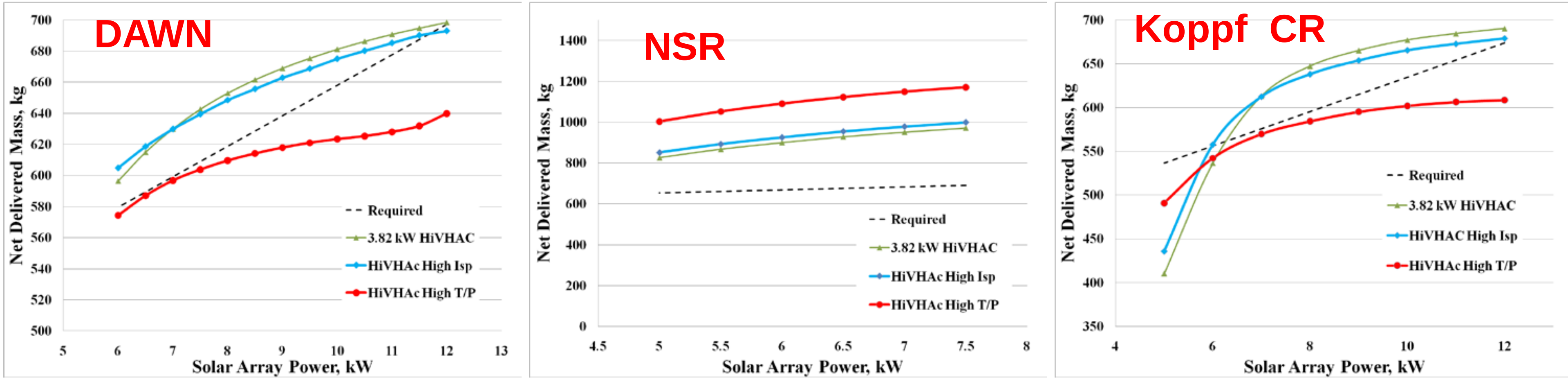
- SPT-140 Thruster Integration Test Results
- Summary

L. Pinero, "Performance of a High-Fidelity 4kW-Class Engineering Model PPU and Integration with the HiVHAc System," AIAA-2016-5031
EP-25, Rm 250B @16:00

Mission Analysis with HiVHAc Throttle Tables

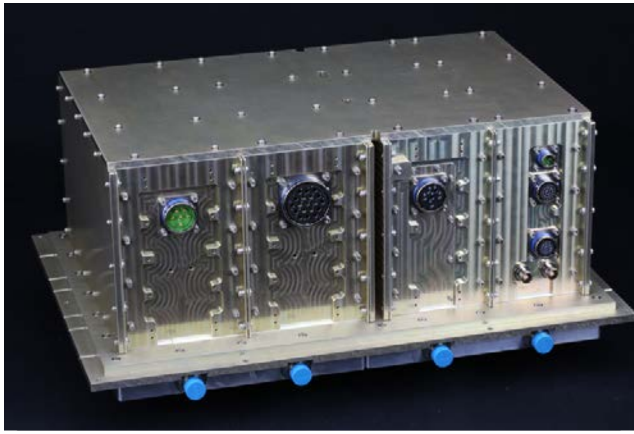


- Mission analysis was performed for 3 Discovery Class missions using the HiVHAc EDU 1 throttle table.
- The Dawn mission has both time constraints and an incredibly high post launch ΔV (11 km/s) requiring both moderate thrust-to-power, but also a higher specific impulse than a conventional Hall thruster.
- The Nereus sample return mission is a relatively low ΔV mission with time constraints, favorable for a higher thrust-to-power thruster.
- The comet rendezvous mission has few constraints and is not thrusting in gravity wells, which favors a high specific impulse throttle table.

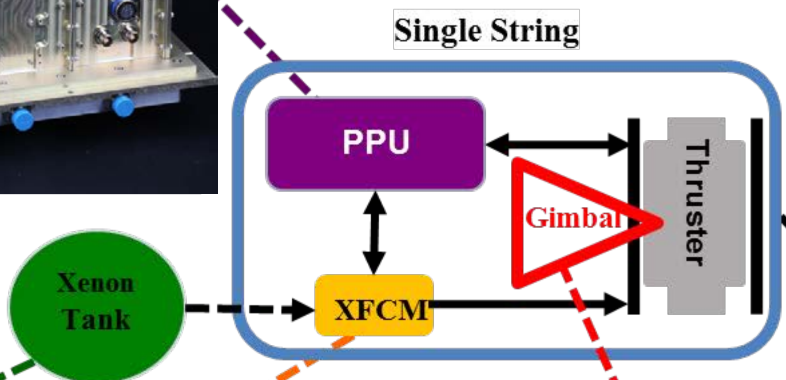
The results of the 3 DRM studies highlight the flexibility of the HiVHAc thruster to meet the needs of a wide range of Discovery class missions

Key Components in the HiVHAc System

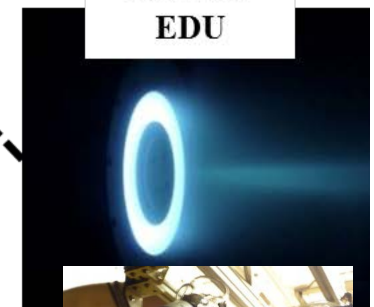
Test HiVHAc system developed component with other SOA Hall thruster(s)

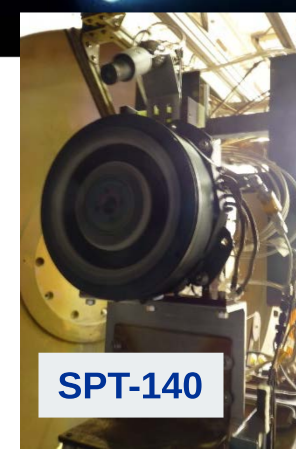


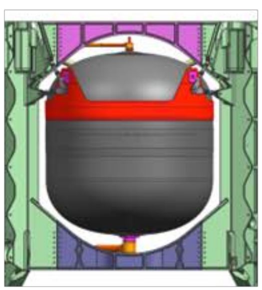
CPE EM
PPU



HiVHAc
EDU







Lt Wt propellant
tank

VACCO Xenon Flow
Control Module (XFCM)

Gimbal

HiVHAc and SPT-140 Hall Thrusters

- The HiVHAc EDU thruster was developed by NASA GRC and Aerojet Rocketdyne
  - 3.9 kW (6 A and 650 V)
  - 58% thrust efficiency
  - 2,700 s
  - In-situ self regulating discharge channel replacement mechanism
  - Thruster undergone random vibration test

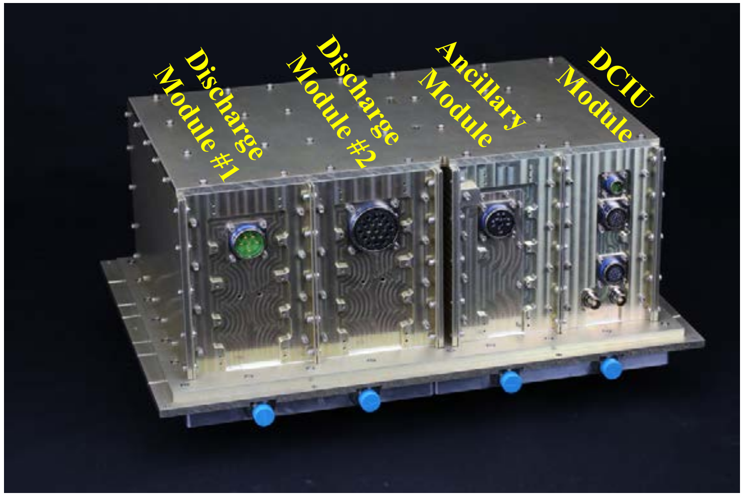
- The SPT-140
  - Manufactured by Fakel Experimental Design Bureau and provided on loan to GRC by Space System Loral (SSL)
  - Nominal 4.5 kW thruster but can operate up to 6 kW
  - Tested with NASA GRC cathode
  - Operating instructions provided by SSL

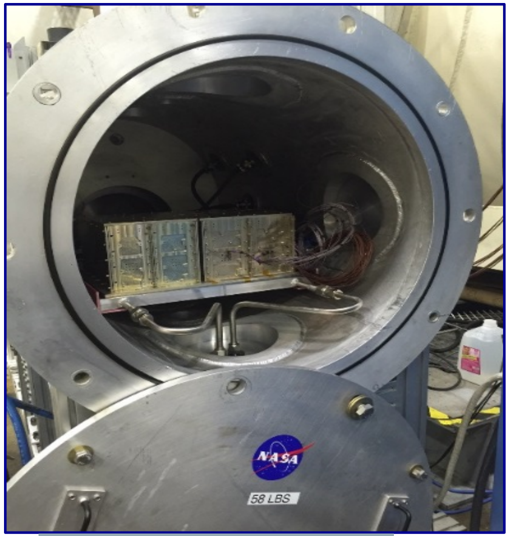
HiVHAc EDU-2 Thruster

SPT-140 with NASA GRC cathode

Colorado Power Electronics Engineering Model PPU

- EM PPU is developed by Colorado Power Electronic with funding from Small Business Innovative Research Program (SBIR)
- Prior to EM unit two brassboard units were built and tested for thousands of hours in vacuum
- The CPE EM PPU is a modular PPU that includes
  - Two discharge modules 2 kW each
  - Ancillary inner magnet module
  - Ancillary outer magnet module
  - Ancillary heater module
  - Ancillary keeper module
  - DCIU module
- CPE EM PPU weigh 15.6 kG
- The CPE PPU is 38.6 cm X 23.2 cm X 16.3 cm



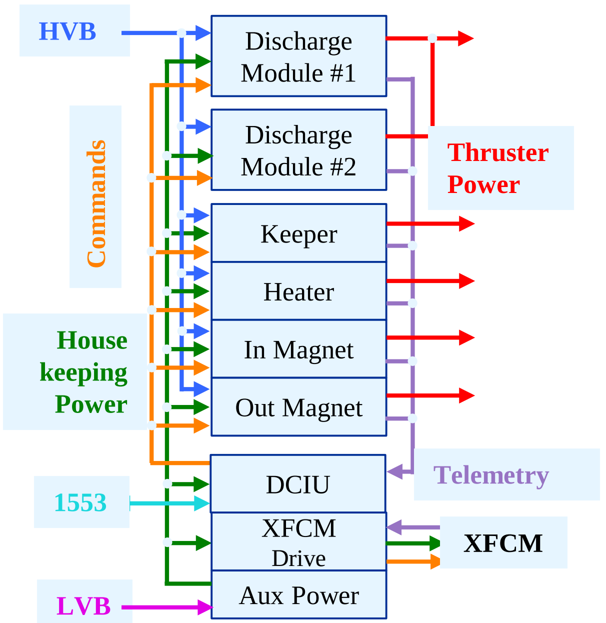


PPU in GRC VF70

L. Pinero, "Performance of a High-Fidelity 4kW-Class Engineering Model PPU and Integration with the HiVHAc System," AIAA-2016-5031
EP-25, Rm 250B @16:00

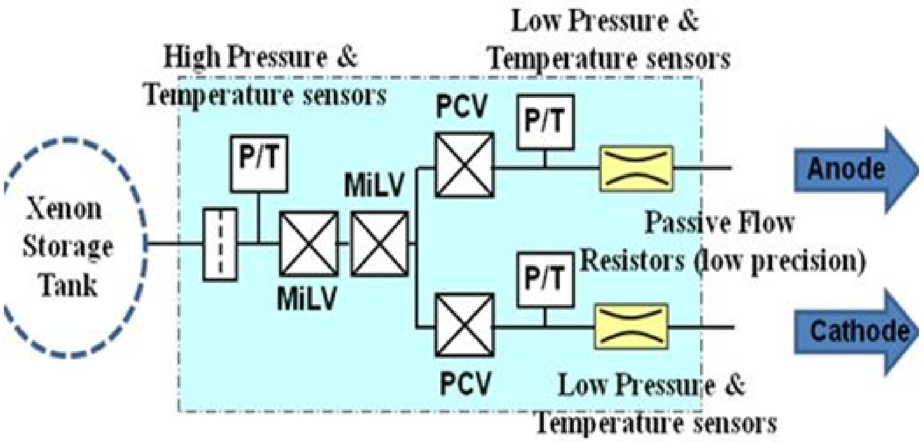
Colorado Power Electronics Engineering Model PPU

EM PPU	Discharge	Magnets (2)	Keeper	Heater
Output Voltage	200 – 700 V	2 – 10 V	5 – 40 V	1 – 15 V
Output Current	1.4 – 15 A	1 – 5 A	1 – 4 A	3.5 – 10 A
Output Power Max	4 kW	50 W	80 W	150 W
Regulation Mode	Voltage or Current	Current	Current	Current
Output Ripple	≤ 5%			
Line/Load Regulation	≤ 2%			
Input Voltage	80 – 160 V (main) and 24 – 34V (housekeeping)			



VACCO Xenon Flow Control Module

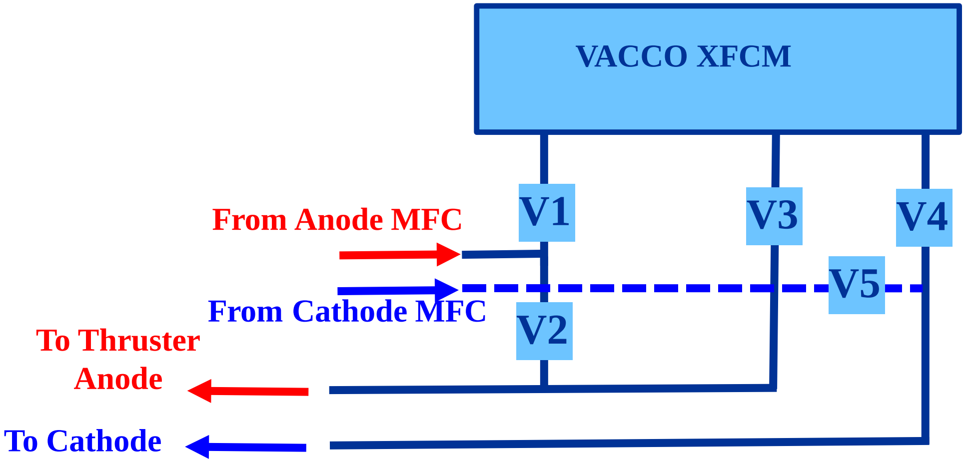
- The VACCO XFCM is the baseline xenon feed system for HiVHAc system
- XFCM incorporates redundant MLV and two piezoelectric control valves
- The XFCM can take xenon diretly from the tank at a pressure range from 10 to 3,000 psia and can provide regulated flow at a range of 0 to 160 sccm

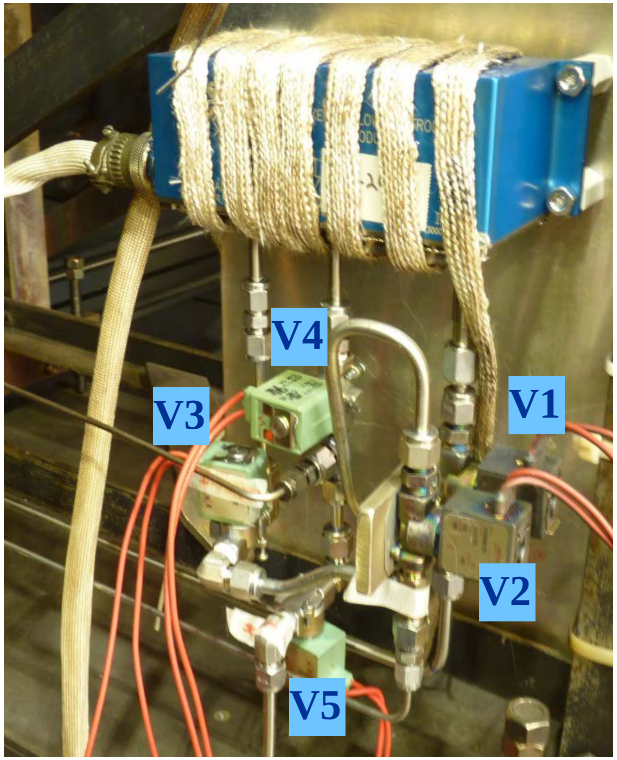


Inlet Pressure Range	10 to 3000 psia
Anode Flow Range	0 to 160 sccm Xenon
Cathode Flow Range	0 to 160 sccm Xenon
Flow Accuracy	±3% of set value (closed loop)
Internal Leakage	1.0×10^{-3} scch GHe
External Leakage	1.0×10^{-6} sccs
Lifetime	10 years, 7,300 cycles, 100% margin
Mass	< 1.25 kg
Power Consumption	< 1 W steady state
Size (W×H×D)	5.0 cm × 7.0 cm ×7.5 cm

VACCO Xenon Flow Control Module Setup in VF-12

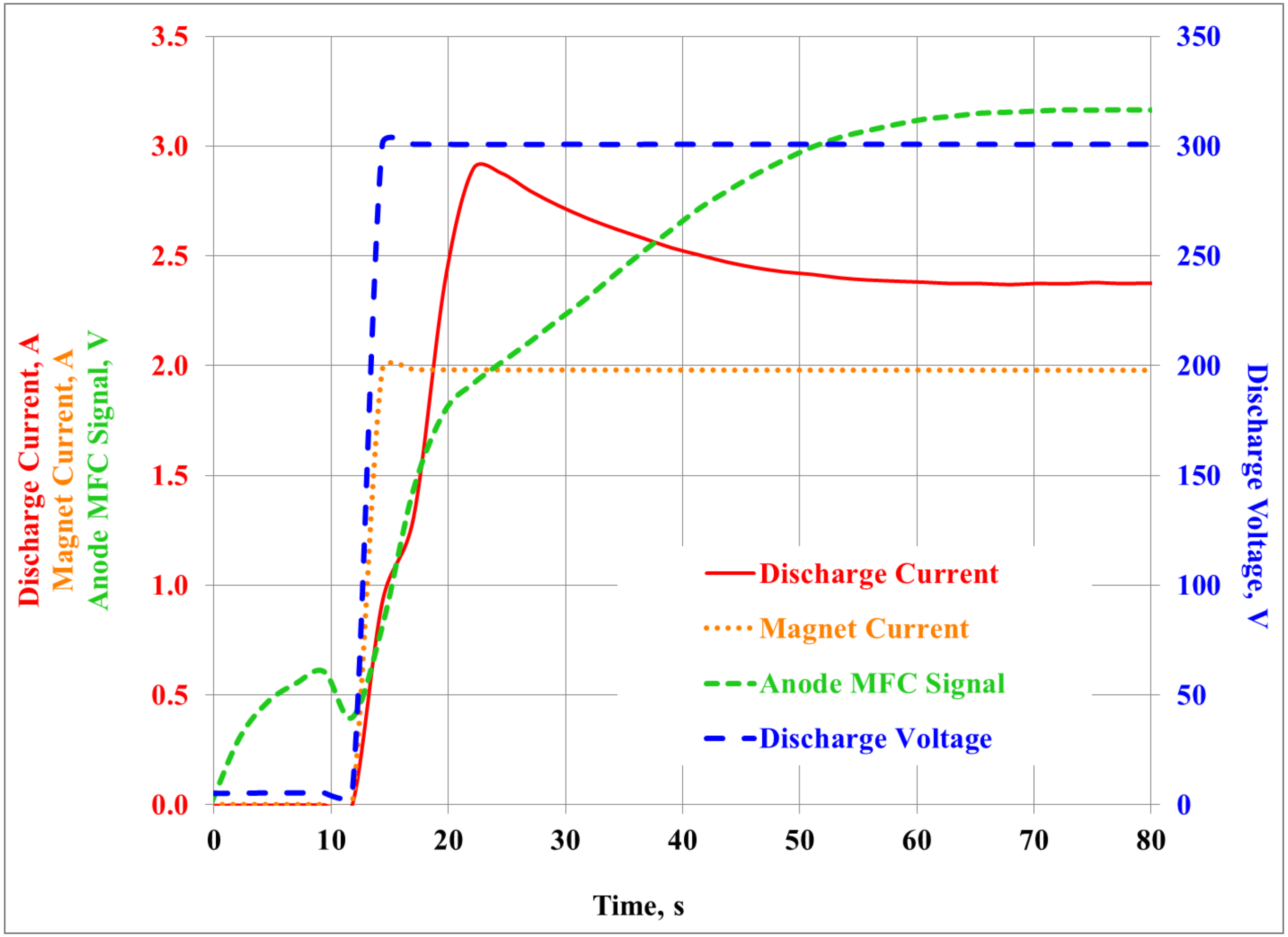
- The XFCM setup in VF-12 with the HiVHAc and SPT-140 thruster allowed for flexibility in thruster operation with the XFCM or the MFCs





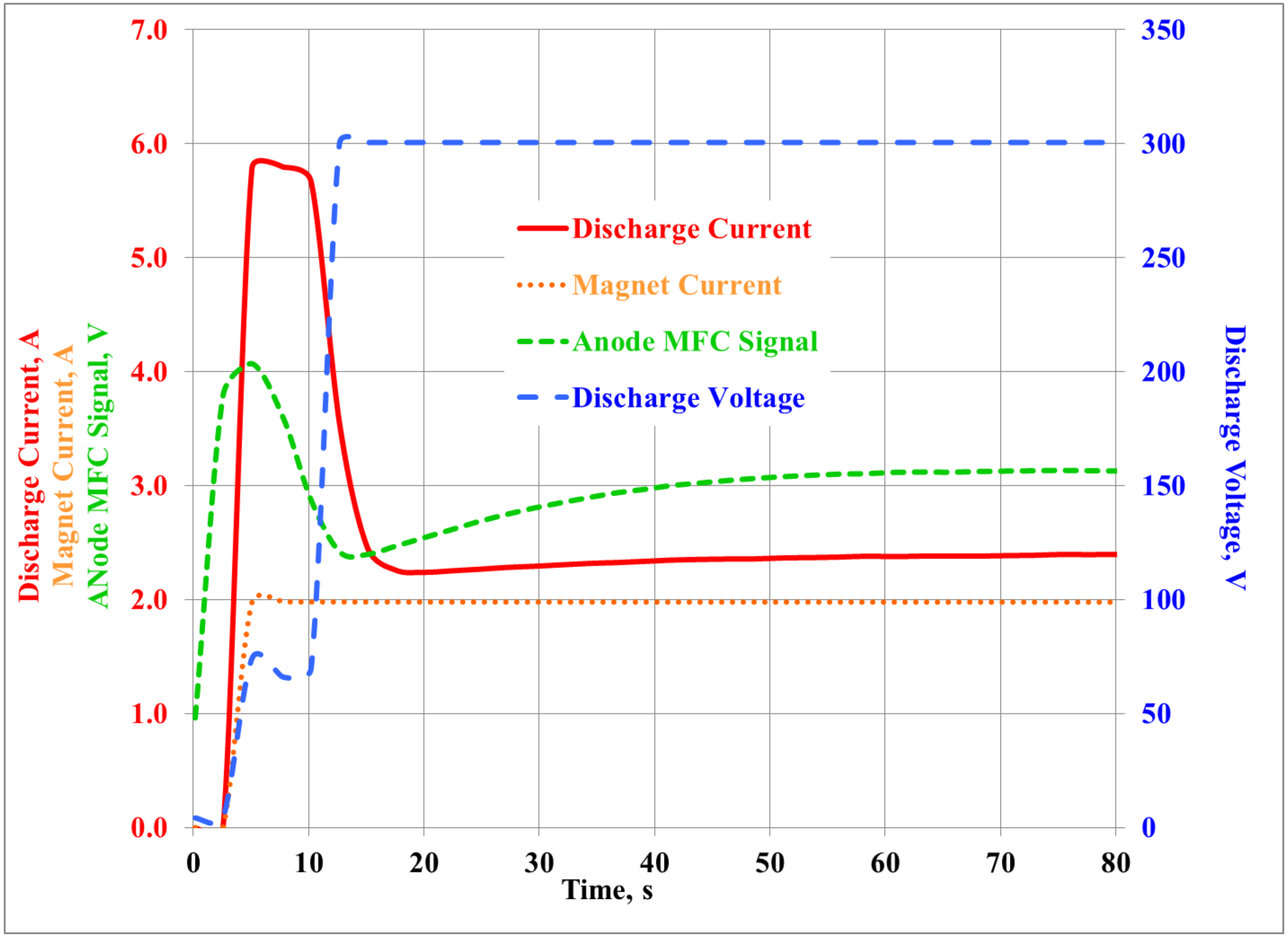
- **XFCM provides anode & cathode flow (V1, V3, & V4 open, V2 &V5 closed)**
- **MFCs provide anode & cathode flow (V2 & V5 open, V1, V2 &V3 closed)**
- **XFCM provides anode flow, MFC provides cathode flow (V1, V3, V5 open, V2 & V4 closed)**

Integrated Test with HiVHAc: Thruster Startup



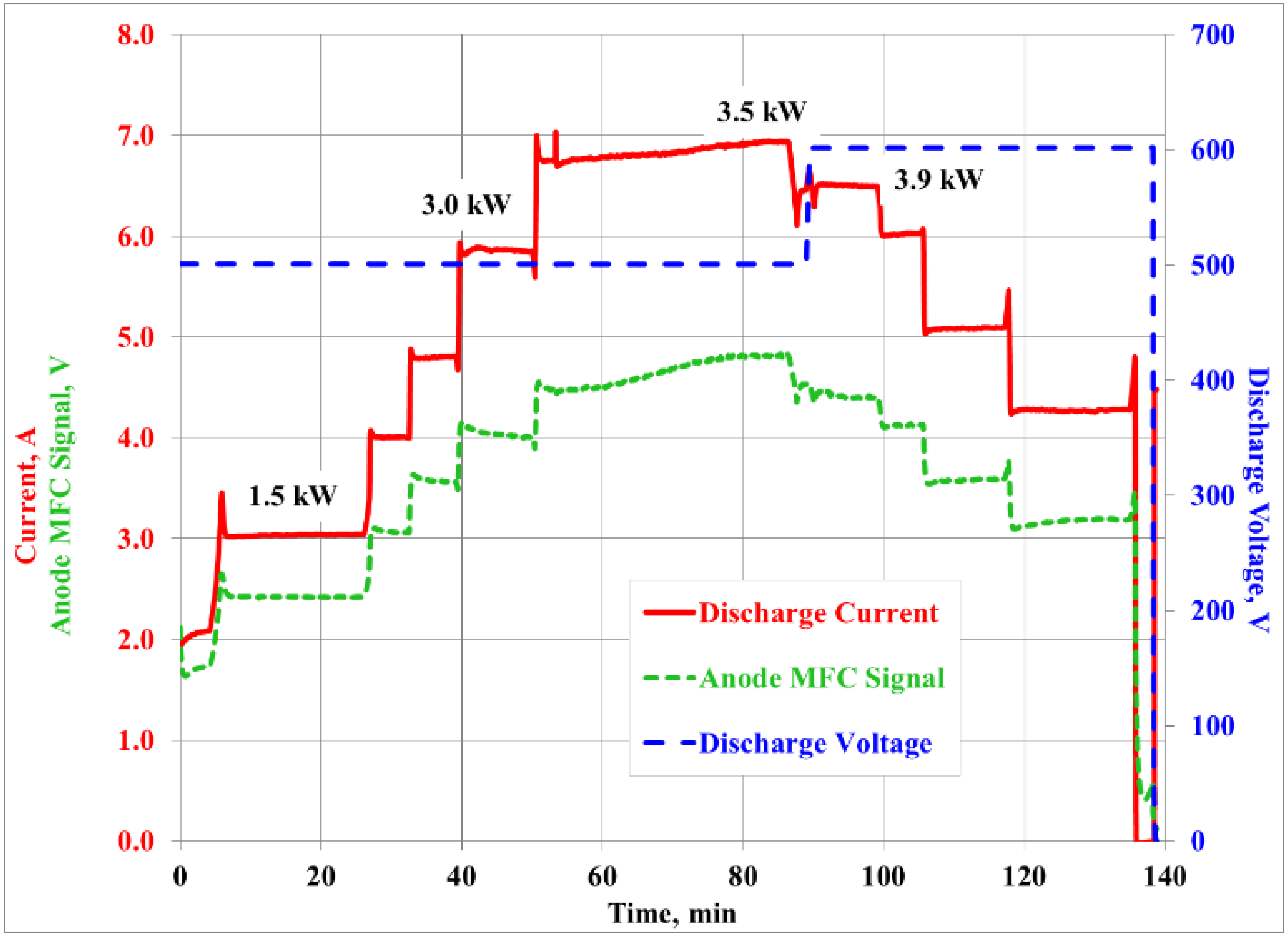
Successful thruster startup was demonstrated in Hall mode

Integrated Test with HiVHAc: Thruster Startup in Glow Mode



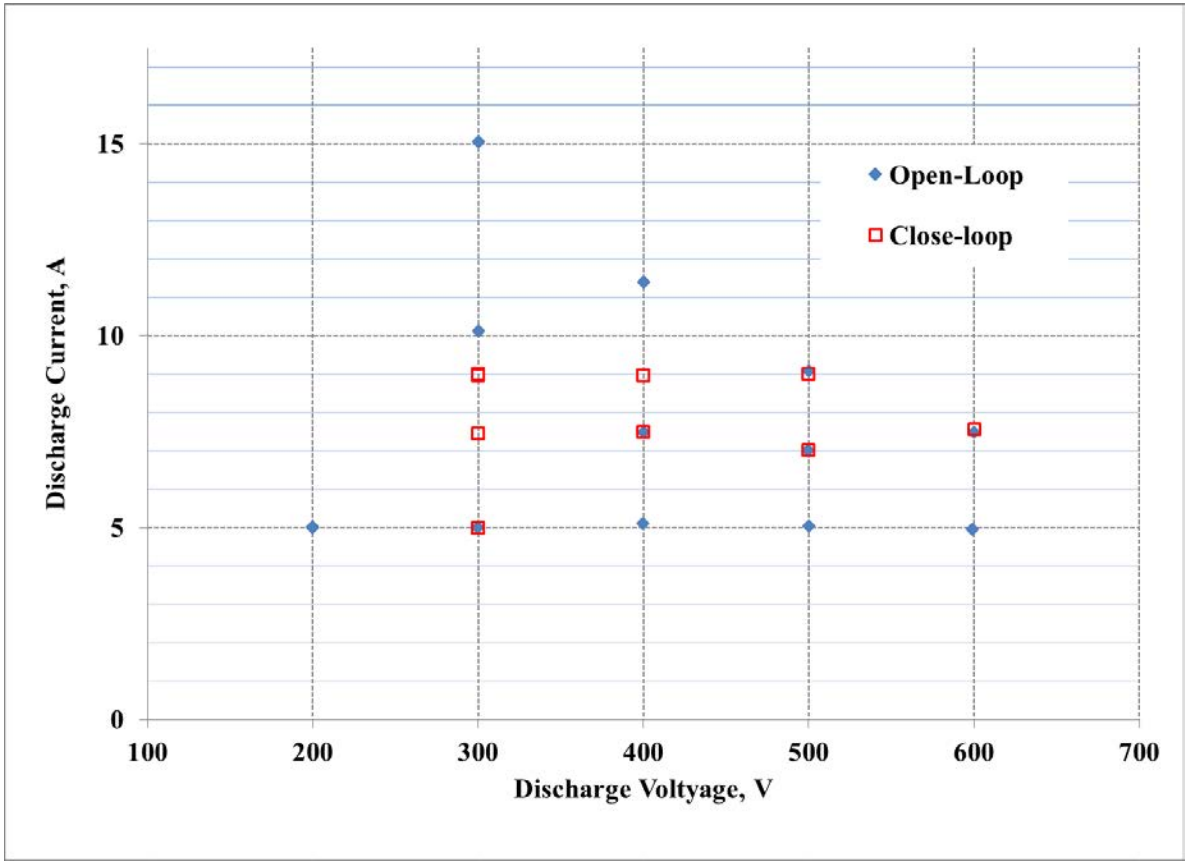
Successful thruster startup was demonstrated in glow mode

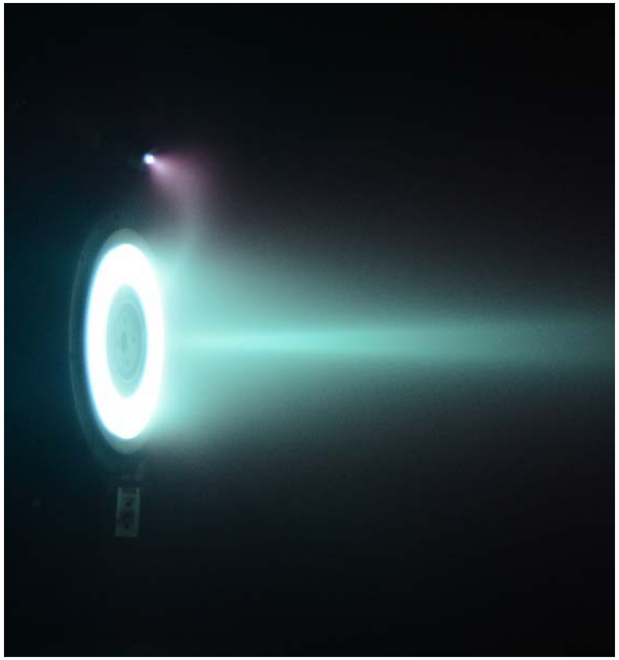
Integrated Test with HiVHAc: Thruster Throttling



HiVHAc thruster throttling was demonstrated in closed loop for all the HiVHAc thruster throttle points

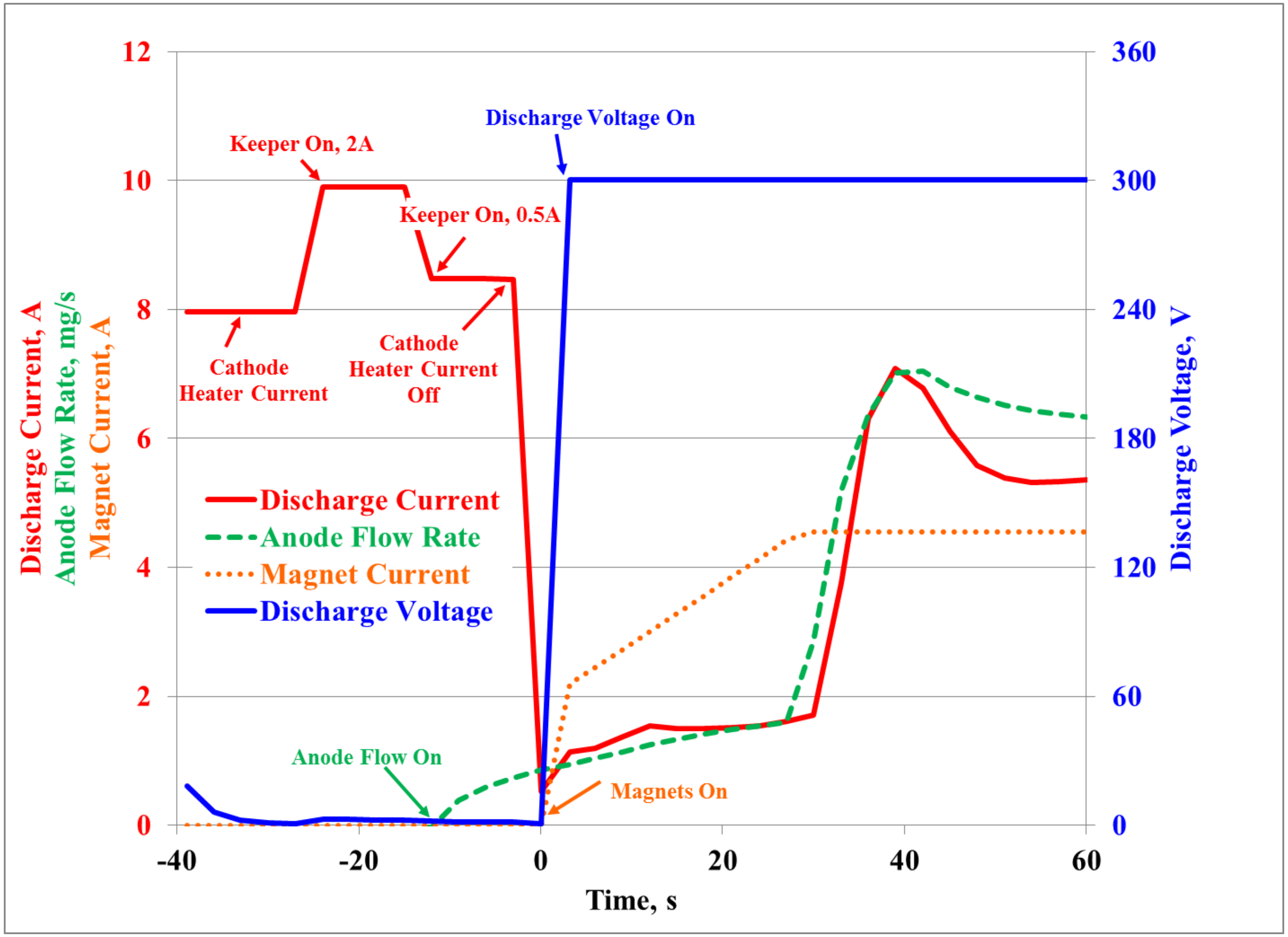
Integrated Test with SPT-140





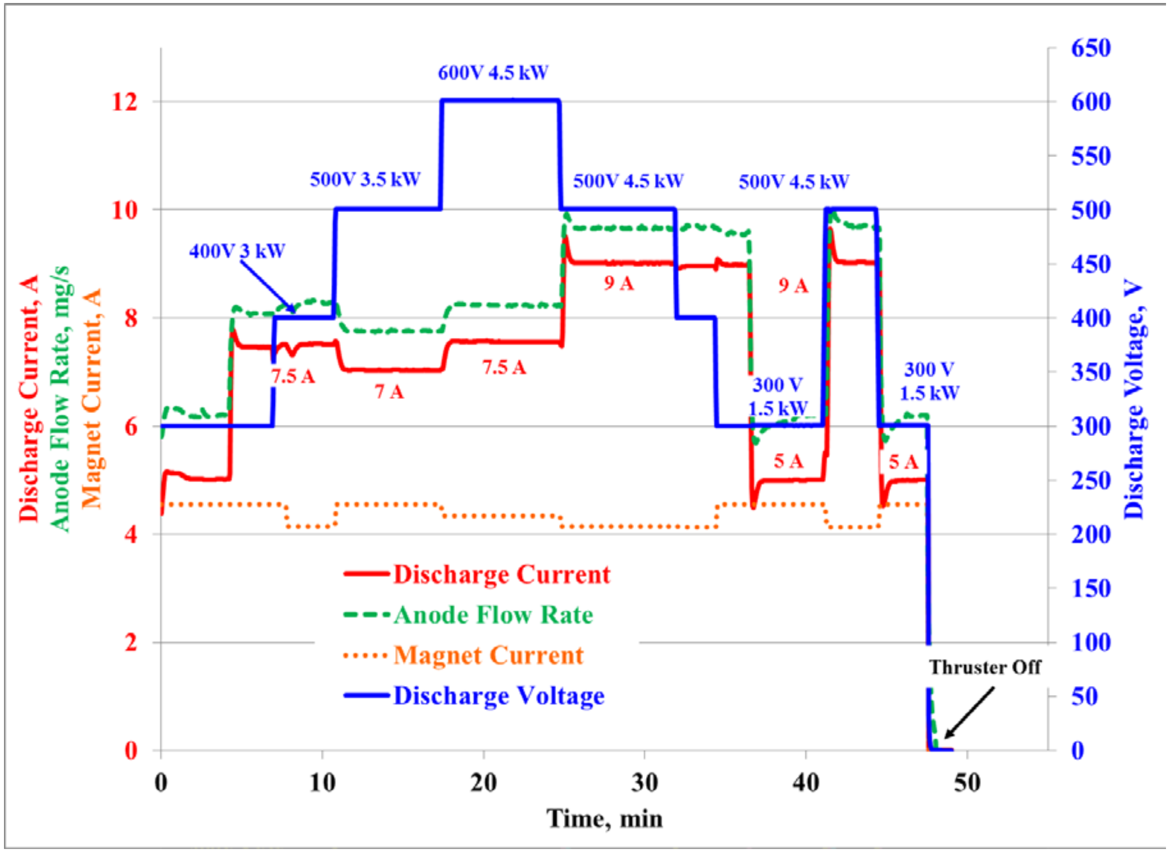
- The SPT-140 thruster was tested at power levels from 1 to 4.5 kW
- The SPT-140 was tested at discharge voltages from 200 to 600 V
- The SPT-140 was tested at discharge currents from 5 to 15 A

Integrated Test with SPT-140: Thruster Startup



The SPT-140 thruster startup was demonstrated in Hall mode with closed-loop control

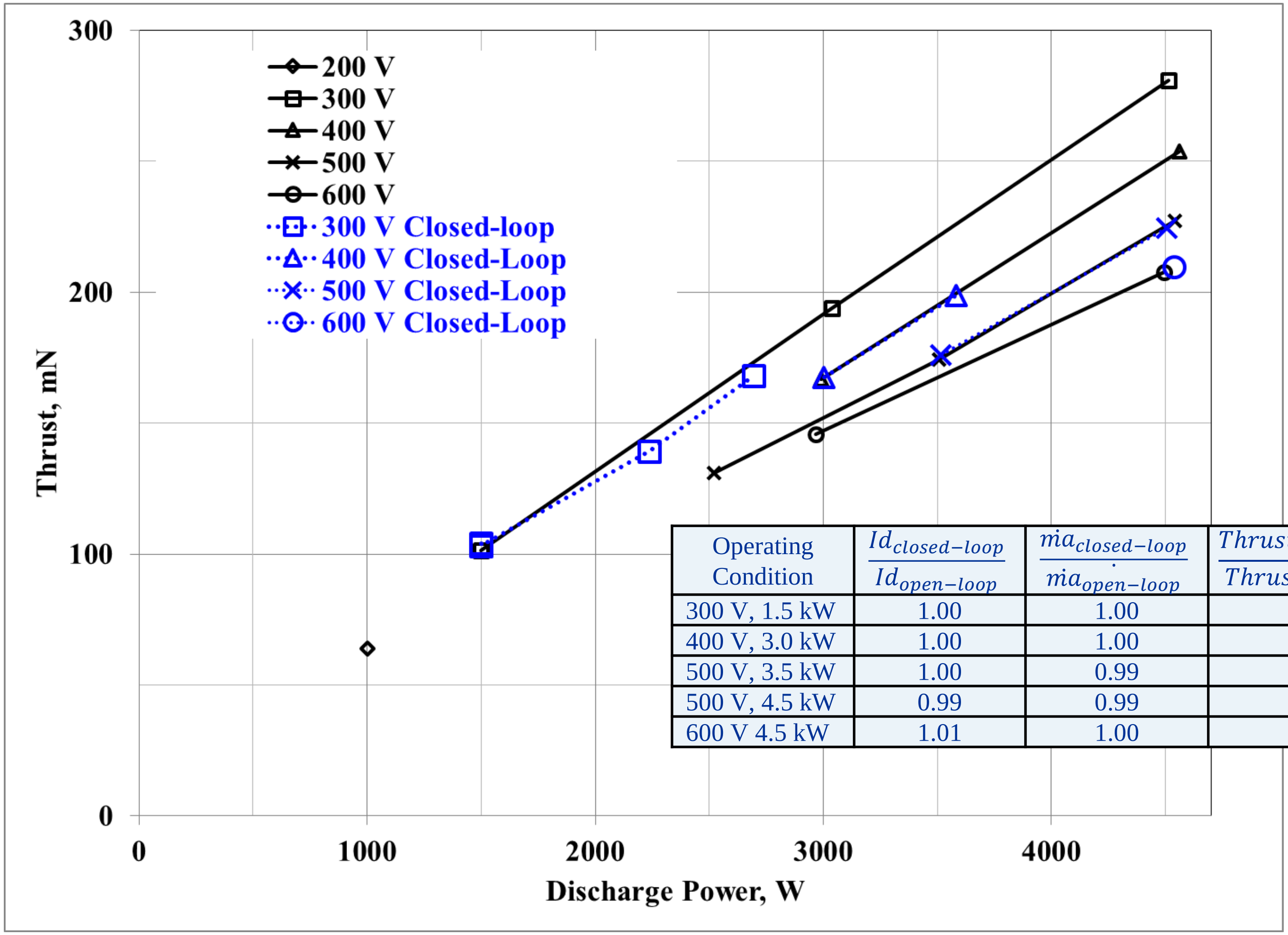
Integrated Test with SPT-140: Thruster Throttling



Test Point #	Thruster Discharge Operating Condition	Discharge Power, kW
1	300 V, 5 A	1.5
2	300 V, 7.5 A	2.25
3	400 V, 7.5 A	3.0
4	500 V, 7 A	3.5
5	600 V, 7.5 A	4.5
6	500 V, 9 A	4.5
7	400 V, 9 A	3.6
8	300 V, 9 A	2.7
9	300 V, 5 A	1.5
10	300 V, 9 A	2.7
11	300 V, 5 A	1.5
	OFF	

- The SPT-140 thruster was throttled across its operating range
- No closed loop operation was attained at 15 A, PID loop parameters require some refinement

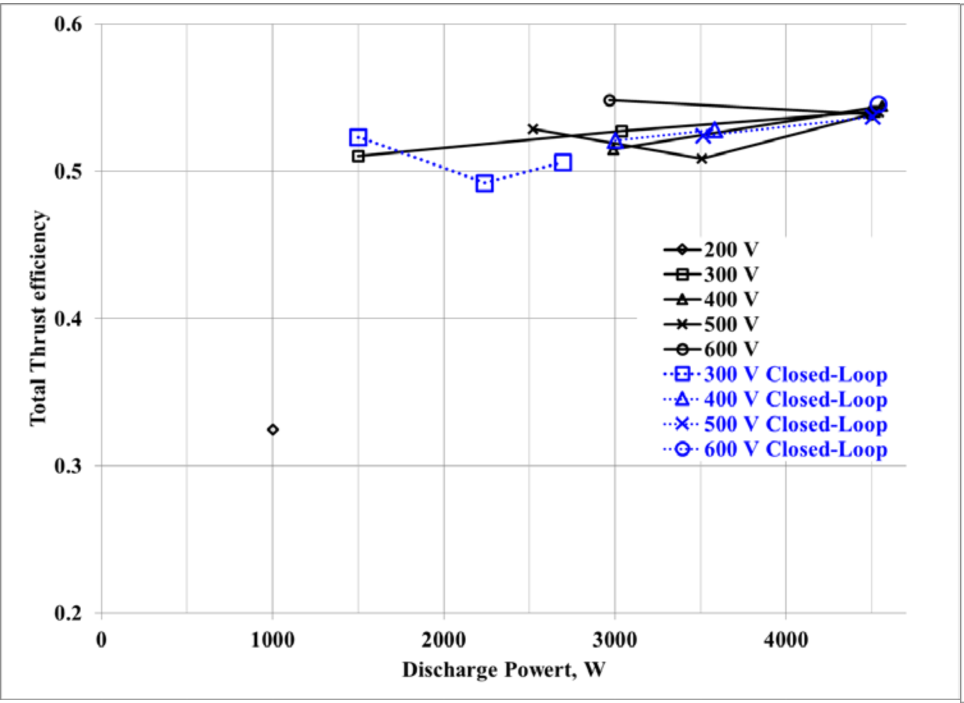
Integrated Test with SPT-140: Open & Closed Loop Operation Thrust Comparison

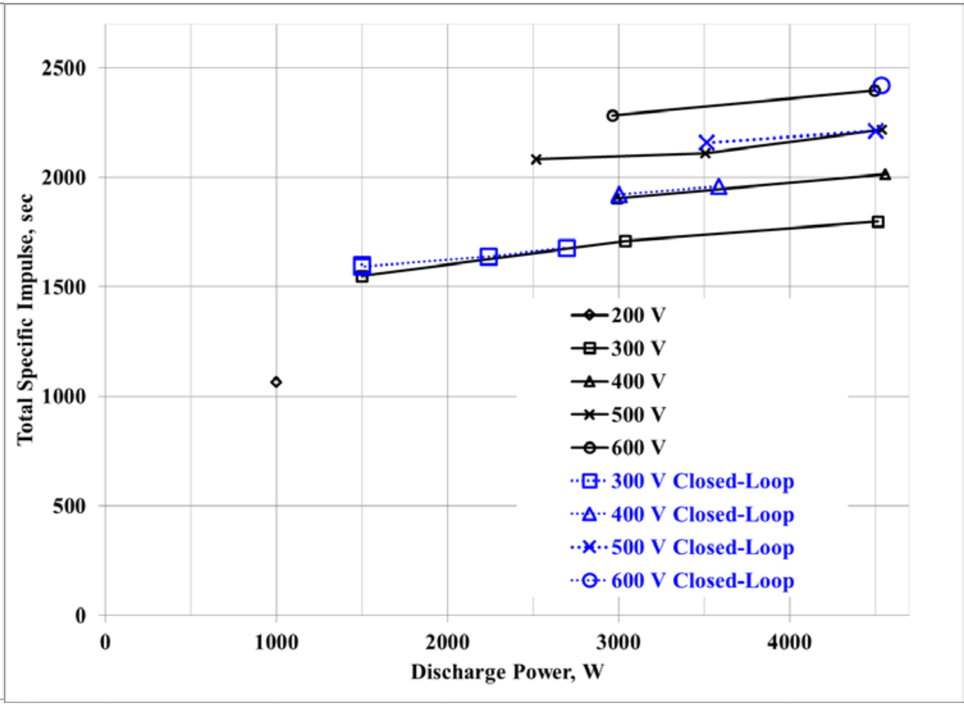


Operating Condition	$\frac{Id_{closed-loop}}{Id_{open-loop}}$	$\frac{\dot{m}a_{closed-loop}}{\dot{m}a_{open-loop}}$	$\frac{Thrust_{closed-loop}}{Thrust_{open-loop}}$
300 V, 1.5 kW	1.00	1.00	1.02
400 V, 3.0 kW	1.00	1.00	1.01
500 V, 3.5 kW	1.00	0.99	1.02
500 V, 4.5 kW	0.99	0.99	1.00
600 V 4.5 kW	1.01	1.00	1.02

- The SPT-140 thruster open and closed-loop operation indicated identical thruster performance

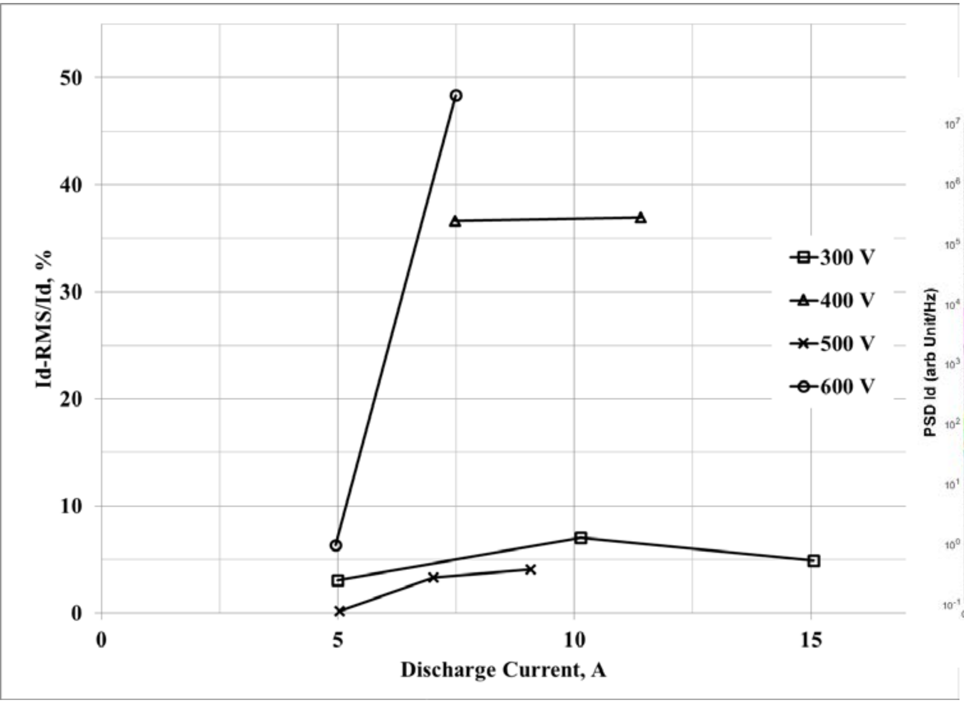
Integrated Test with SPT-140: Open & Closed Loop Operation Thrust Efficiency and Specific Impulse Comparison

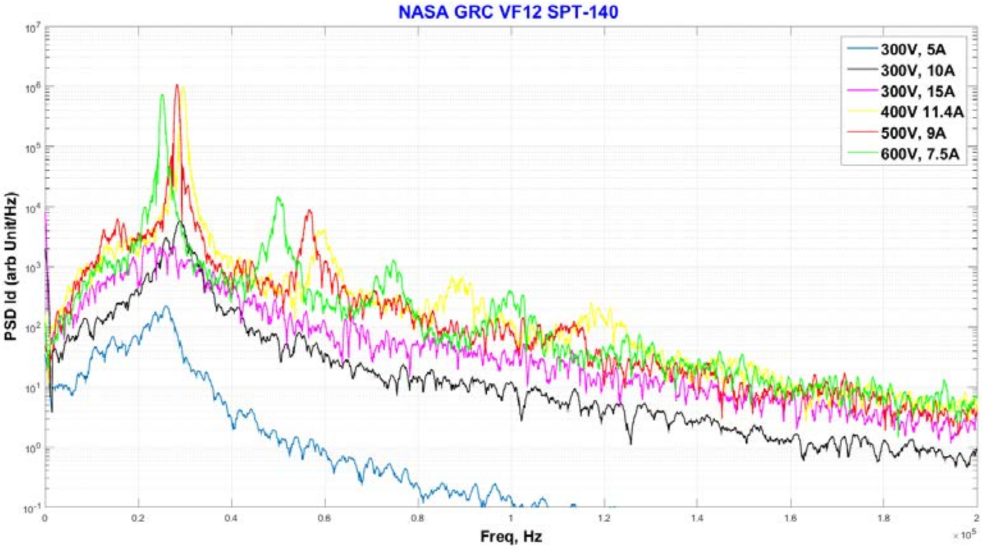




- The SPT-140 thruster open and closed-loop operation indicated identical thruster performance

Integrated Test with SPT-140: Discharge Current Oscillations





- The SPT-140 thruster oscillation levels and PSD profile at 300 and 400 V was almost identical values reported by JPL in 2014
- Oscillation levels at 500 and 600 V were not similar since the tests at GRC did not perform magnet tuning (at 300 and 400V magnet settings were provide by SSL)

CPE/HiVHAc PPU Prototype Demonstration Unit

- CPE is developing the next generation of CPE PPU-PMU
- Output specifications were changed to enable operation of other commercial thrusters
  - Discharge Power
  - Magnet voltage and current
  - Heater voltage and current
- Input voltage range was changed to satisfy power requirements of commercial spacecraft busses and NASA missions
- Additional functionality:
  - Magnet reversal
  - Independent discharge module control
  - XFCM heater power and control to enable high flow rate at low temperature
  - Health status flags
  - Safety interlocks and lockouts
  - Telemetry
    - ✓ Input
    - ✓ Discharge ripple
  - Correct minor issues identified during EM PPU testing

PDU PPU	Discharge	Magnets (2)	Keeper	Heater
Output Voltage	200 – 700 V	2 – 20 V	5 – 40 V	1 – 13 V
Output Current	1.4 – 15 A	1 – 7.5 A	1 – 2 A	3.5 – 21 A
Output Power Max	4.5 kW	108 W	80 W	210 W
Regulation Mode	Voltage or Current	Current	Current	Current
Output Ripple	≤ 5%			
Line/Load Regulation	≤ 2%			
Input Voltage	68 – 140 V (main) and 24 – 34V (housekeeping)			

SUMMARY

- NASA GRC is continuing the development of key elements of the HiVHAc system for implementation in NASA missions
- Key technologies under development include the thruster and the PPU
  - VACCO XFCM is at TRL 7
- CPE recently delivered to NASA GRC the EM PPU which includes a DCIU
- Integrated testing of the CPE EM PPU with the HiVHAc and SPT-140 thrusters was performed
- Both integrated tests demonstrated the full operation range of both thrusters. Tests also identified programming modifications that can be implemented to further enhance robustness of closed-loop operation
- CPE is further developing the EM PPU (PMU) to be compatible with commercial and NASA spacecraft and mission needs

Acknowledgments

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- The authors would like to thank Kevin Blake, George Jacynycz, and Michael McVetta for supporting the assembly and installation of the PPU and thruster in the vacuum facilities, as well as maintaining and operating the vacuum facility.