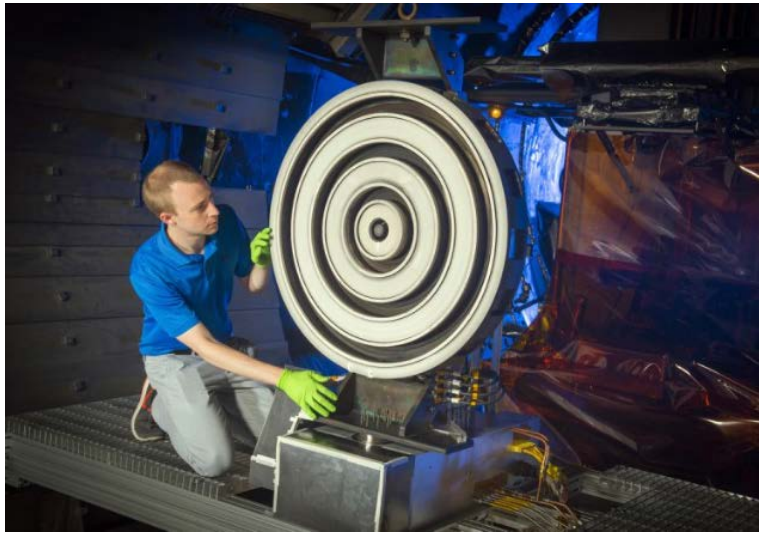
Power Processing and Flow Control for a 100kW Hall Thruster System



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OUTLINE

AEROJET ROCKETDYNE

- XR-100 program summary
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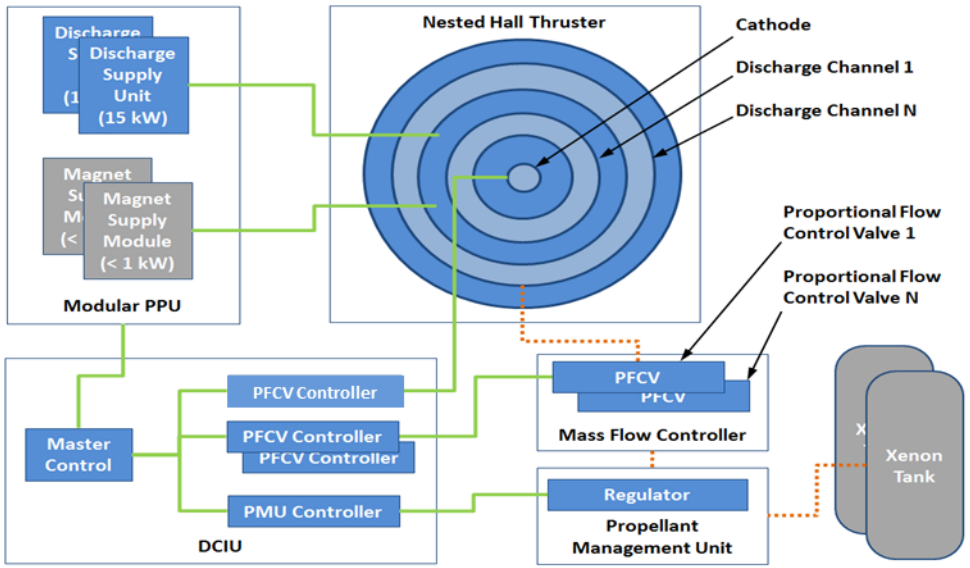
  - Program status
- EP string architecture overview
- PPU-Discharge Supply Unit (DSU)
  - Discharge Supply Unit architecture
  - Test results
- Mass Flow Controller (MFC) and Propellant Management Unit (PMU) hardware overview
- MFC control through PPU electronics
  - Controls architecture
  - Test results
- Conclusion

XR-100 Program Summary



Legend:

Aerojet Rocketdyne Current Scope

Not Current Scope

Acronyms:
PFCV: Proportional flow control valve
PPU: Power Processing Unit
DCIU: Digital Control Interface Unit

Program Goals and Target for Space Flight System

Metric		XR-100 Objective
Requirement	TRL 5 demonstration power	100 kW
	TRL 5 steady state operation time	100 h
Goal	Specific Impulse	~2,000 to ~5,000 s
	Thrust per thruster	>5 N
	In-space lifetime capability	>50,000 h
	Operational lifetime capability	>10,000 h
	System efficiency	>60%
	Power per thruster	100 kW
	System kg/kW	<5 kg/kW

XR-100 goal is to operate hardware at 100kW and demonstrate TRL 5

PROGRAM STATUS

AEROJET ROCKETDYNE

Year One

- Completed 10kW Discharge Supply (DSU) Unit bench test
- Completed Mass Flow Controller bench test

Year Two

- Completed an integrated system test at University of Michigan with the Nested Hall Thruster, one Discharge Supply Unit and the Mass Flow Controller(MFC)
  - Demonstrated 10kW at 800V and 10kW at 400V output power
  - Demonstrated closed loop flow control xenon

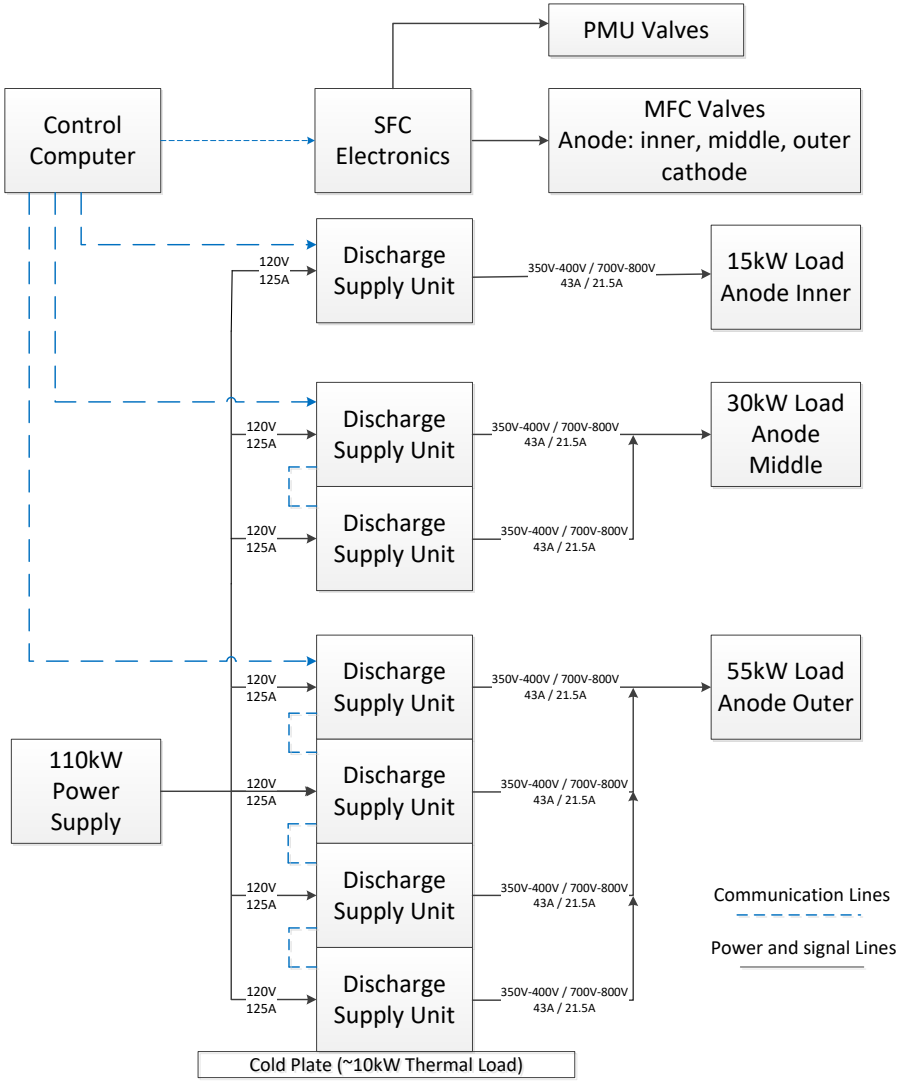
Year Three

- Demonstrated 40kW bench test with three DSU in parallel powering a common load at output of 400V and 100 amps
- 100kW integrated system test scheduled to occur at NASA GRC in late 2018 with the Nested Hall Thruster

Program has made solid annual progress per the plan working up to the 100kW test

XR-100 System Block Diagram

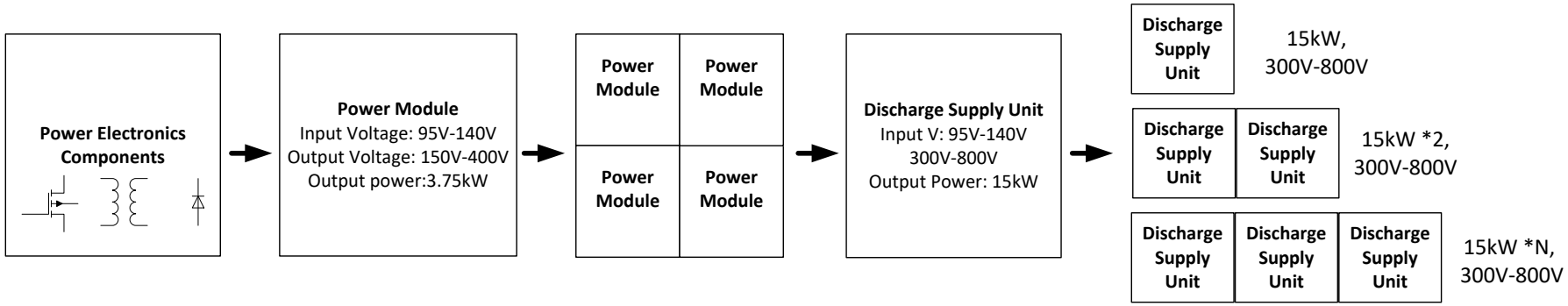
- To achieve TRL 5, AR designed the following testbed which will power 100kW of thruster load at completion of the three year contract
- Test bed was architected as shown, but the build up and demonstration has been completed through planned incremental development
- The full testbed buildup is now in process
- SFC = System Flow Controller



Critical Elements of future flight system have been built into a integrated testbed

Discharge Supply Unit Architecture

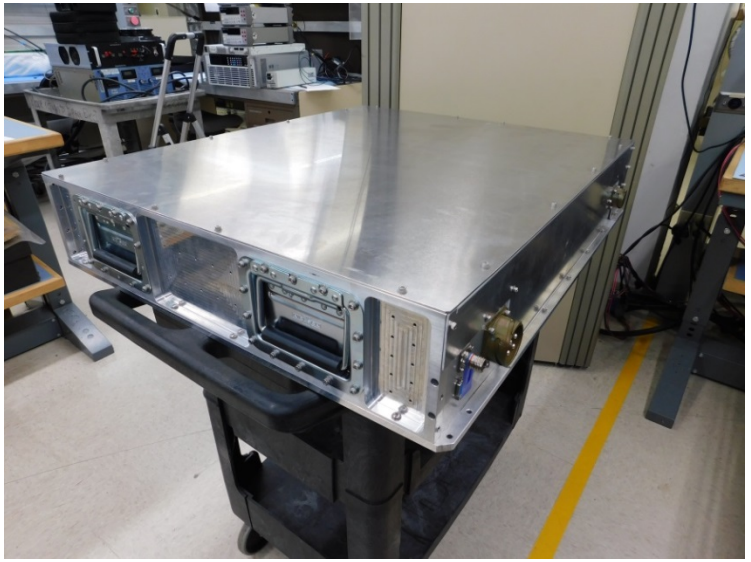
- To Get to 100kW of output power a modular design was developed
- A Power Module (PM) produces 150-400V at 3.75kW, target efficiency at full power for each module is >95%
- Power Modules are combined to make a 15kW DSU, multiple DSU can be combined to power higher kW power thruster channels
- Each PM has local analog control circuit, but a digital control system synchronizes power modules to work together to regulate total output voltage and limit output current



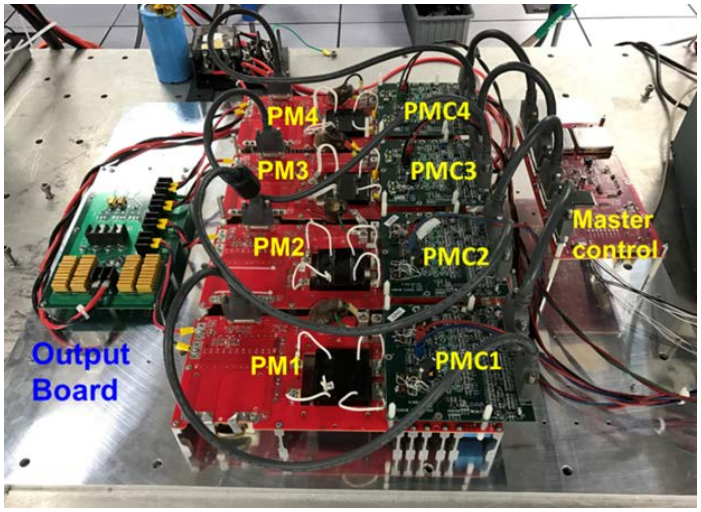
Modular design is able to be configured for a wide range of operating conditions without redesign

XR-100 Discharge Supply Unit

- Input voltage: 95V – 140V, unregulated
- Output Voltage and Output Current:
  - High thrust mode: 150V-400V @37.5A
  - High ISP mode: 300V-800V @18.75A
- Output Power: 15kW for both modes
- Efficiency: greater than 95% at max power
- Provides:
  - Closed loop output voltage control with programmable current limiting
  - Programmable digital control loop gains
  - Voltage set point adjustable in 200mV increments
  - Current limit adjustable to within 100mA
  - Fault shut down protection
  - Capable of riding through thruster induced spark events
  - Can parallel DSU output to achieve higher output power at a common load
  - Digital command and telemetry interface



Assembled DSU, size ~ 2.5'x 3'



DSU prototype, PMC = power module controller

DEMONSTRATED PERFORMANCE

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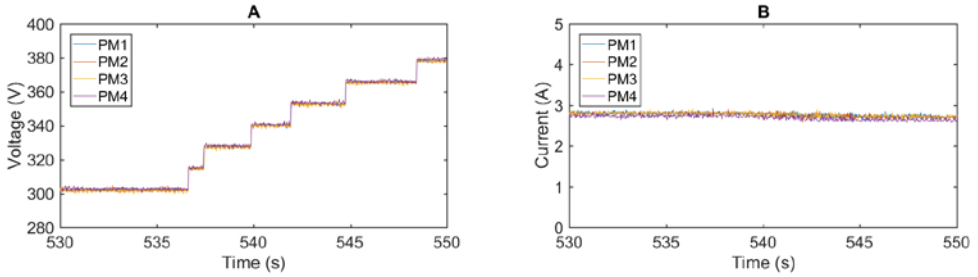
- DSU efficiency demonstrated at UofM with the Nested Hall Thruster inner channel

Input Voltage	Input Current	Calculated Input Power	Output Voltage	Output Current	Calculated Output Power	Efficiency
107.0 V	99.6 A	10,657 W	400.4 V	25.56 A	10,234 W	**96.0%**
103.6 V	103.8 A	10,753 W	400.4 V	25.94 A	10,386 W	**96.5%**
104.0 V	85.6 A	8,902 W	602.0 V	14.37 A	8,650 W	**97.1%**
105.8 V	97.2 A	10,283 W	705.6 V	14.16 A	9,991 W	**97.1%**
105.9 V	97.0 A	10,272 W	800.0 V	12.50 A	10,000 W	**97.3%**

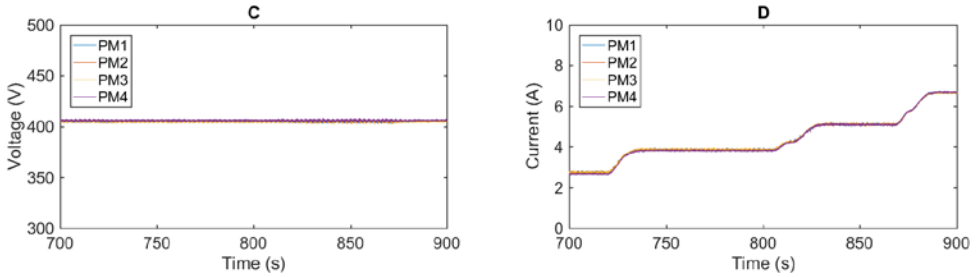
- Telemetry data from each power module during DSU operation
- Each graph has four overlapping traces

Power balance during discharge voltage adjustment



- Power processed by each module is balanced during transients and steady state operation

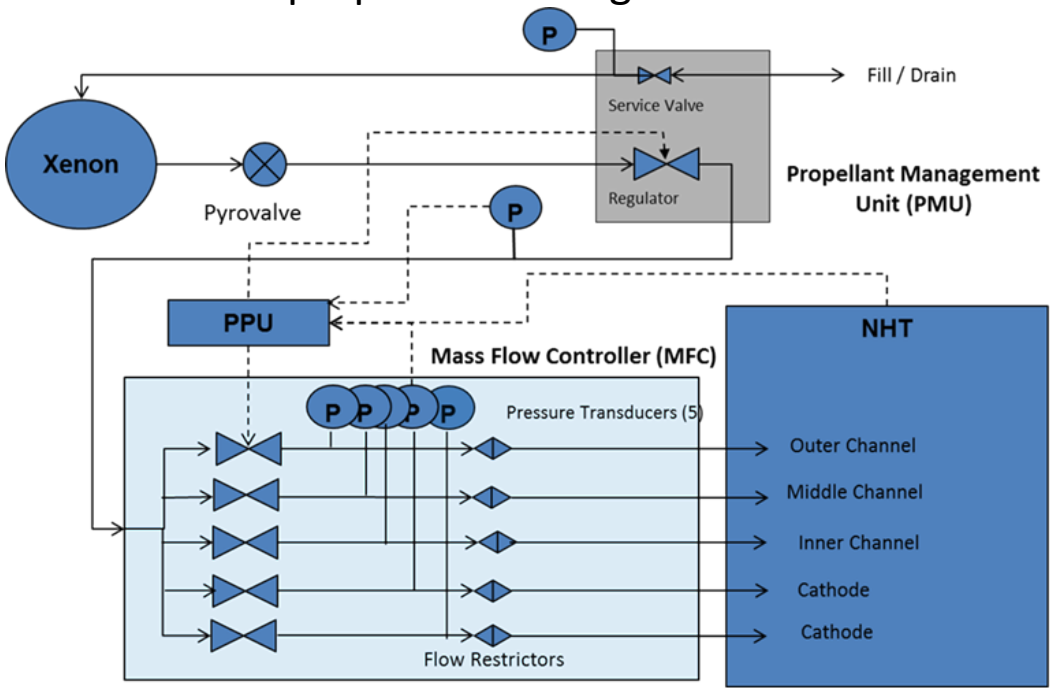
Power balance during discharge current adjustment

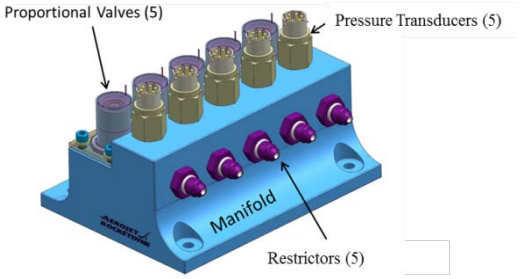


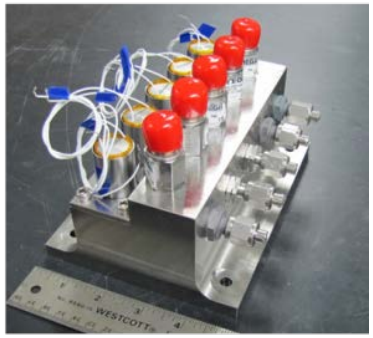
Design performed exceptionally well while power Nested Hall Thruster to 10kW

MFC AND PMU HARDWARE

- Proportional Flow Control Valves (PFCV), flow restrictors and pressure transducer make up the MFC and PMU
- PFCV valve position is proportional to an applied valve coil current (0-300mA)
  - Valve design has been improved since the UofM test to only require 200mA max
- Pressure transducer located between PFCV and flow restrictors generates a pressure signal proportional to flow rate
- The same hardware used to provide flow control to the Thruster channels is also used in the propellant management unit

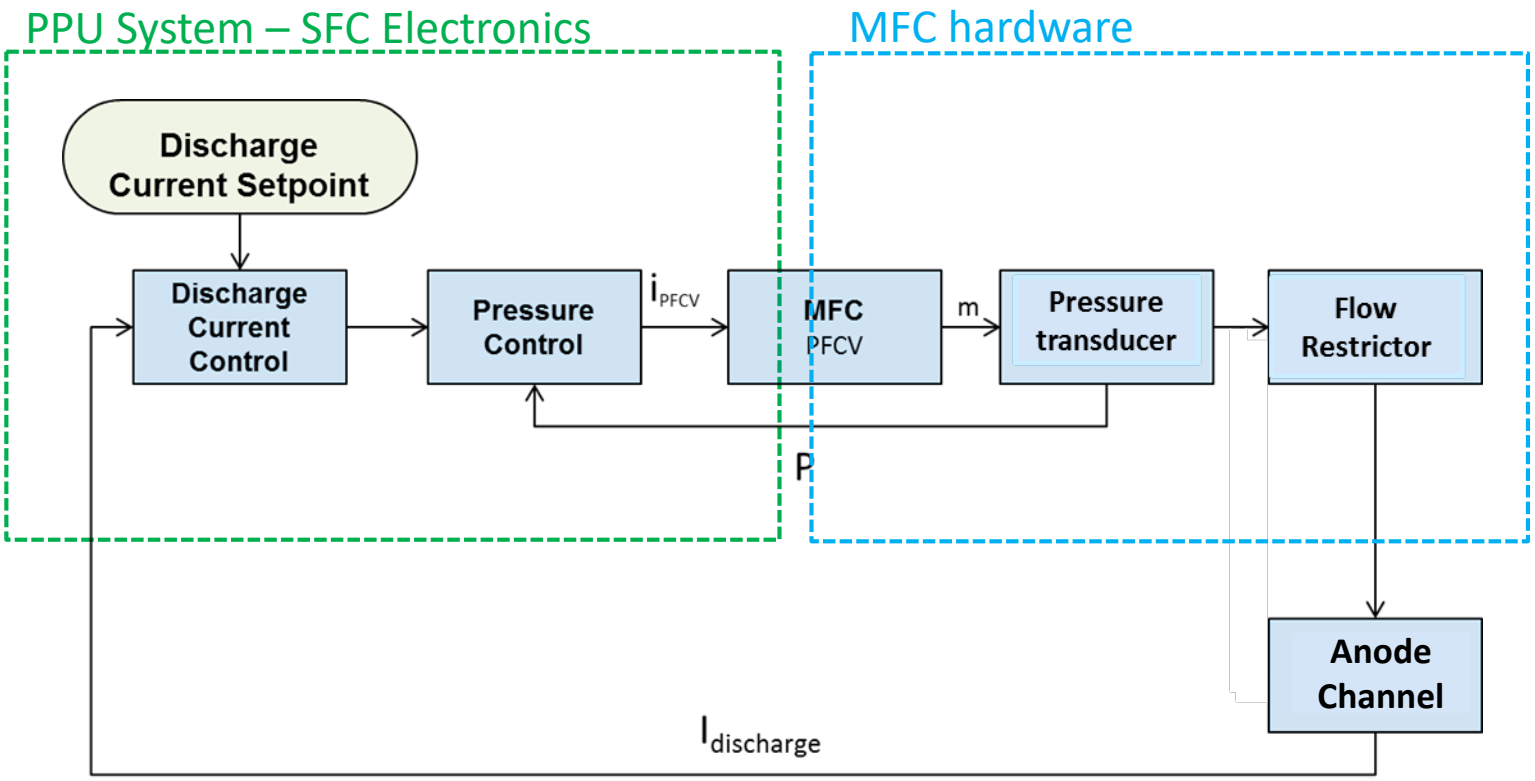






PPU Flow Control Modes

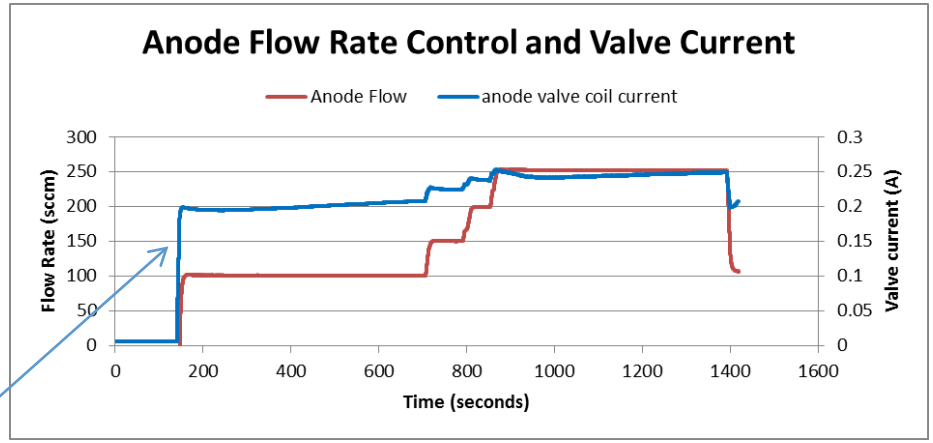
- PPU orchestrates the operation of thruster/xenon flow in multiple modes
- Can operate the valves in open loop or closed loop control of flow rate or closed loop control of discharge current
- Closed loop discharge mode assures discharge current is constant



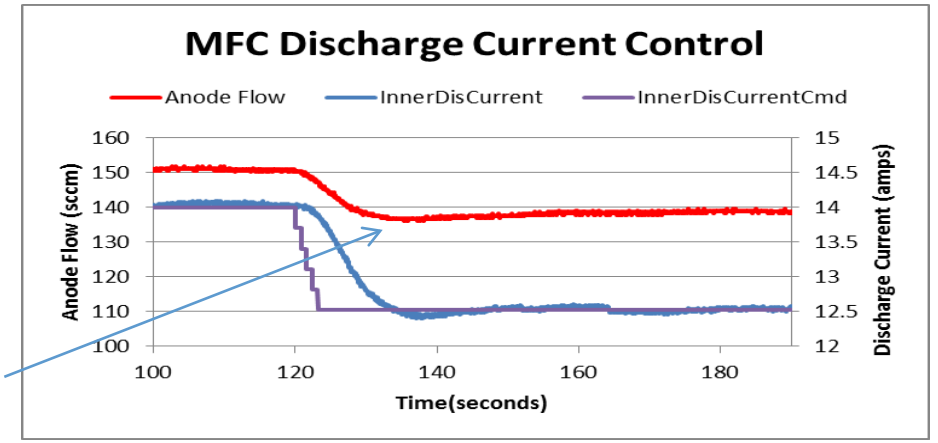
INTEGRATED MFC/SFC PERFORMANCE

- Team was able to show the MFC, SFC electronics and Discharge Supply Unit can operate a thruster in a stable manner

- Demonstrated cathode flow control
- Demonstrated anode flow control
- Demonstrated discharge current control
- Used AR developed System Flow Controller (SFC) Electronics for all modes of operation
- Tuned control system during testing at UofM using digital control systems programmable gain feature



Coil current adjusted to maintain flow

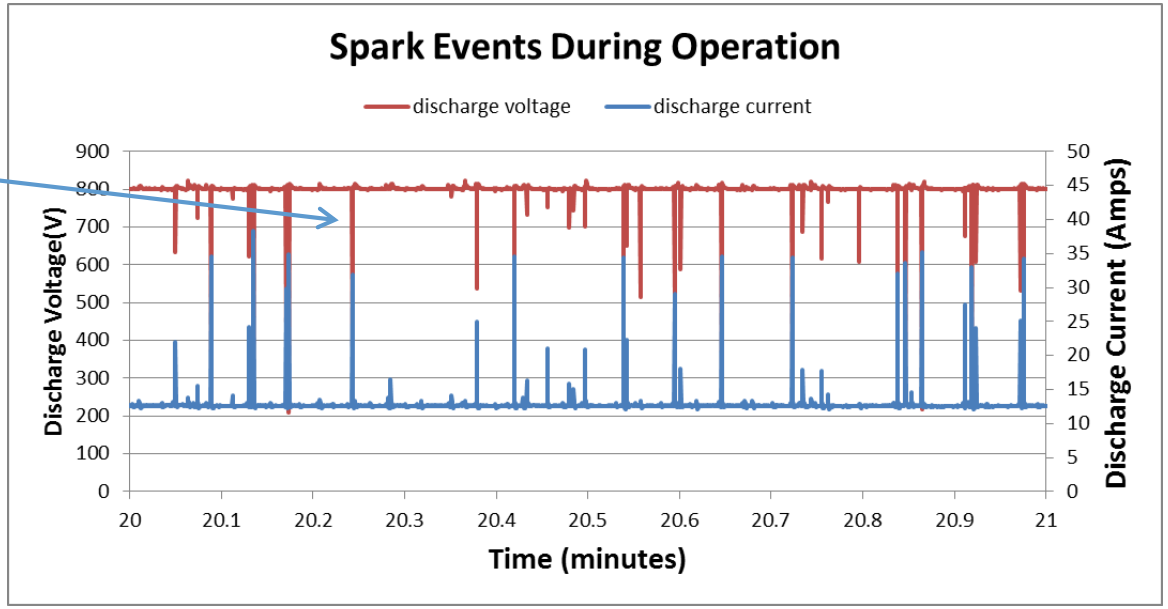


Flow adjusted to maintain discharge current

System Robustness

- During 10kW testing at higher voltages, the thruster was producing a near short circuit load to DSU for short transient amounts of time ~2-3 events every 10 seconds
- DSU, SFC and MFC system operated through these events without triggering shutdown limits and had stable output voltage and constant discharge current despite the high number of disturbances

During spark events the discharge voltage collapses and discharge current spikes to high levels, but the electronic controls assure recovery and stability



Aerojet Rocketdyne system demonstrated discharge voltage and flow stability while thruster was behaving in a off nominal mode

CONCLUSION

AEROJET ROCKETDYNE

- Developed a modular PPU architecture capable of powering multiple thruster channels to a combined 100kW of power
- Developed and manufactured a Mass Flow Control valve system capable of providing propellant management and thruster gas flow control
- Demonstrated closed loop control of a single channel of the Nested Hall Thruster at 10kW of power, with Aerojet Rocketdyne hardware controlling the discharge voltage, discharge current and thruster gas flow rates
- Demonstrated 40kW bench test with three DSU in parallel powering a common load at output of 400V and 100 amps

On track to demonstrating 100kW operation of the Nested Hall Thruster with the AR PPU and MFC

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