Sub-kW Class Hall-Effect Thruster Power Processing Unit for Wide Output Range Applications

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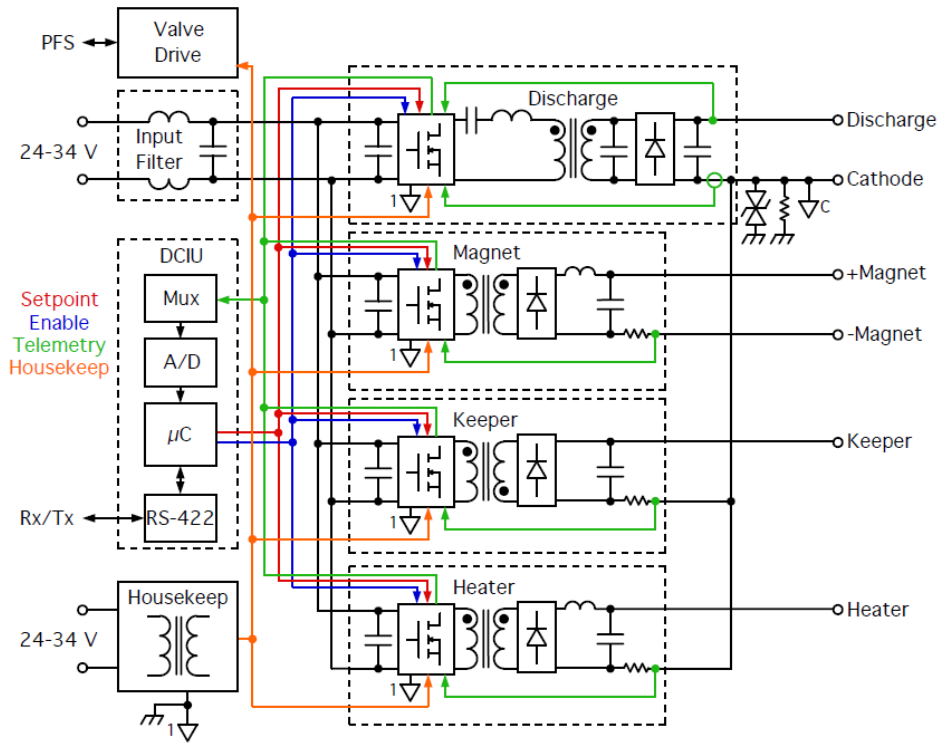
Introduction

- The Small Spacecraft Electric Propulsion (SSEP) project seeks to mature high propellant throughput sub-kW Hall-effect thruster based electric propulsion (EP) for NASA deep space and interplanetary science missions
  - Small spacecraft allow for lower cost, more frequent science missions
  - EP is a key enabling technology for many of these missions
  - Most sub-kW systems developed primarily for low-Earth orbit (LEO) market
  - Gaps exist between the capability of these EP systems and the EP needs of a deep space or interplanetary science mission
- In addition to previously reported work on development of a high propellant throughput sub-kW Hall-effect thruster, GRC is additionally developing an accompanying power processing unit (PPU)
  - Capability to operate over a wide output range
  - Developed with longer mission lifetimes in mind to support high propellant throughput thrusters
  - Seek to mature the technology with commercial partners where mission capability needs justify the increased cost (e.g. geosynchronous Earth orbit (GEO) or medium Earth orbit (MEO) applications
  - Currently each of the PPU power supplies is at a breadboard level of maturity

PPU System Architecture Overview

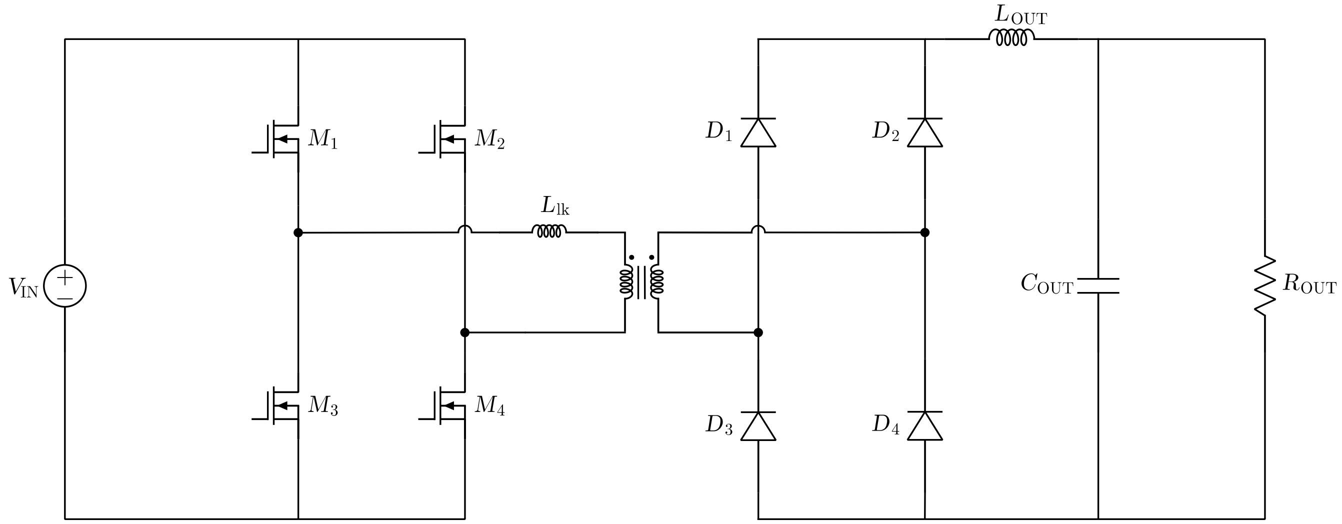
- Input voltage range designed to support standard small spacecraft 28 V bus
  - Discharge power supply maintains 1 kW output over input and output voltage range
  - Design supports xenon or krypton propellants with no power supply modifications
- Auxiliary power supplies are fully independent power supplies
  - Retains flexibility for anomaly resolution
  - PPU design targeted for thrusters with heated cathodes
  - Cathode heater and electromagnet power supply share a common two-switch forward topology design
  - Cathode keeper is a flyback design with DC ignition
- Discharge power supply capability for wide range operation prompted topology trade study



Parameter	Cathode Keeper	Electromagnets	Cathode Heater	Discharge
Input Voltage [V]	24 – 34	24 – 34	24 – 34	24 – 34
Output Current [A]	0.5 – 1	1 – 5	1 – 8	1 – 5
Output Voltage [V]	5 – 40*	1 – 12	1 – 12	200 – 500
Maximum Output Power [W]	25	60	80	1000
Line/Load Regulation Performance [%]	≤ 2	≤ 2	≤ 2	≤ 2
Phase Margin [degrees]	≥ 45	≥ 45	≥ 45	≥ 45
Gain Margin [dB]	≥ 10	≥ 10	≥ 10	≥ 10

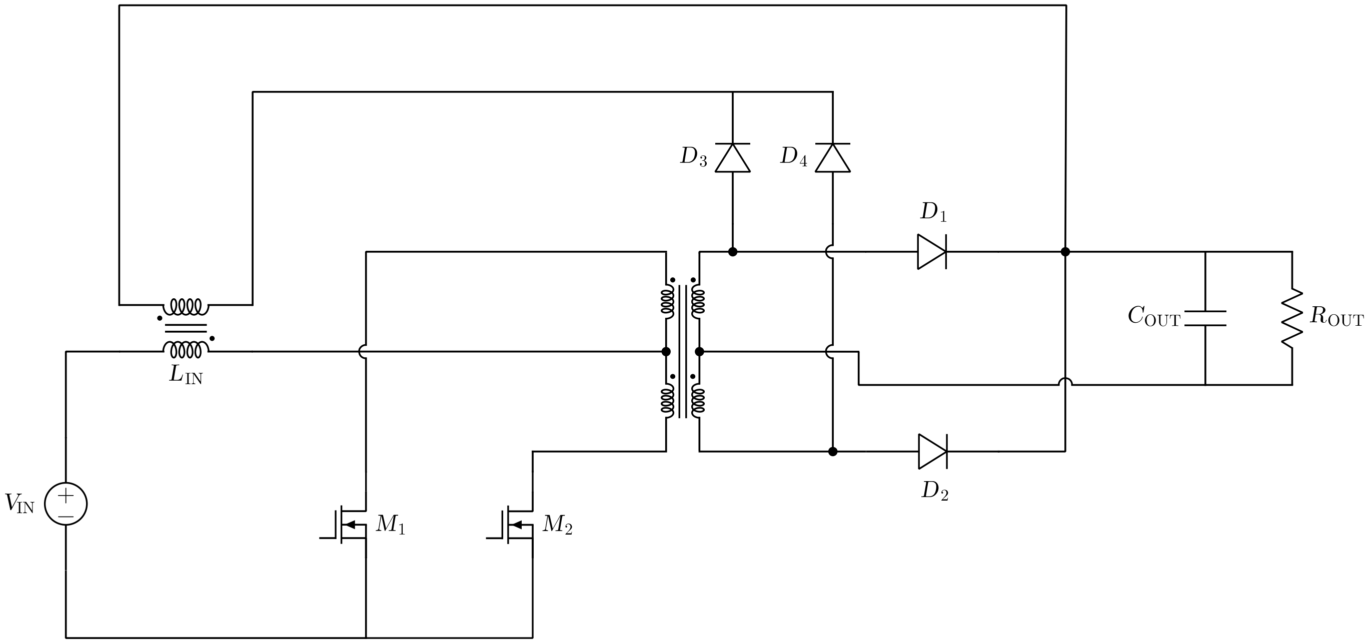
Discharge Power Supply Trade Study

- Buck-derived full-bridge topology (pulse-width modulation (PWM) or phase-shift control)
- Pros:
  - Straightforward implementation with several rad hard integrated circuit controllers available
  - Low voltage stress on input side switches from bridge configuration
  - Zero-voltage switching (ZVS) for phase-shift control
- Cons:
  - High-voltage transients on output rectifiers
  - Large turns ratio transformer required
  - Primary side RMS currents are large when operating at full power at low output voltages



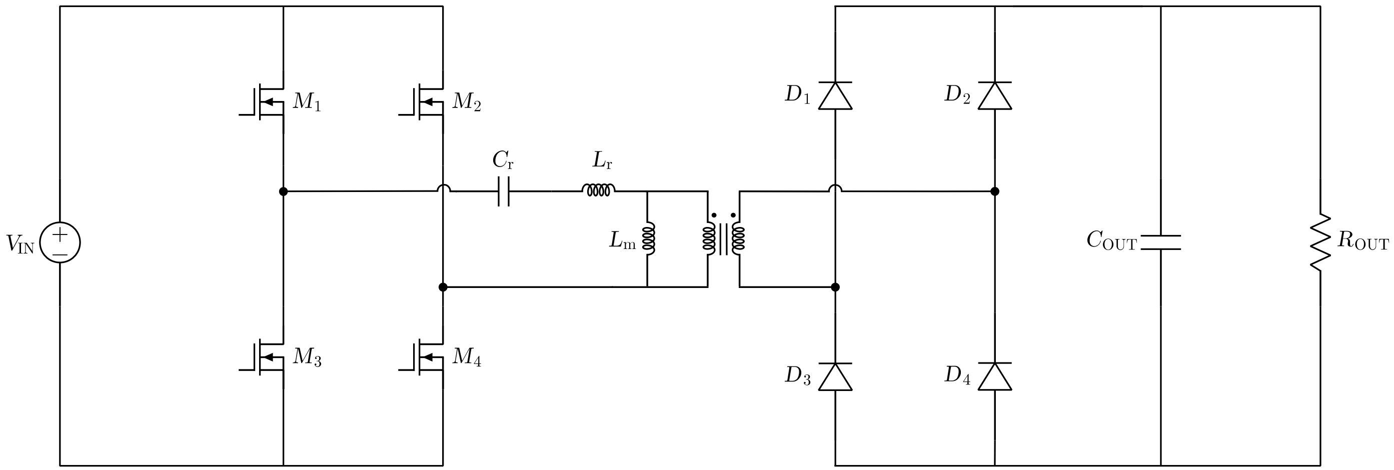
Discharge Power Supply Trade Study

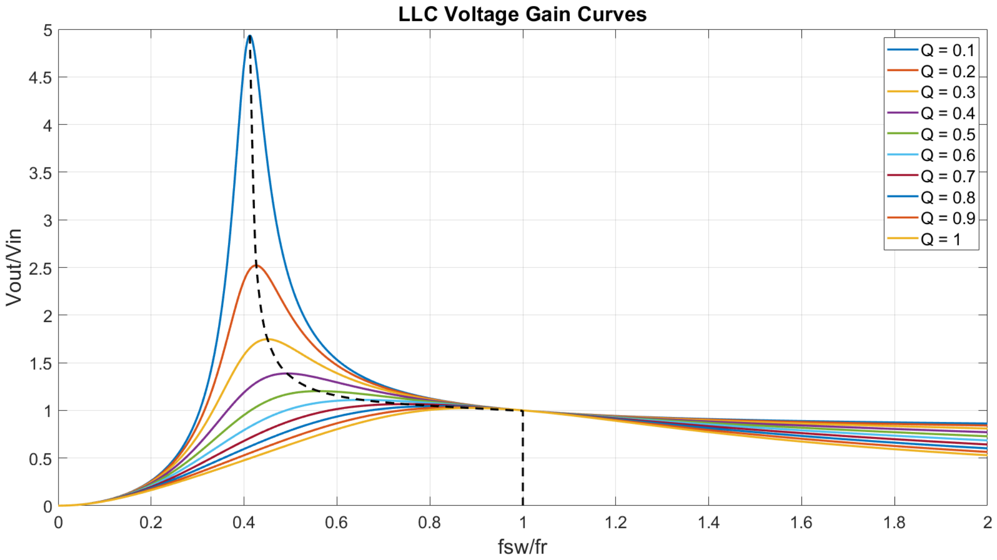
- Flyback-current-fed push-pull (Weinberg) topology
- Pros:
  - Robust against input switch cross conduction
  - Capable of operating as an isolated boost topology
  - Only low-side drive is required for the input switches
- Cons:
  - High-voltage transients on input switches
  - ZVS is difficult to achieve
  - Preferred boost mode operation not directly supported by any rad hard integrated circuit controllers



Discharge Power Supply Trade Study

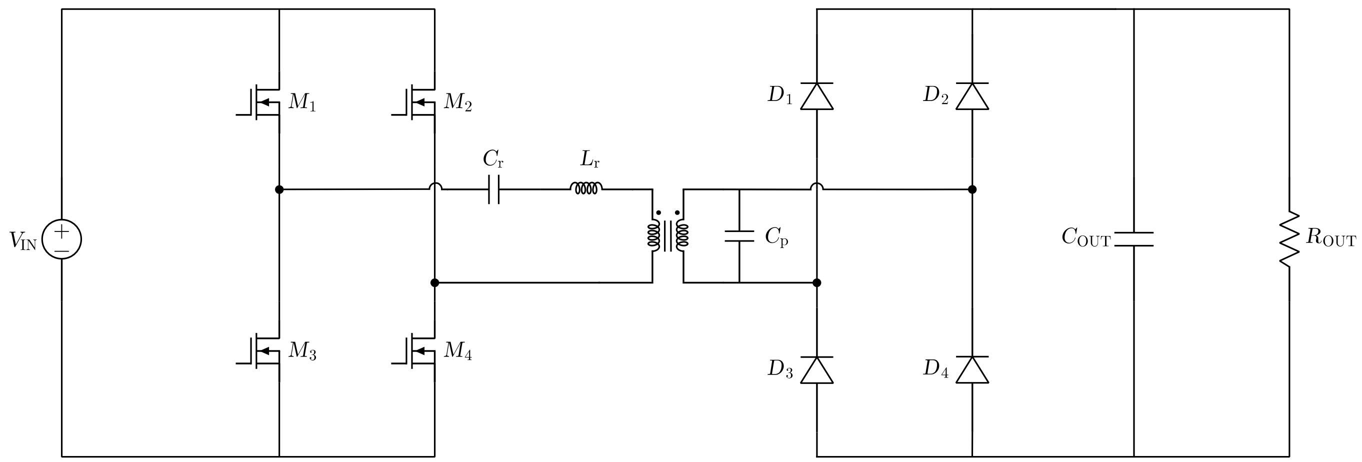
- LLC resonant topology
- Pros:
  - ZVS switching of input switches and zero-current switching (ZCS) of output rectifiers
  - Minimal voltage transients on both input switches and output rectifiers
  - Voltage gain can be greater than unity
- Cons:
  - Not supported by any rad hard integrated circuit controllers
  - Difficult to control inrush currents at startup
  - Wide switching frequency variation is required for regulation in wide output range applications

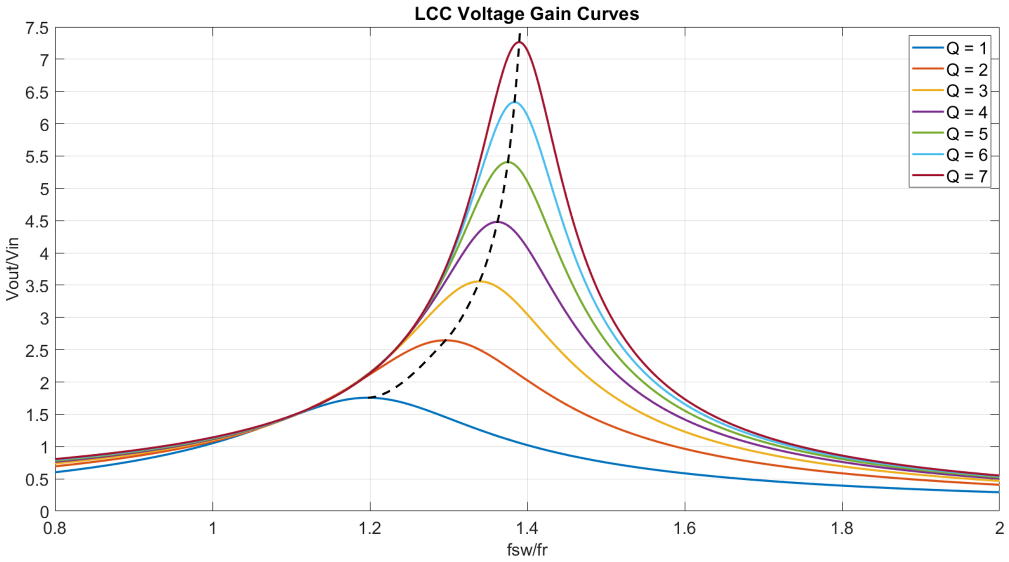




Discharge Power Supply Trade Study

- LCC resonant topology
- Pros:
  - ZVS switching of input switches and zero-current switching (ZCS) of output rectifiers
  - Minimal voltage transients on both input switches and output rectifiers
  - Voltage gain can be greater than unity
- Cons:
  - Not supported by any rad hard integrated circuit controllers
  - Light load efficiency is lower than other topologies

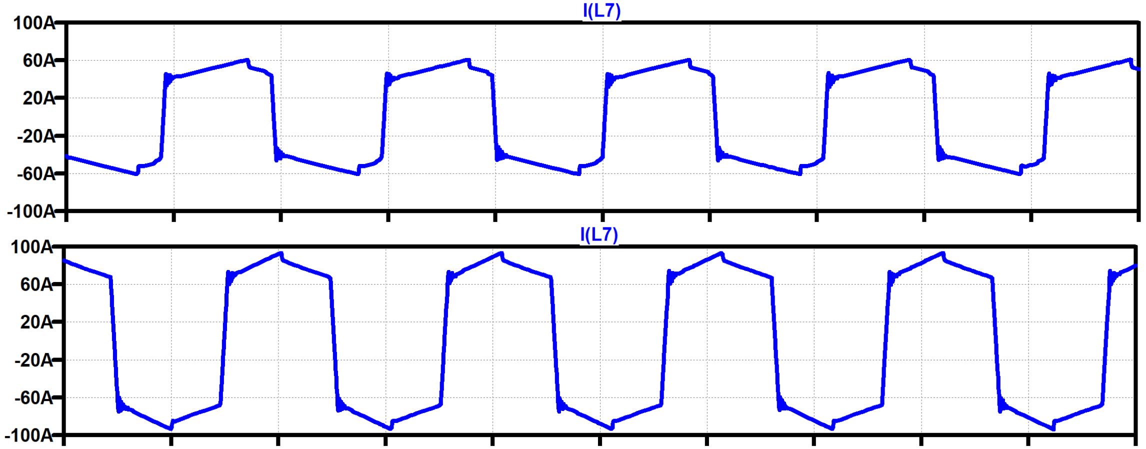




Discharge Power Supply Trade Study

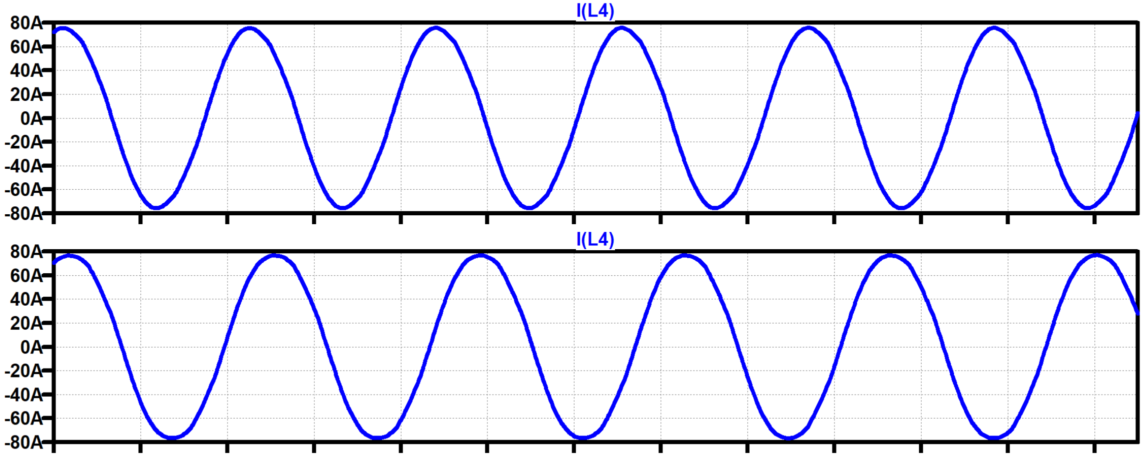
- Heritage topology approaches struggle maintaining efficient operation over wide output voltage ranges
  - PWM and phase-shifted full bridge topologies struggle with high current output conditions under full load
  - Weinberg converters struggle at the high output voltage conditions due to the reflected output voltage
- Resonant converters exhibit behavior that is synergistic with how Hall thrusters are operated
  - While the LLC converter has favorable characteristics, the switching frequency range required for regulation is too large
- The LCC topology was selected as the discharge supply topology for this PPU from this study

Phase-shifted full-bridge design



(Top) RMS Current: 49.8 A, (Bottom) RMS Current: 76.7 A

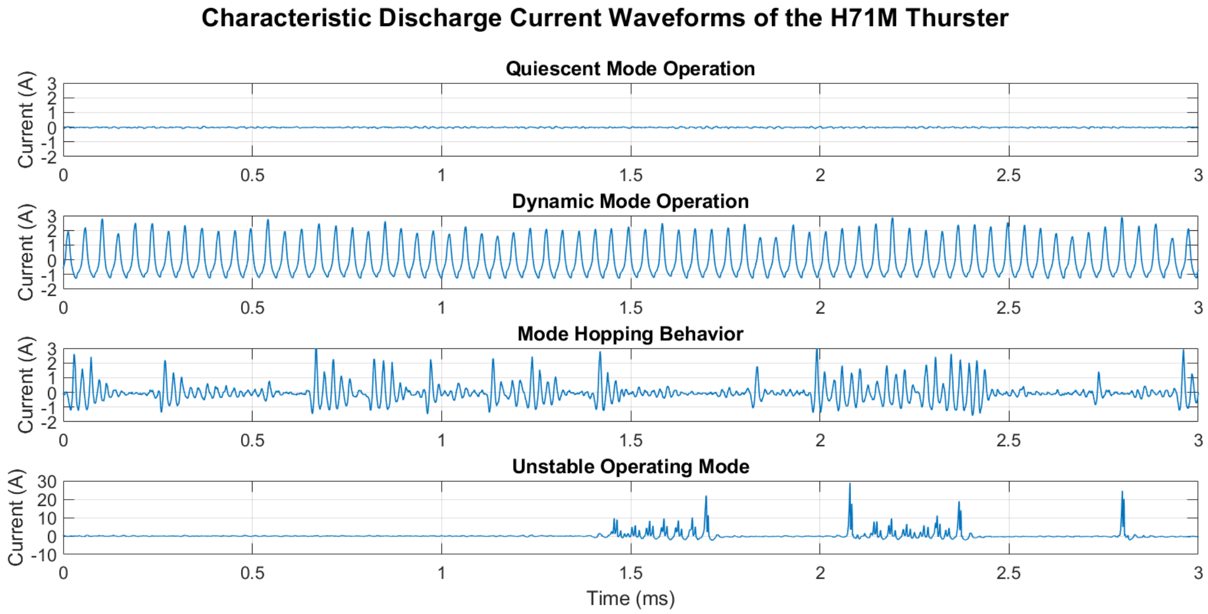
Full-bridge LCC design



(Top) RMS Current: 54.1 A, (Bottom) RMS Current: 56.6 A

Telemetry Considerations for PPUs

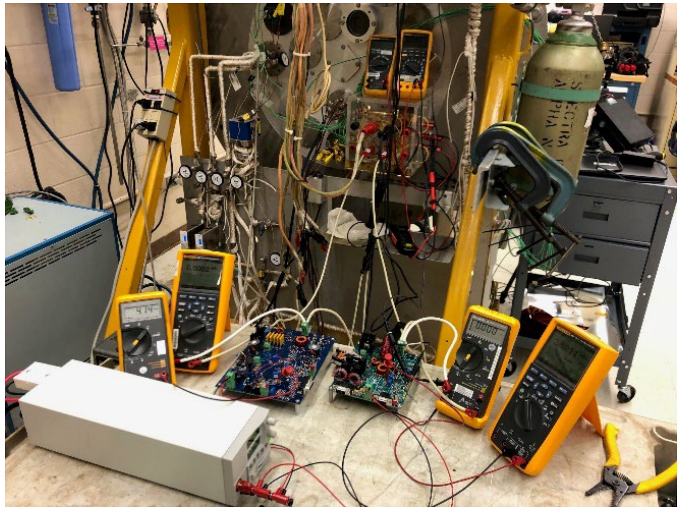
- Adequate telemetry is needed in the PPU to assess Hall thruster operational stability
  - PPU telemetry is often limited to save costs
  - Only one type of telemetry may exist for the discharge oscillation current (e.g., rectified average or RMS)
- One type of telemetry for the discharge oscillation current is often insufficient to assure stability
  - Unstable modes exist that an RMS or averaging telemetry circuit may not detect
  - This PPU design incorporates rectified average, true peak-to-peak, and digital over threshold telemetry channels

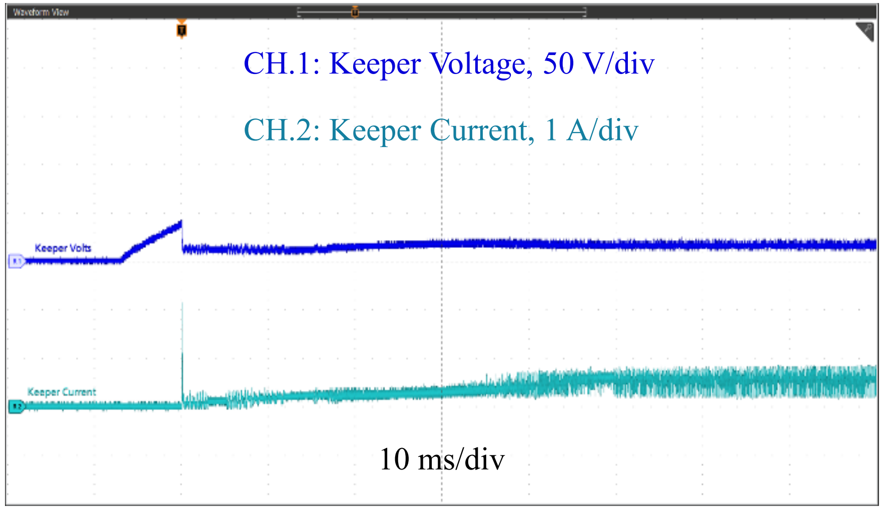


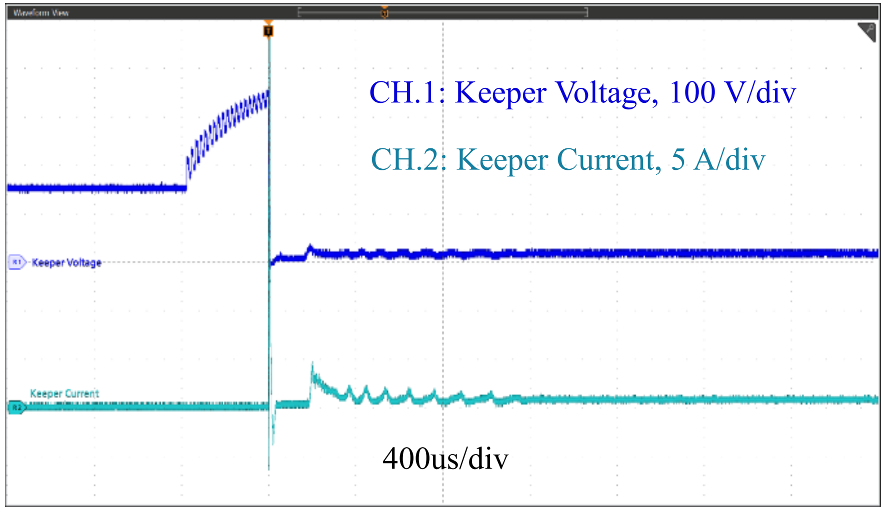
Mode	RMS Value [A]	Peak-to-Peak Value [A]
Quiescent	0.04	0.21
Dynamic	1.1	4.2
Mode-Hopping	0.60	4.9
Unstable	2.0	31.3

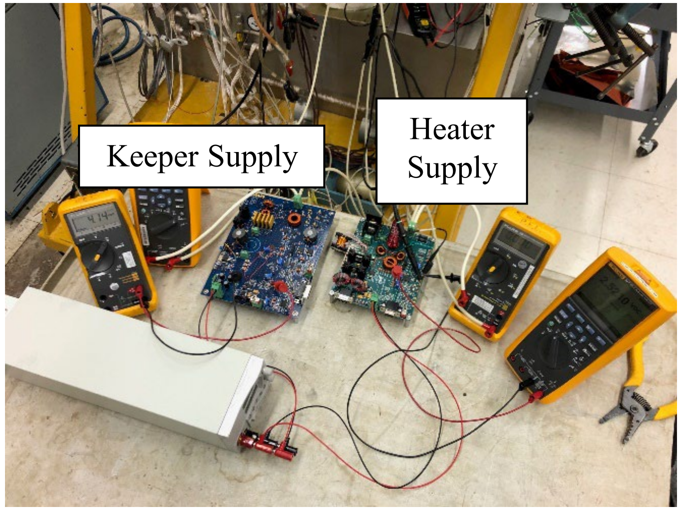
Auxiliary Power Supply Cathode Testing

- An H71M cathode assembly was used for validation testing of the cathode heater and cathode keeper power supply design in VF-56 at GRC
  - Testing was to verify capability of design to ignite and sustain a cathode plasma
  - Cathode heating times were reduced from nominal setting to make cathode ignition more difficult
  - Keeper circuit uses a DC ramp for ignition instead of a pulse train
  - Capable of up to 300 V open-circuit with supplementary voltage multiplier stage
- Heater and keeper power supplies operated with a cathode as expected





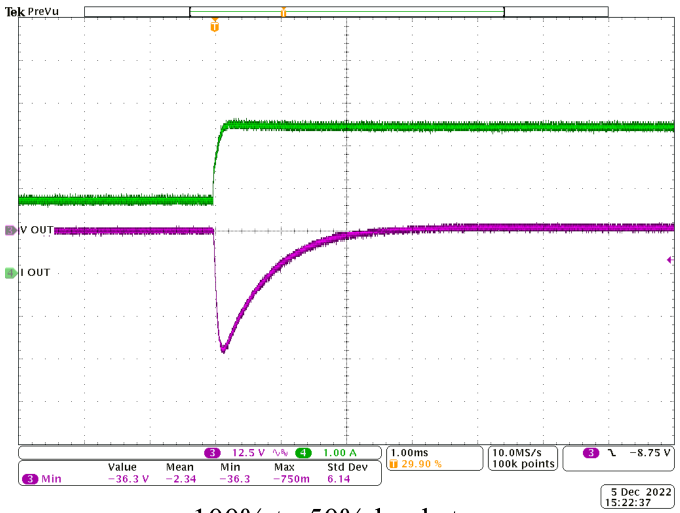




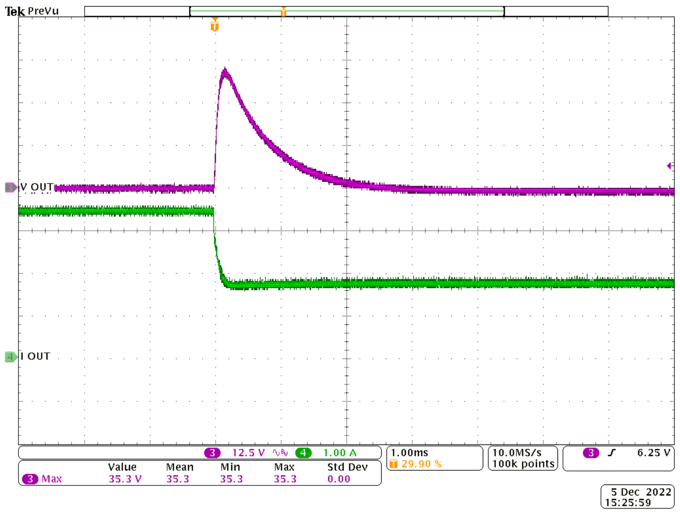
LCC Discharge Power Supply Bench Testing

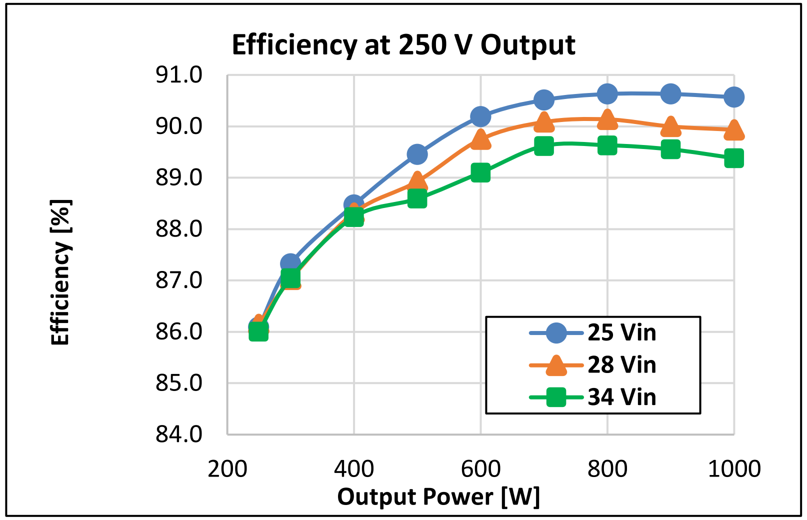
- The LCC discharge supply was evaluated for steady-state efficiency, transient load step, and soft-start performance
  - Efficiency was measured from 200 – 500 V up to 1 kW, at three different input bus conditions
  - Load step performance was evaluated using a 50% to 100% load step with a rise and fall time of 0.6 A/µs
  - Overshoot and undershoot was measured to be less than 40 V with a 2% settling time of less than 3 ms

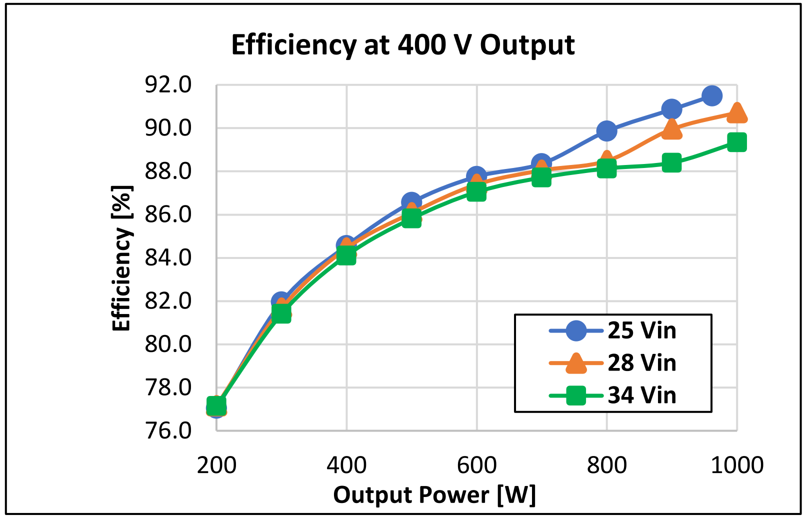
50% to 100% load step



100% to 50% load step

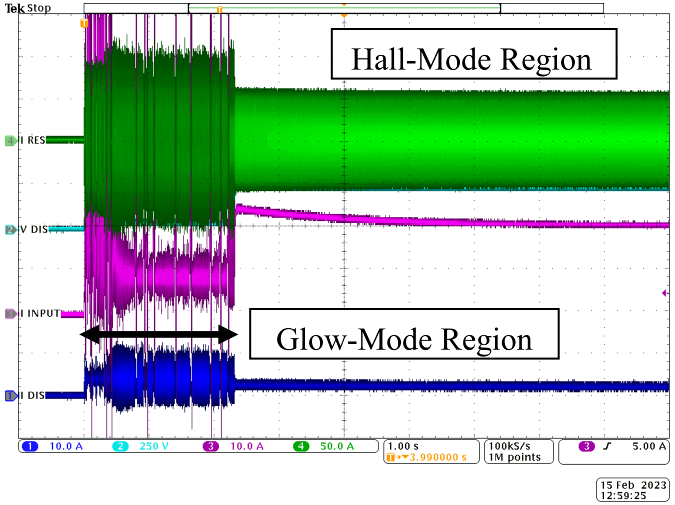




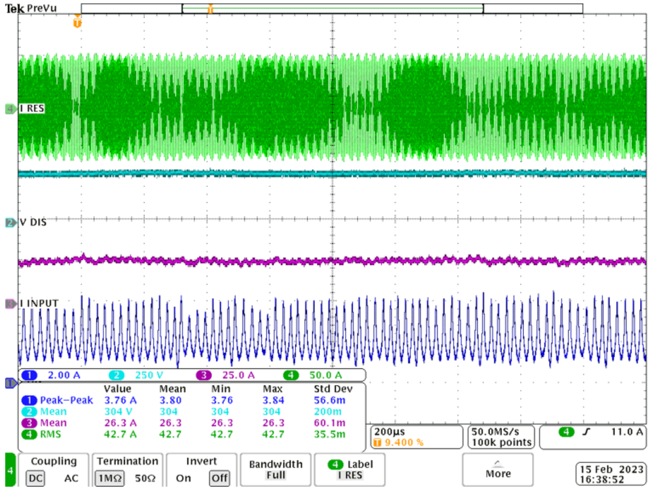


VF-8 Integrated Testing

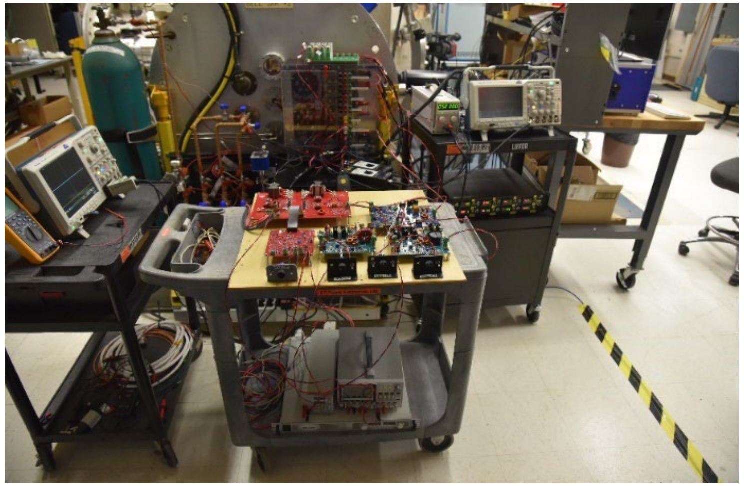
- Integrated testing was performed in VF-8 at NASA GRC using each of the breadboard power supplies with the H71M Hall thruster
  - Xenon propellant used; flow controlled by facility support equipment
  - Glow-mode startup sequencing was used during the testing
    - Startups were successful, though discharge supply instability observed during glow-mode
  - Adjustment of the current limit control and increasing the output filtering is expected to alleviate the issue
- Demonstrated operation between 200 – 350 V from 200 up to 900 W

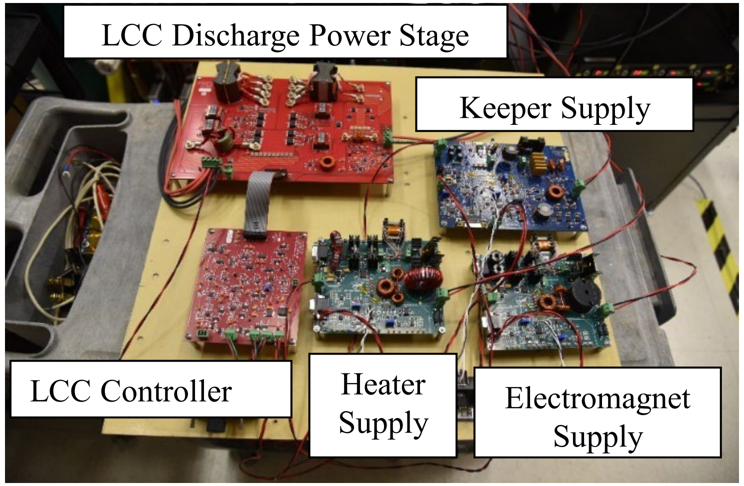


Glow-Mode Startup



Steady-state 300 V, 600 W condition





Conclusion

- Capability gaps exist between currently qualified sub-kW EP strings and propulsive needs for deep space or interplanetary science missions
- The NASA SSEP project continues to mature the technology of a wide output range PPU able to meet these requirements
- This wide output range PPU designed around an LCC discharge power supply can meet a unique range of mission requirements and supports both xenon and krypton thruster operation without design changes
- Sufficient telemetry circuits are being designed into the PPU to assure stable thruster operation
- Integrated testing of the PPU breadboards have been successfully completed
- Second iterations of these breadboards are being designed to further mature the technology
  - The next revision of the discharge supply will employ an integrated resonant inductor and planar transformer along with rad hard gallium nitride (GaN) high electrons mobility transistors (HEMTs) to provide a significant boost to efficiency
  - The next revision of the auxiliary power supplies will seek to incorporate them onto a single circuit board to inform packaging studies
- Goal to mature the design to an engineering development unit next year that will have proper fit, form, and function