The Impact of Harness Impedance on Hall Thruster Discharge Oscillations

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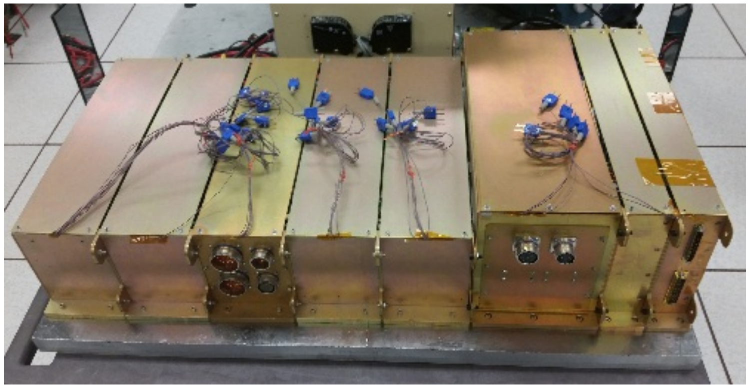
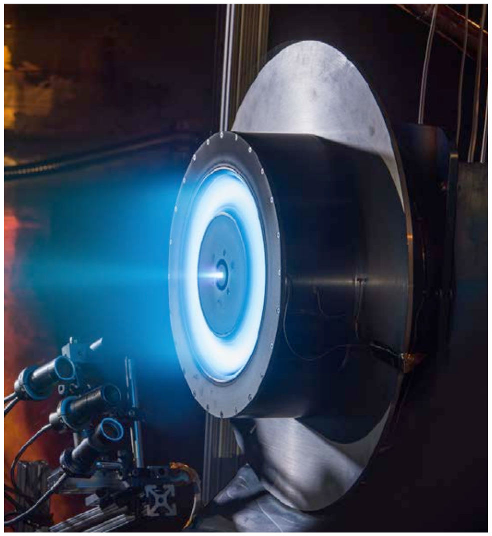
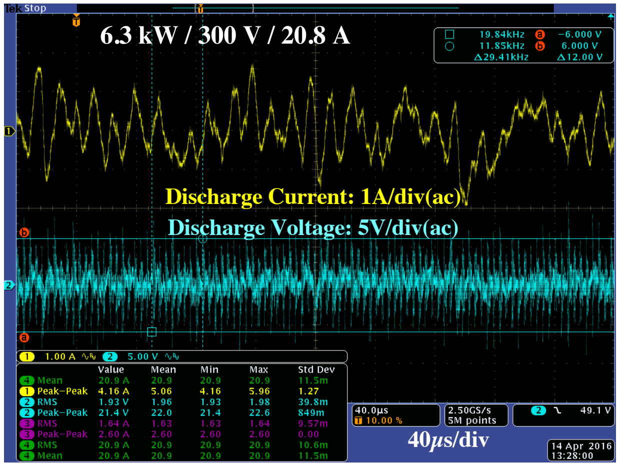
Background

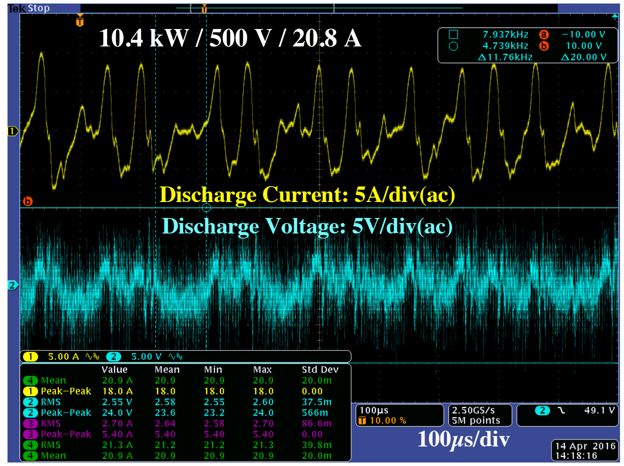
- GRC and JPL started development of a high power Hall thruster and PPU in 2012
- Building block for a 40 kW-class solar electric propulsion (SEP) system
- Hall Electric Rocket Magnetic Shielding (HERMeS) thruster was developed
  - Power = 12.5 kW
  - Thrust > 600 mN
  - Specific Impulse ~ 3,000 s
- HP-120/800V power processing unit (PPU) was developed
  - Input = 100 – 140 V
  - Discharge output = 300 – 800 V
  - Peak total efficiency > 95%
  - Vacuum compatible brassboard
- Transitioned to Aerojet Rockedyne under Advanced Electric Propulsion System (AEPS) contract
- Development, qualification and fabrication of flight hardware
  - Thruster
  - PPU with integral digital controller
  - Xenon flow controller
  - Harnesses

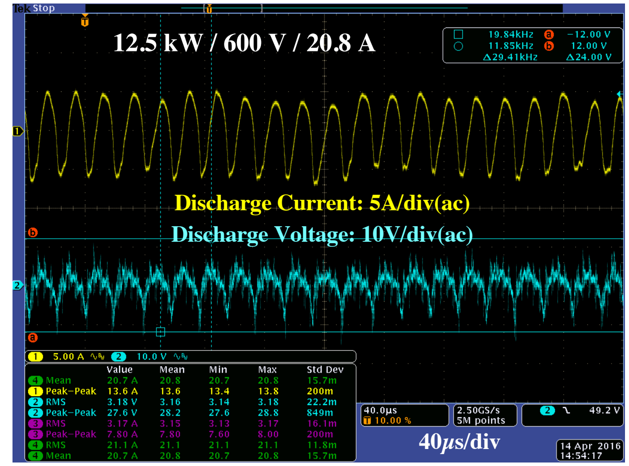




Discharge Oscillations

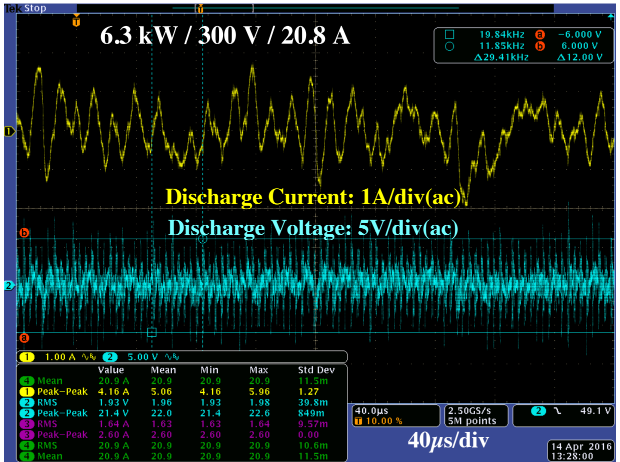


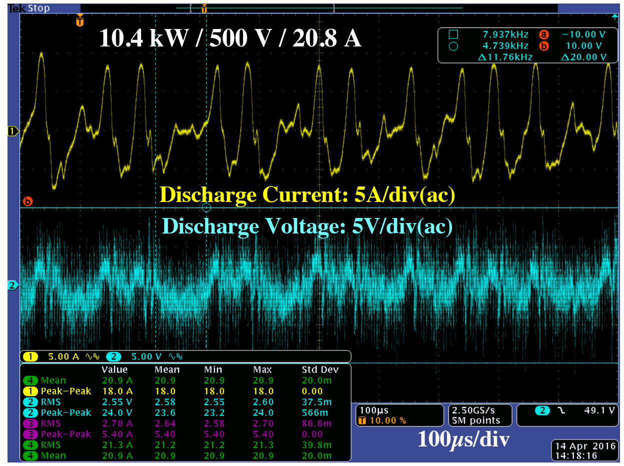


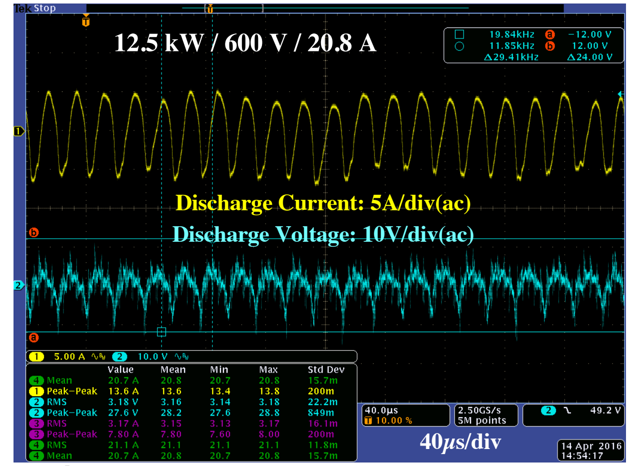


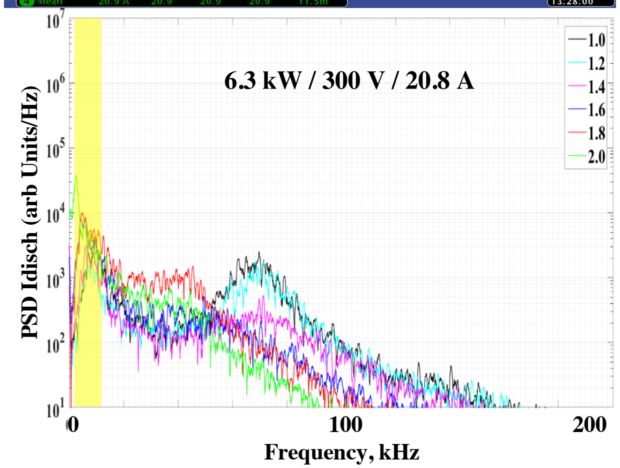
- Hall thrusters exhibit characteristic discharge current and voltage oscillations during steady-state operation
- Current oscillations are caused by propellant ionization, magnetic field gradients and plasma instabilities
- Low frequency components or “breathing mode” oscillations can significantly impact PPU design
- Oscillations of the HERMeS thruster show different “modes”

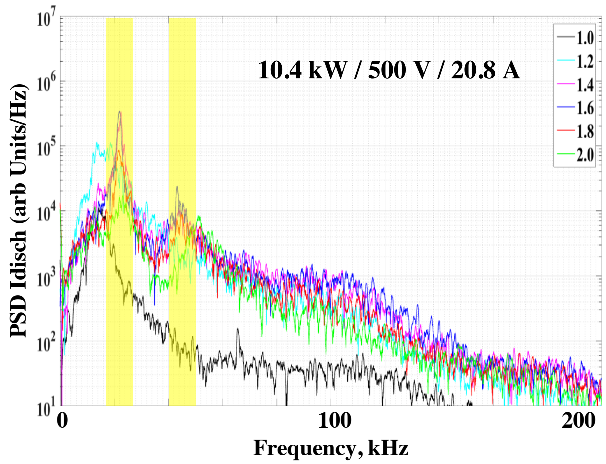
Discharge Oscillations

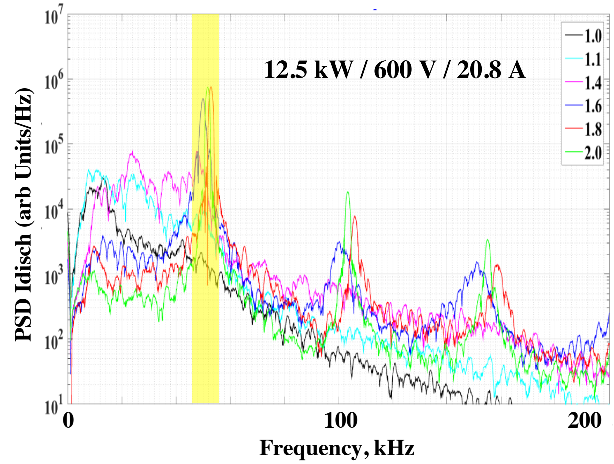






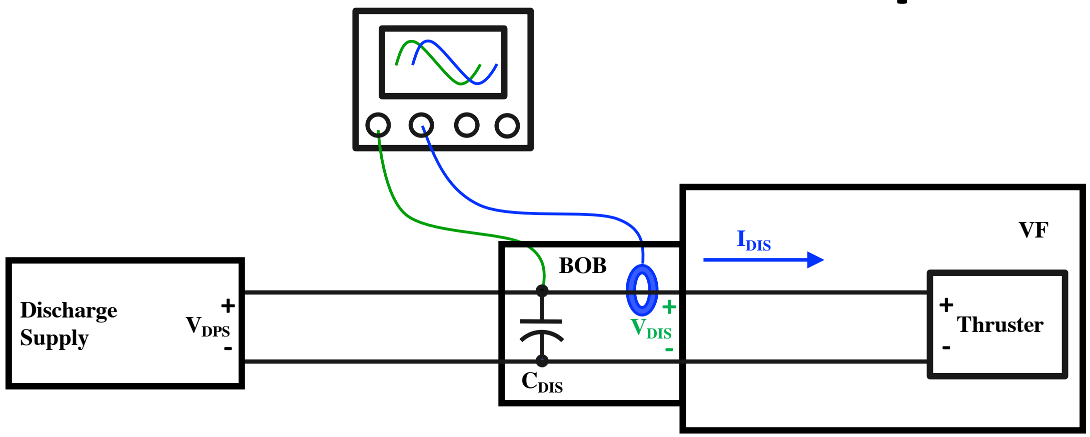


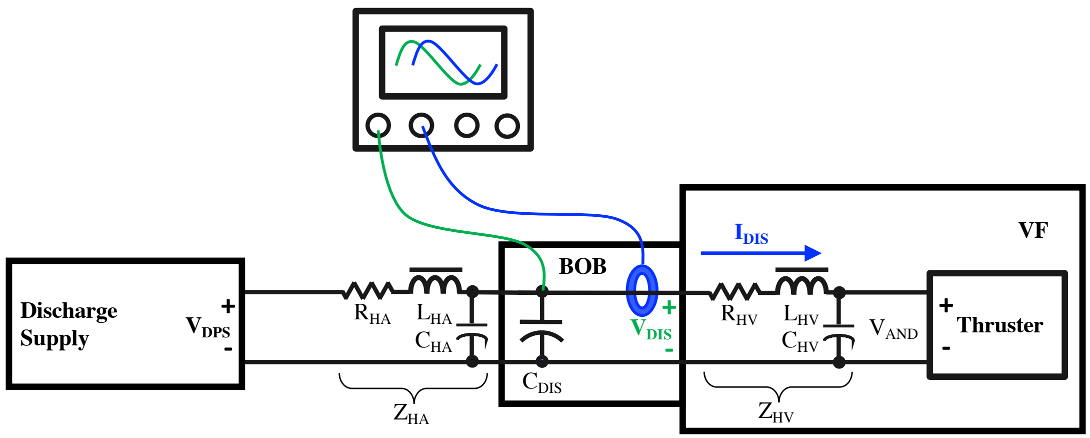




- Lowest frequency peaks occur at approximately 5 to 50 kHz
- Even when oscillations appear to be very sinusoidal, there are relatively large peaks at much higher frequencies
- AEPS needed answers to several questions including:
  - How to specify discharge voltage ripple?
  - How much discharge filter is needed?
  - What specifications are critical for harness?
  - Is discharge voltage ripple a problem?

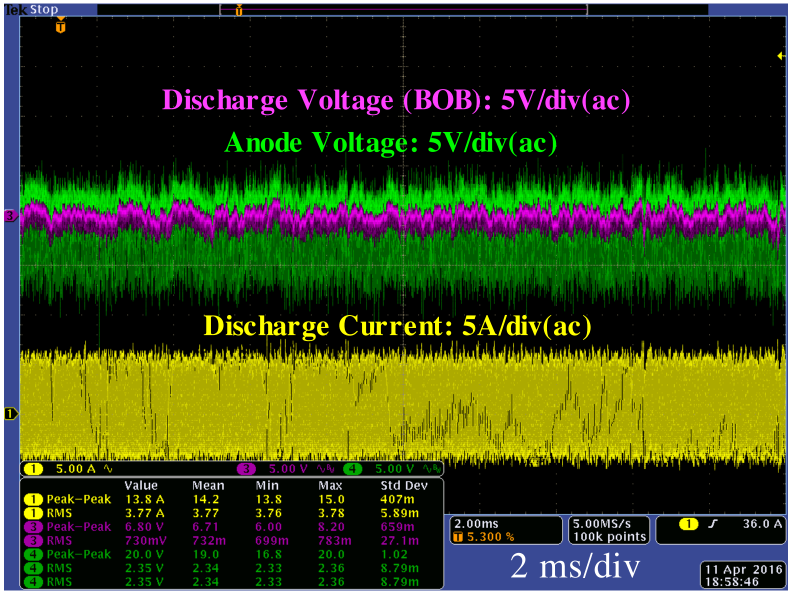
Hall Thruster Test Setup

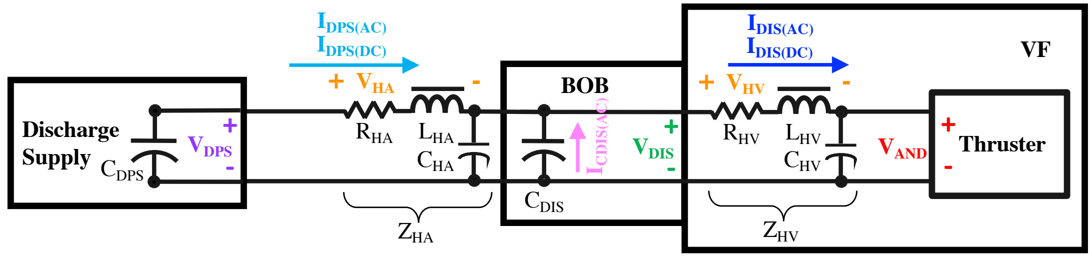




- Typical Hall thruster experimental test setup includes a discharge supply and a break-out-box (BOB)
- Electrical harnesses in ambient and vacuum have a finite impedance
- This is particularly important in large vacuum facilities like VF-5 (4.5m dia) and VF-6 (7.5m dia)
- $Z = \sqrt{R^2 + (X_L - X_C)^2}$
  - $X_L = 2\pi f L$ and $X_C = 1/(2\pi f C)$
- Rule-of-thumb inductance value for typical twisted-pair harness is approximately 380 nH/m
- Vacuum harness inductance can impact discharge oscillations

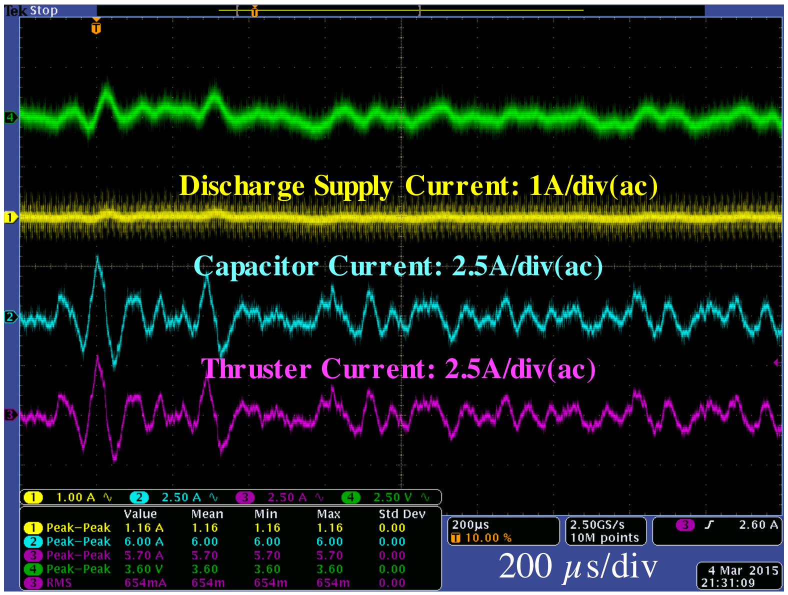
Discharge Circuit Analysis

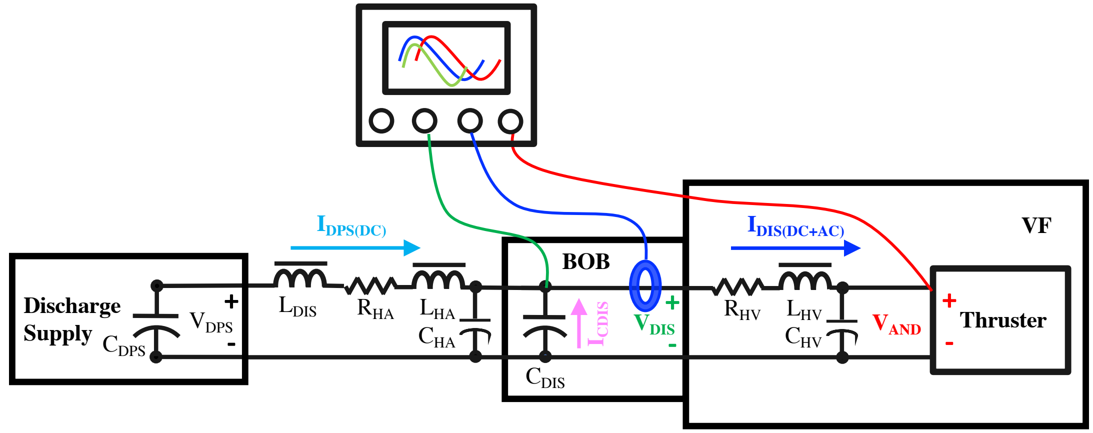




- Discharge current has DC and AC components ($I_{DIS(DC)}$ & $I_{DIS(AC)}$)
  - DC component is provided by the discharge supply ($I_{DPS(DC)}$)
  - AC component is provided by discharge filter capacitor ($I_{CDIS(AC)}$) and discharge supply ($I_{DPS(AC)}$)
- AC currents generate a voltage drop on harness impedances (V_{HA} & V_{HV})
- Discharge filter capacitor reduces voltage ripple at the BOB caused by discharge supply oscillations ($I_{DPS(AC)}$) and ambient harness impedance (**Z_{HA}**)
- Discharge current oscillations ($I_{DIS(AC)}$) and vacuum harness impedance (**Z_{HV}**) generate voltage ripple at thruster anode (V_{AND})
- Voltage ripple at the thruster anode (V_{AND}) will be higher than voltage ripple at discharge filter capacitor (V_{DIS})

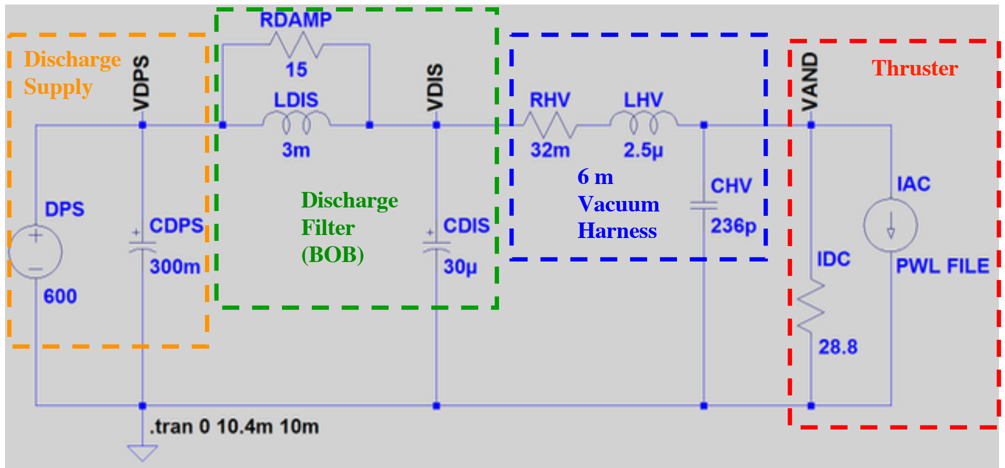
Discharge Filter Optimization Test





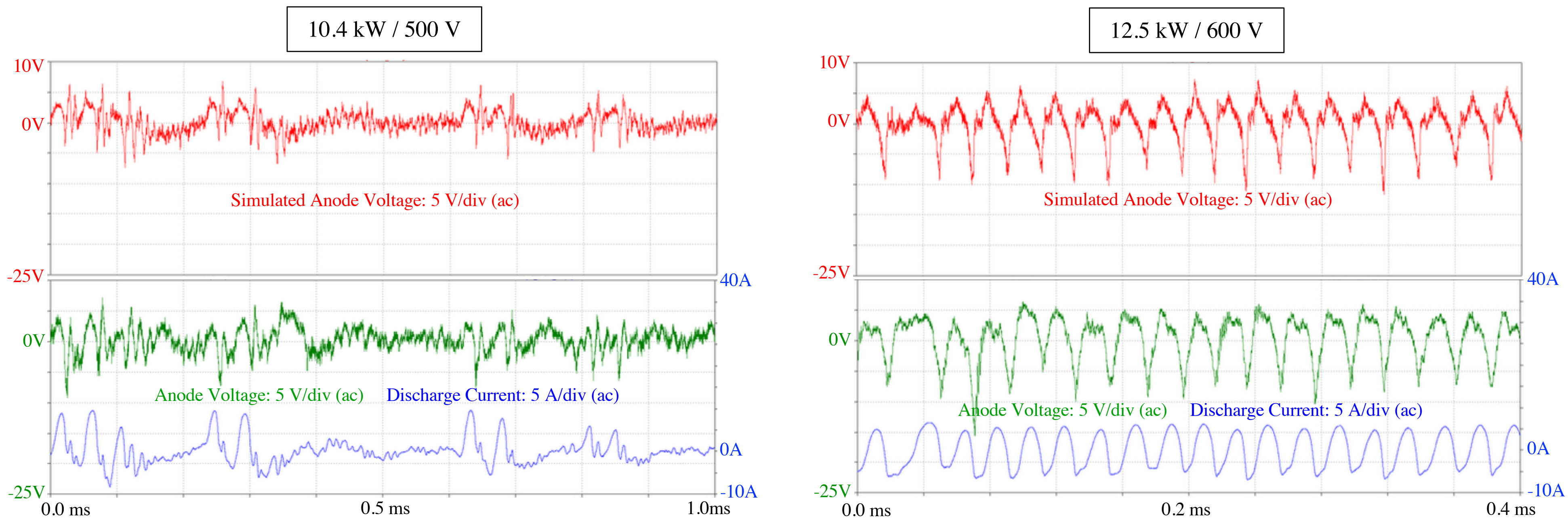
- Test was conducted to determine minimum amount of capacitance required to control discharge voltage ripple
- An inductor **(L_{DIS})** was added to:
  - Minimize AC component from discharge supply **($I_{DPS(AC)}$)**
  - Force discharge capacitor **(C_{DIS})** supply AC component
- Discharge voltage was sensed at thruster anode **(V_{AND})** and compared to discharge voltage at BOB **(V_{DIS})**
- Discharge filter capacitor **(C_{DIS})** was gradually reduced from 200 µF
- A 30 µF capacitor is minimum required to control voltage ripple
- Capacitor changes did not affect discharge current oscillations

Discharge Harness Model



- A simple lumped element model was used for harness that includes a resistor, inductor and capacitor
  - This model is valid because the harness is much shorter that wavelength of oscillations
  - The values used match measurements of 6 m harness in VF-5
- Discharge supply was modeled as DC voltage source and large output capacitors as in laboratory power supplies
- Discharge filter components were included
- Thruster was modeled as:
  - DC component represented by resistor
  - AC component represented by current source programmed with data captured with digital oscilloscope

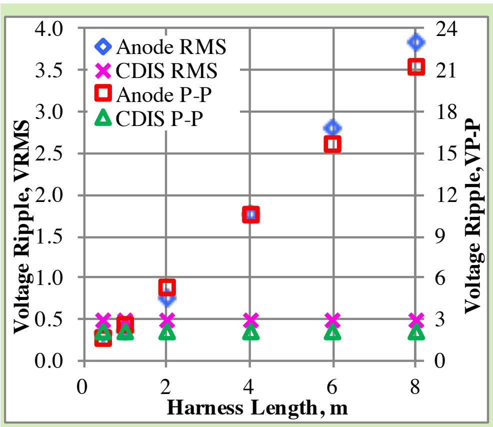
Simulation Results

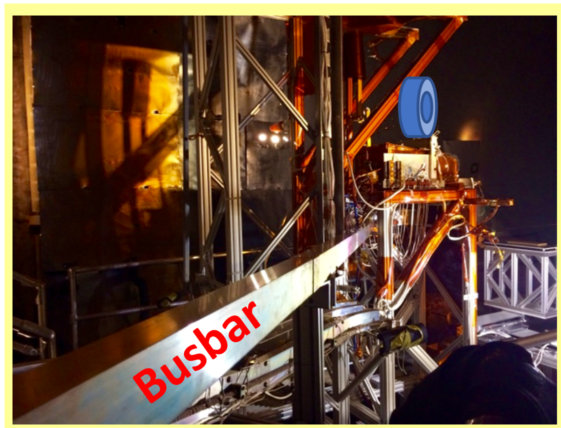


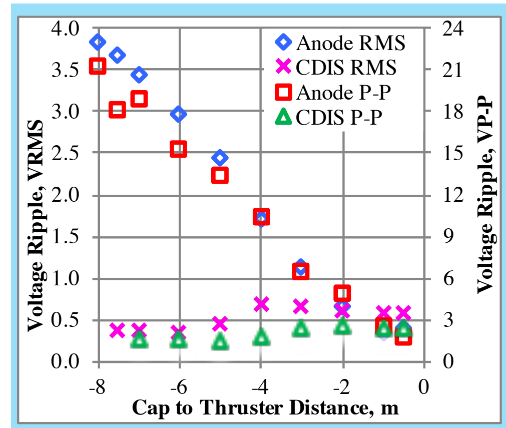
- Simulated and measured discharge anode voltages are very similar
- P-P and RMS ripple voltages from simulation are within 14% of measured values
- Discharge anode voltage ripple is cause exclusively by voltage drop on harness by discharge current oscillations
- Plasma do not have a significant contribution to voltage ripple and behave like capacitive load
- To minimize voltage oscillations, thruster anode harness inductance must be minimized

Low Inductance Harness Design

Option	Pros	Cons
1. Minimize length	Low complexity	Limited by test setup
2. Twisted / braided wires	Low complexity	Limited effectiveness Impacts harness design (flexibility and cost)
3. Capacitor distance to thruster	Effective Insensitive to length Flight heritage	Mechanical, thermal and vacuum impacts on capacitor Can impact discharge output filter design
4. Coaxial cable	Low inductance	Difficult to implement for high power Limited flexibility
5. Parallel-plate busbar	Low inductance Easy to fabricate Scalable	Rigid Difficult to implement in spacecraft

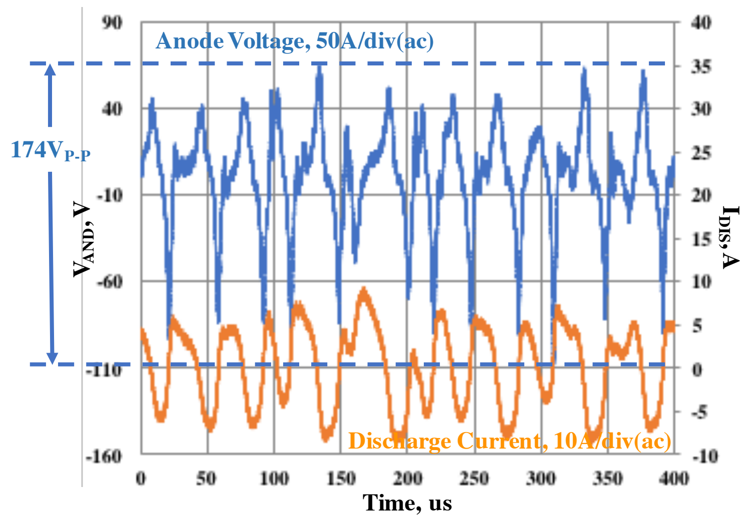


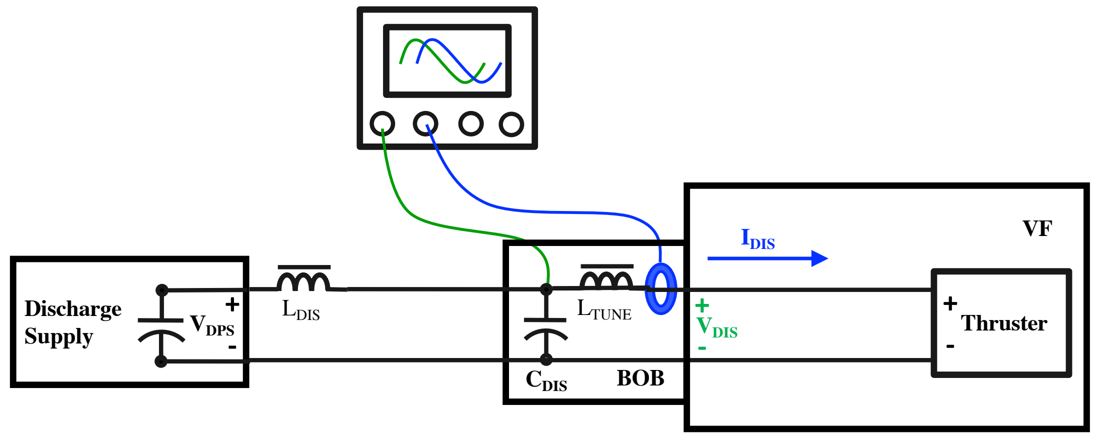




- The longest harness required for AEPS (8 m) will generate voltage ripple of 3.6% P-P and 0.7% RMS at full power
- Parallel-plate busbar was implemented in VF-5 and VF-6 at NASA GRC
  - Inductance was reduced to < 20 nH/m
  - The 4.5 m busbar in VF-6 has only 90 nH inductance or 4.4% of a typical twisted-wire harness

Ripple Sensitivity Test





- A test was conducted to assess the effect of discharge voltage ripple on thruster performance
- A 30 µH "tuning" inductor was added in the BOB after the discharge filter capacitors C_{DIS} to artificially increase discharge voltage ripple at the thruster anode
- Anode voltage ripple ~174 V_{P-P} while operating at 12.5 kW/600 V
- No significant change in thruster performance (thrust, efficiency, current oscillations, etc.)
- Impact on life, plume and EMI still has to be assessed

Conclusion

- The primary cause of discharge voltage oscillations is the voltage drop generated by high frequency discharge current oscillations flowing through the finite impedance of the electrical harness
- The inductance of the discharge harness must be minimized to reduce voltage oscillations
- Increasing the discharge filter capacitor is not an effective method to reduce voltage ripple
- A simple lumped element model can be used to predict discharge voltage oscillations if high frequency discharge current components are included
- Inductance can be reduced using several techniques
- For testing in vacuum facilities, a parallel-plate busbar was effective and easy to implement
- Discharge voltage ripple does not impact thruster performance
- Other possible impacts still require investigation