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High Input Voltage, Silicon Carbide Power Processing Unit Performance Demonstration

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AIAA Propulsion & Energy Conference, 27-29 July 2015
Orlando, Florida

Outline

- Introduction
- Design Overview
- Design Specifications
- Test Setup
- Performance Results
- Forward Work
- Conclusion
- Acknowledgements

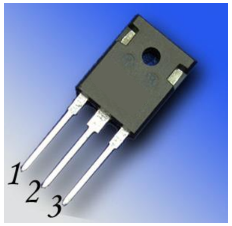
Introduction

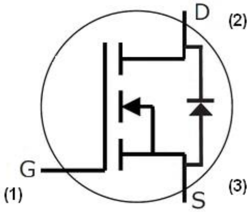
- NASA's Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program was focused on developing a high-power, high-voltage Solar Electric Propulsion (SEP) system to revolutionize future missions requiring moving cargo and humans beyond low earth orbit.

A 300-kilowatt spacecraft concept for human exploration of Mars

Introduction

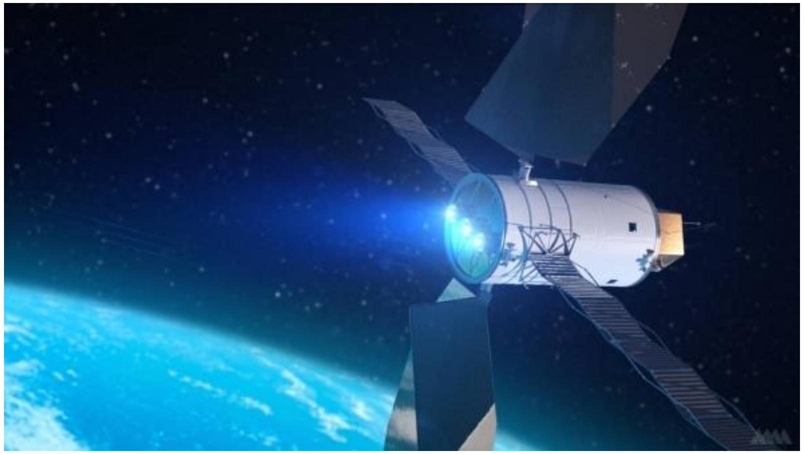
- In support of the STMD GCD, NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL) were tasked with demonstrating a high-power electric propulsion string.
  - Hall Effect Thruster Technology Demonstration Unit
  - High Input Voltage Brassboard Power Processing Unit (PPU)
- This presentation focuses on the design, integration, and demonstration of the brassboard PPU.
  - The brassboard PPU leverages previous design work of a breadboard discharge supply with Silicon Carbide (SiC) power switching devices.



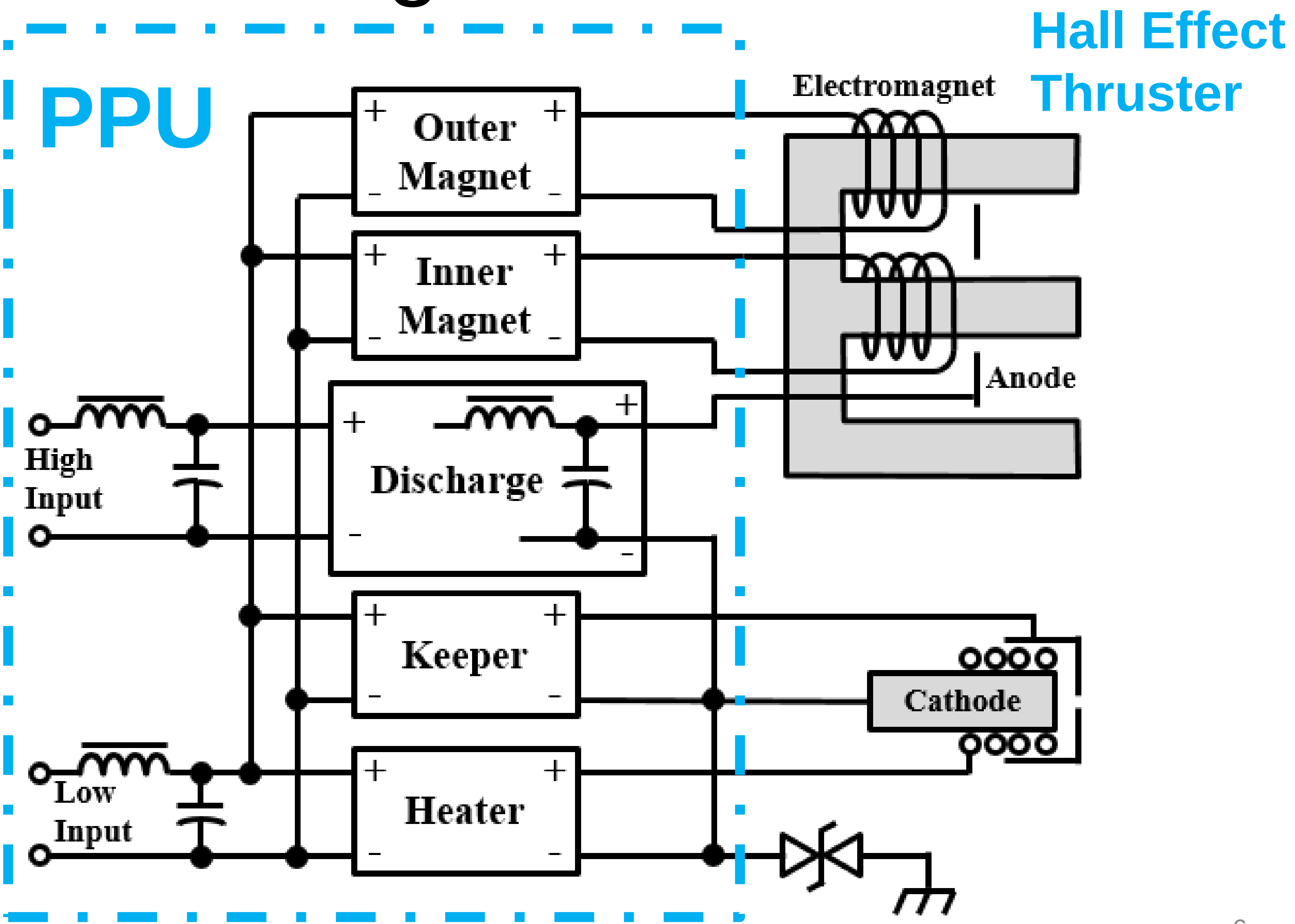


Introduction

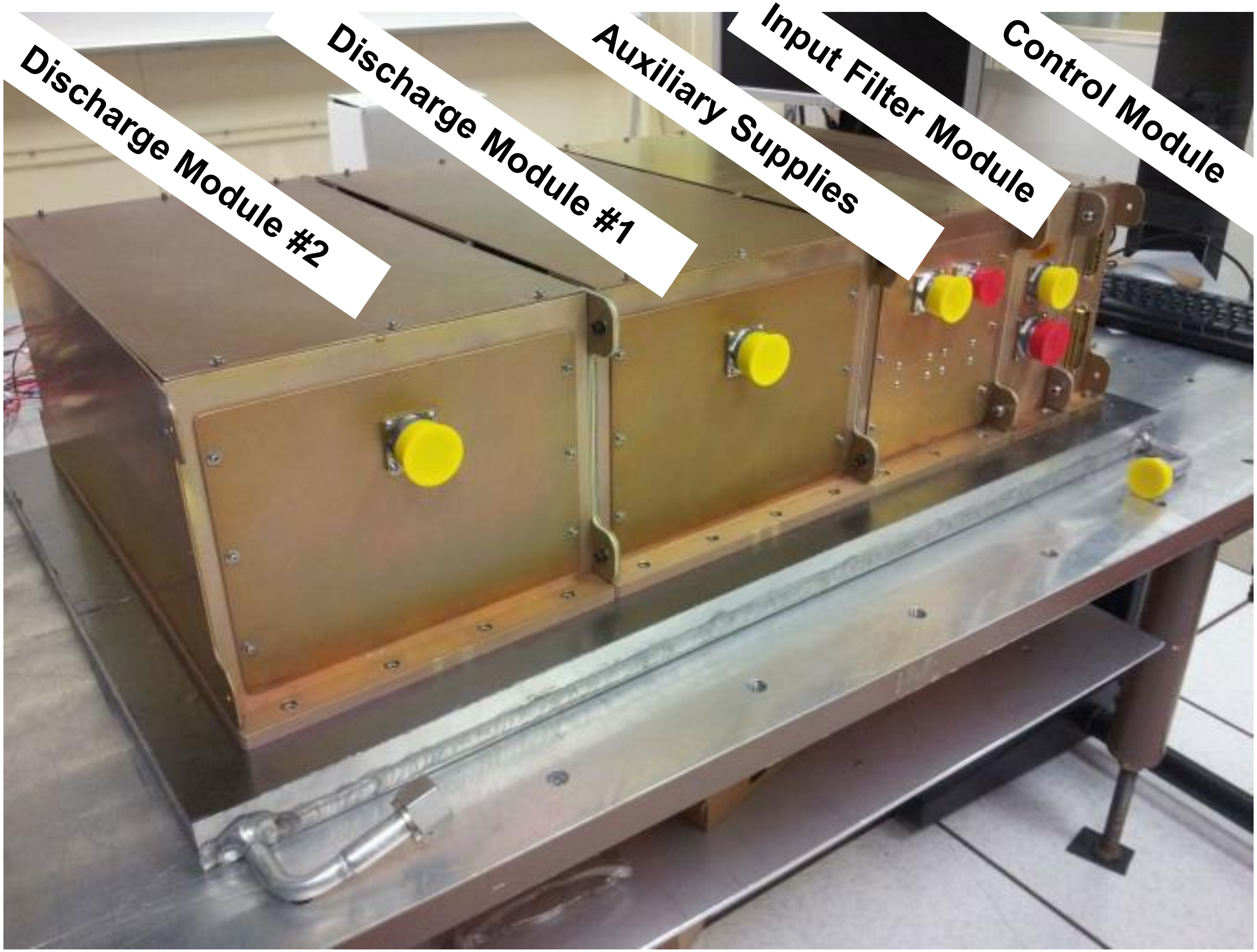
- Today, STMD is still developing and demonstrating innovative in-space propulsion technologies.
- A proposed SEP Technology Demonstration Mission would use technologies developed under the GCD program to support the design and flight of a SEP spacecraft.
  - 50-kW class SEP spacecraft
  - Electric propulsion for primary in-space propulsion



Design Overview



Design Overview



Design Specifications

	Maximum Output Power	Output Voltage Range	Output Current Range	Regulation Mode	Line/Load Regulation	Ripple
Discharge Supply	15 kW	300-400 VDC	37.5-50 ADC	Voltage	≤ 2%	≤ 5% peak-peak of regulated parameter
Inner Magnet and Outer Magnet Supplies	200 W	2-20 VDC	1-10 ADC	Current	≤ 2%	≤ 5% peak-peak of regulated parameter
Heater Supply	324 W	6-36 VDC	3-9 ADC	Current	≤ 2%	≤ 5% peak-peak of regulated parameter
Keeper Supply	90 W	10-30 VDC	1-3 ADC	Current	≤ 2%	≤ 5% peak-peak of regulated parameter

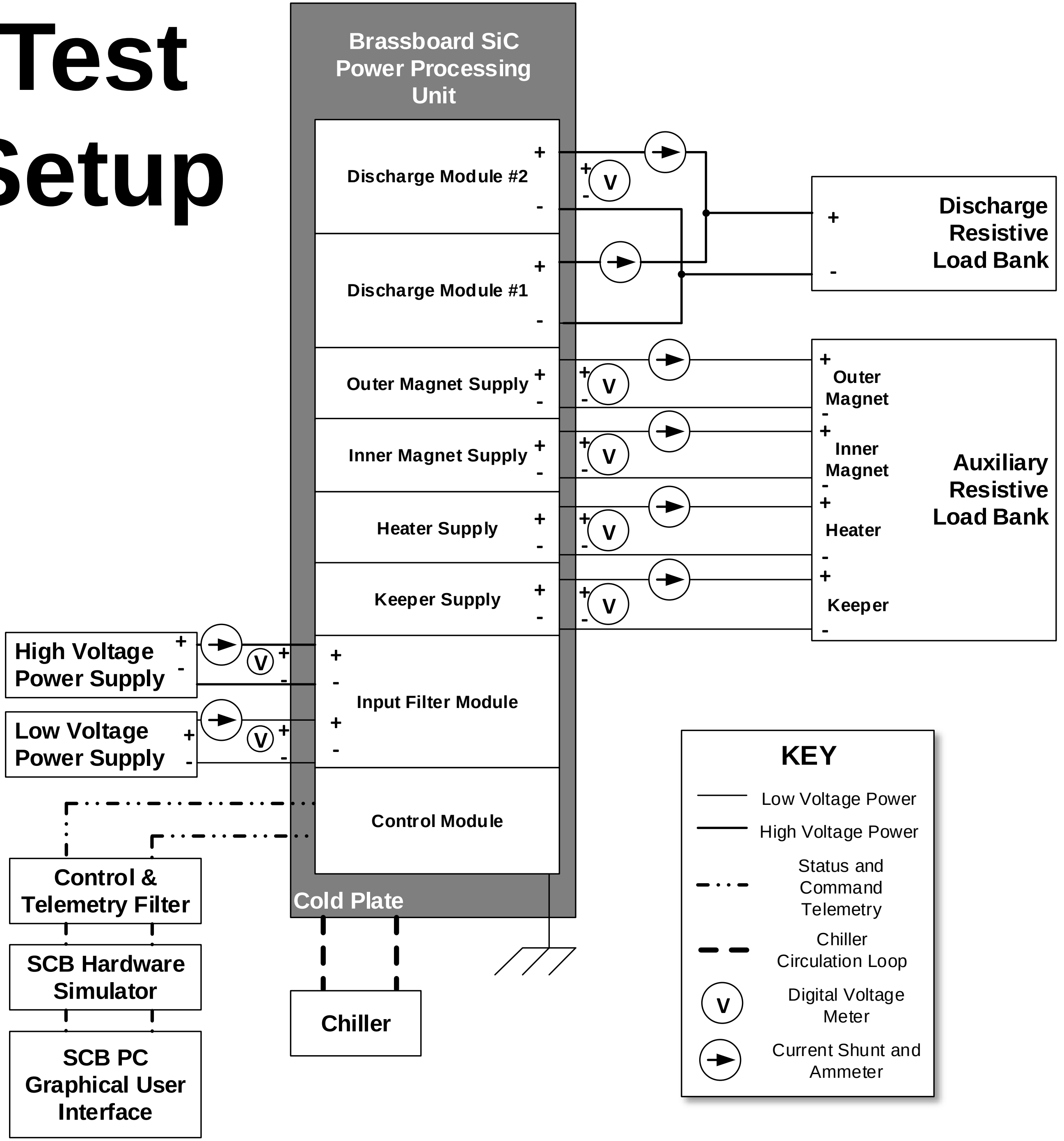
Power Supply Design

	Description	Topology	Control	Switching Frequency
Discharge Supply	Two 7.5 kW power supply modules with the outputs connected in parallel externally	Full-bridge converter with paralleled SiC MOSFETS and a single bridge rectifier with SiC Schottky diodes	PWM based on peak and average current control and an outer voltage control loop	30 kHz
Auxiliary Supplies (Inner Electromagnet, Outer Electromagnet, Heater, and Keeper)	Four separate power supplies; modular circuit board designs	Full-bridge converter with silicon MOSFETs	PWM based on peak and average current control	60 kHz

Control and Filter Design

- **Master Control Board**
  - Communication and control interface between the individual power supplies and the System Control Board (SCB)
  - Receives analog and digital commands from the SCB and analog and digital telemetry from the power modules and input filters
  - Generates PWM synchronization signals and the ignitor pulse command
- **System Control Board**
  - Provides a control interface between the PPU, the thruster propellant feed system, and the flight system
  - Currently under development at JPL
- **Input Filters**
  - Separate filters for each input power bus
  - Each filter consists of a differential low-pass stage and a common-mode inductor

Test Setup

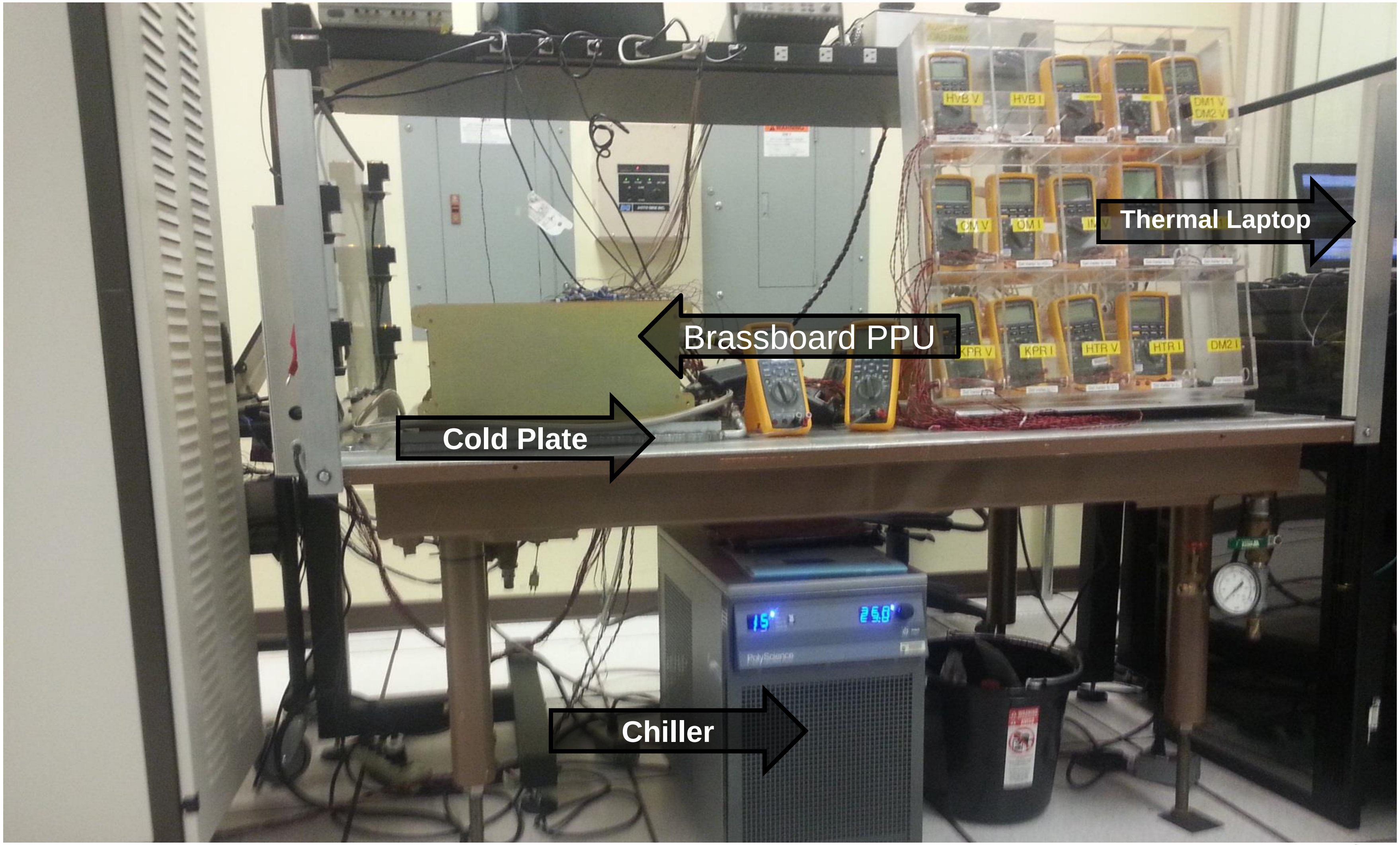


Brassboard SiC Power Processing Unit
Discharge Module #2
Discharge Module #1
Outer Magnet Supply
Inner Magnet Supply
Heater Supply
Keeper Supply
Input Filter Module
Control Module
Cold Plate
Discharge Resistive Load Bank
Outer Magnet
Inner Magnet
Heater
Keeper
Auxiliary Resistive Load Bank
High Voltage Power Supply
Low Voltage Power Supply
Control & Telemetry Filter
SCB Hardware Simulator
SCB PC Graphical User Interface
Chiller
KEY
Low Voltage Power
High Voltage Power
Status and Command Telemetry
Chiller Circulation Loop
Digital Voltage Meter
Current Shunt and Ammeter

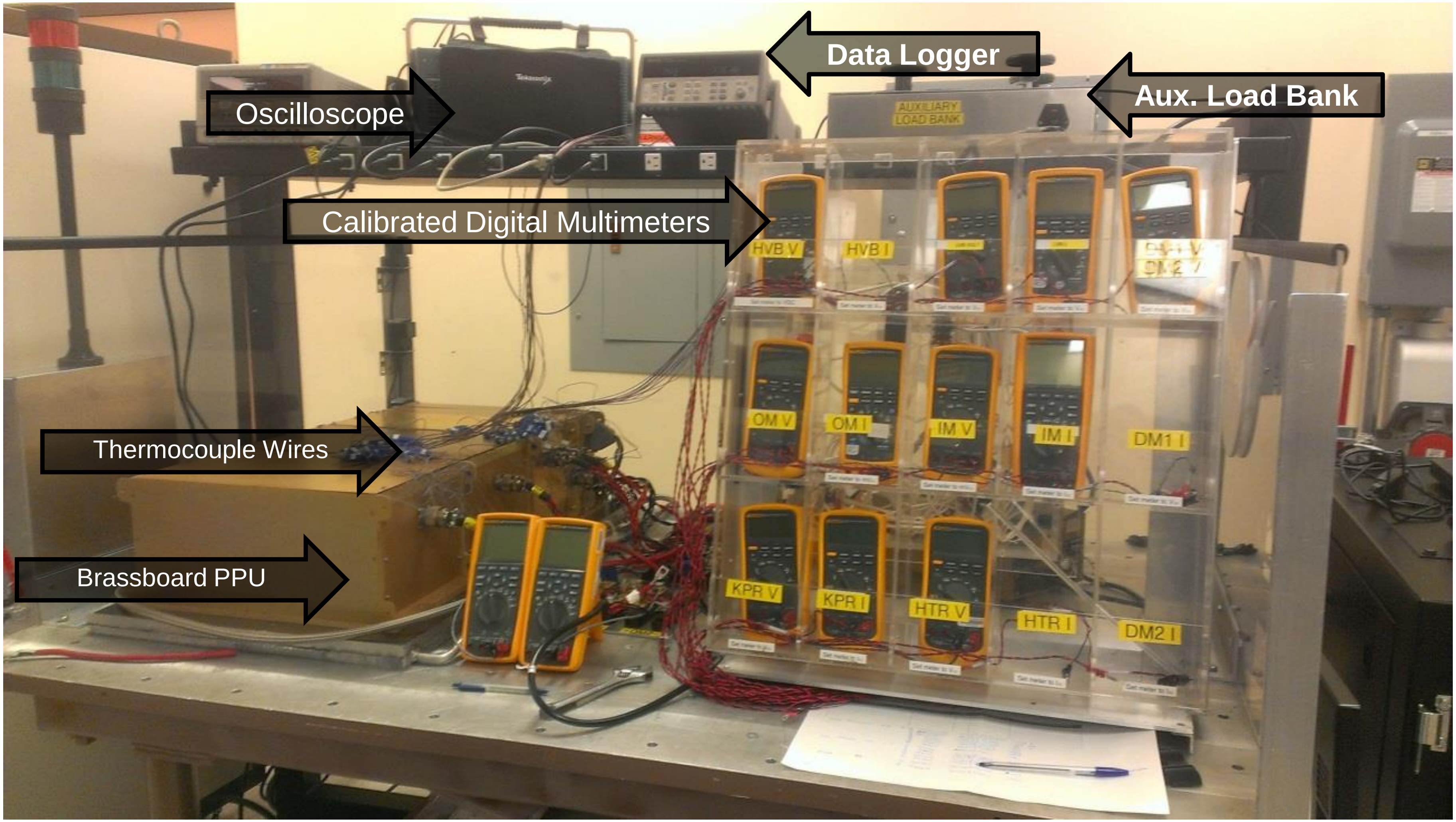
Test Setup

- **All of the instrumentation used for performance measurements during ambient testing was calibrated.**
- **Resistive load banks were used to simulate the thruster loads for both the ambient and vacuum testing.**

Test Setup



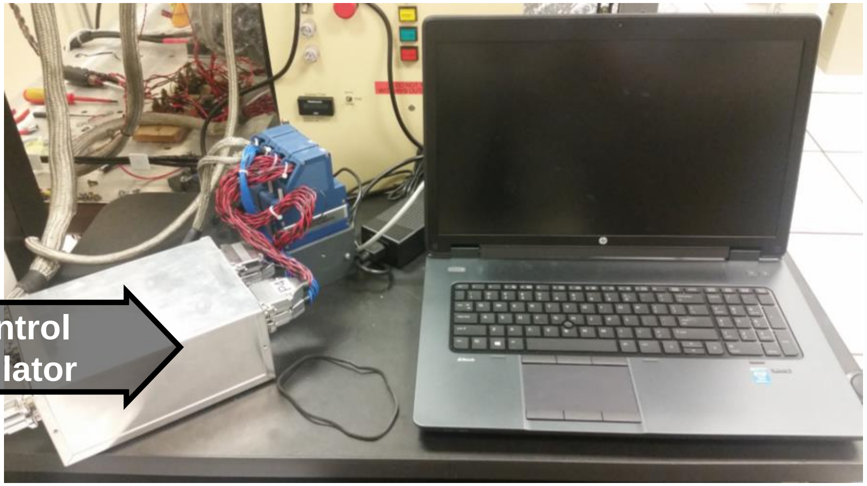
Test Setup


Data Logger
Aux. Load Bank
Oscilloscope
Calibrated Digital Multimeters
Thermocouple Wires
Brassboard PPU
AUXILIARY LOAD BANK
HVB V
HVB I
OM V
OM I
IM V
IM I
DM1 I
KPR V
KPR I
HTR V
HTR I
DM2 I

Test Setup

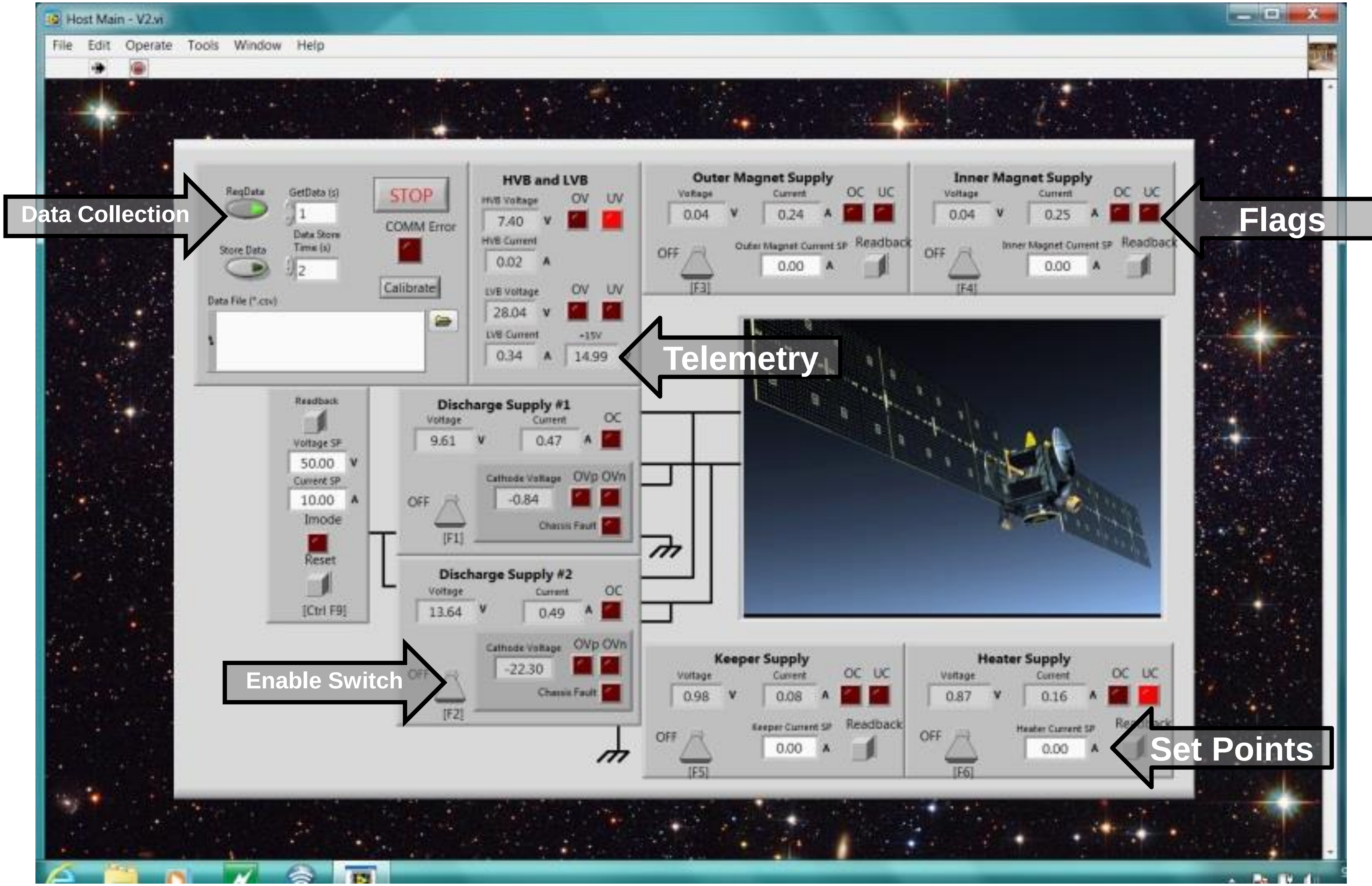
Discharge Load Bank

Power Supplies



System Control Board Simulator

Test Setup

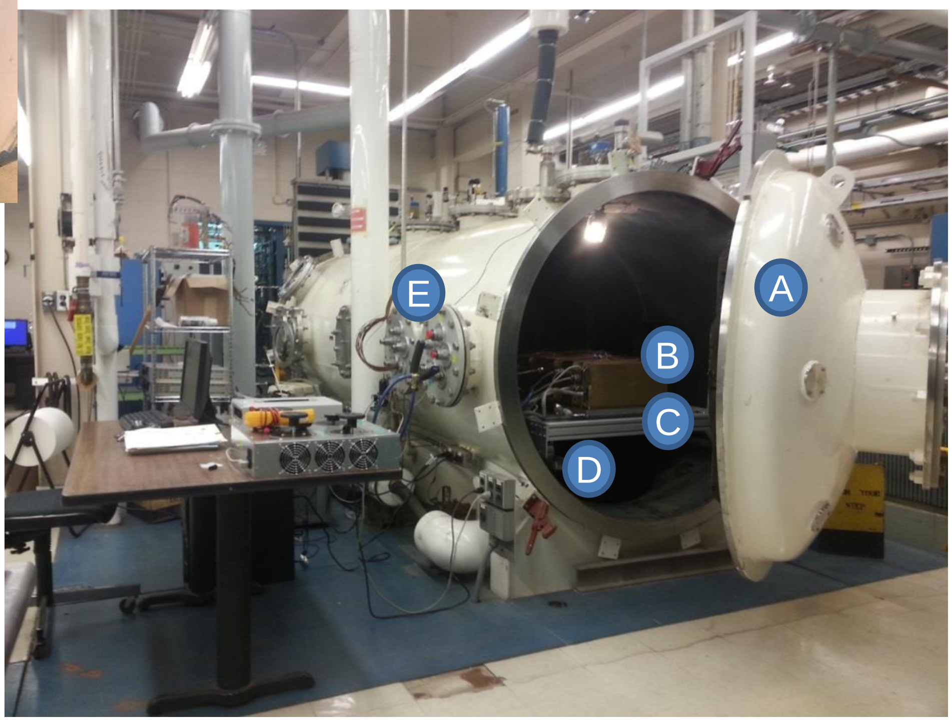


Host Main - V2.vi
File Edit Operate Tools Window Help
Data Collection
Flags
Telemetry
Enable Switch
Set Points
ReqData
GetData (s)
Store Data
Data Store Time (s)
Data File (*.csv)
STOP
COMM Error
Calibrate
HVB and LVB
HVB Voltage
HVB Current
LVB Voltage
LVB Current
OV UV
+15V
Outer Magnet Supply
Inner Magnet Supply
Voltage Current OC UC
Outer Magnet Current SP
Inner Magnet Current SP
Readback
OFF
[F3]
[F4]
Discharge Supply #1
Discharge Supply #2
Cathode Voltage
OVp OVn
Chassis Fault
[F1]
[F2]
Readback
Voltage SP
Current SP
Imode
Reset
[Ctrl F9]
Keeper Supply
Heater Supply
Keeper Current SP
Heater Current SP
[F5]
[F6]

Test Setup

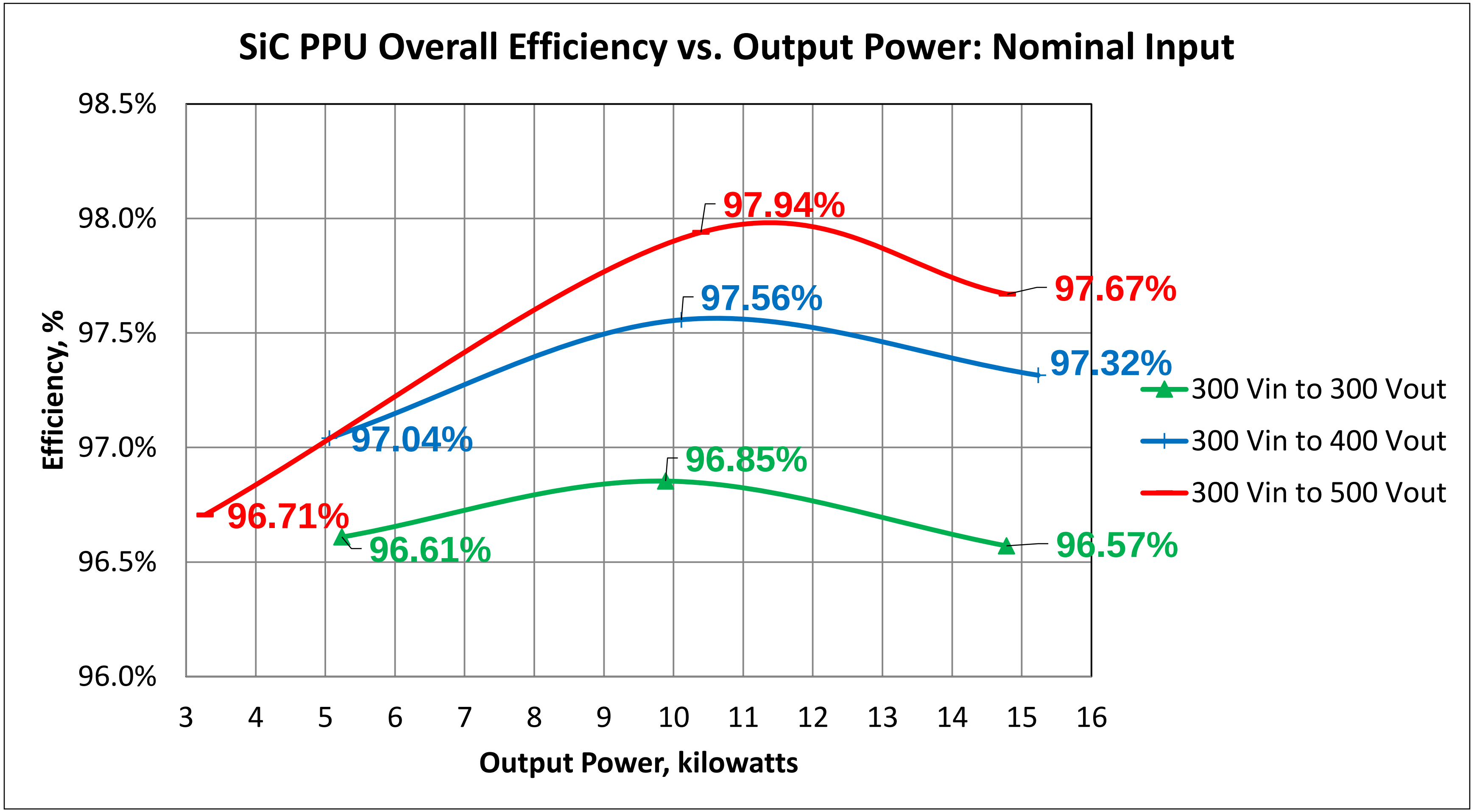
KEY

A: GRC Vacuum Facility 8 (VF-8)
B: HP-300V-PPU
C: Cooling Plate
D: Test Table
E: Tank Feedthroughs



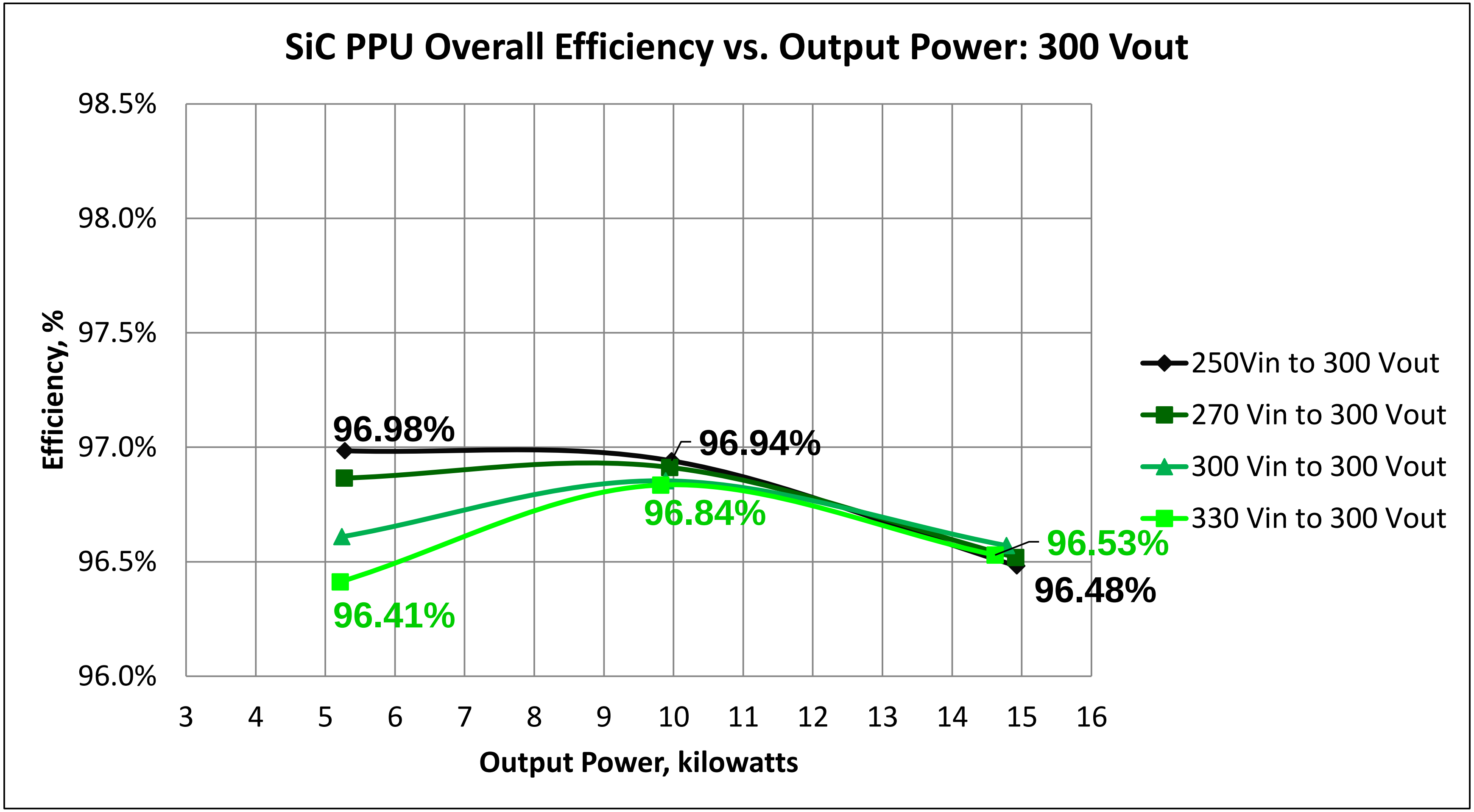
- **Vacuum tank pressure was controlled by a separate facility control system to ≤ 10^{-5} Torr**

Performance Results



$$Efficiency = \frac{(Discharge\ Output\ Power + \sum Auxilary\ Output\ Power + Housekeeping\ Power\ )}{(Low\ Voltage\ Power\ Input + High\ Voltage\ Power\ Input)}$$

Performance Results



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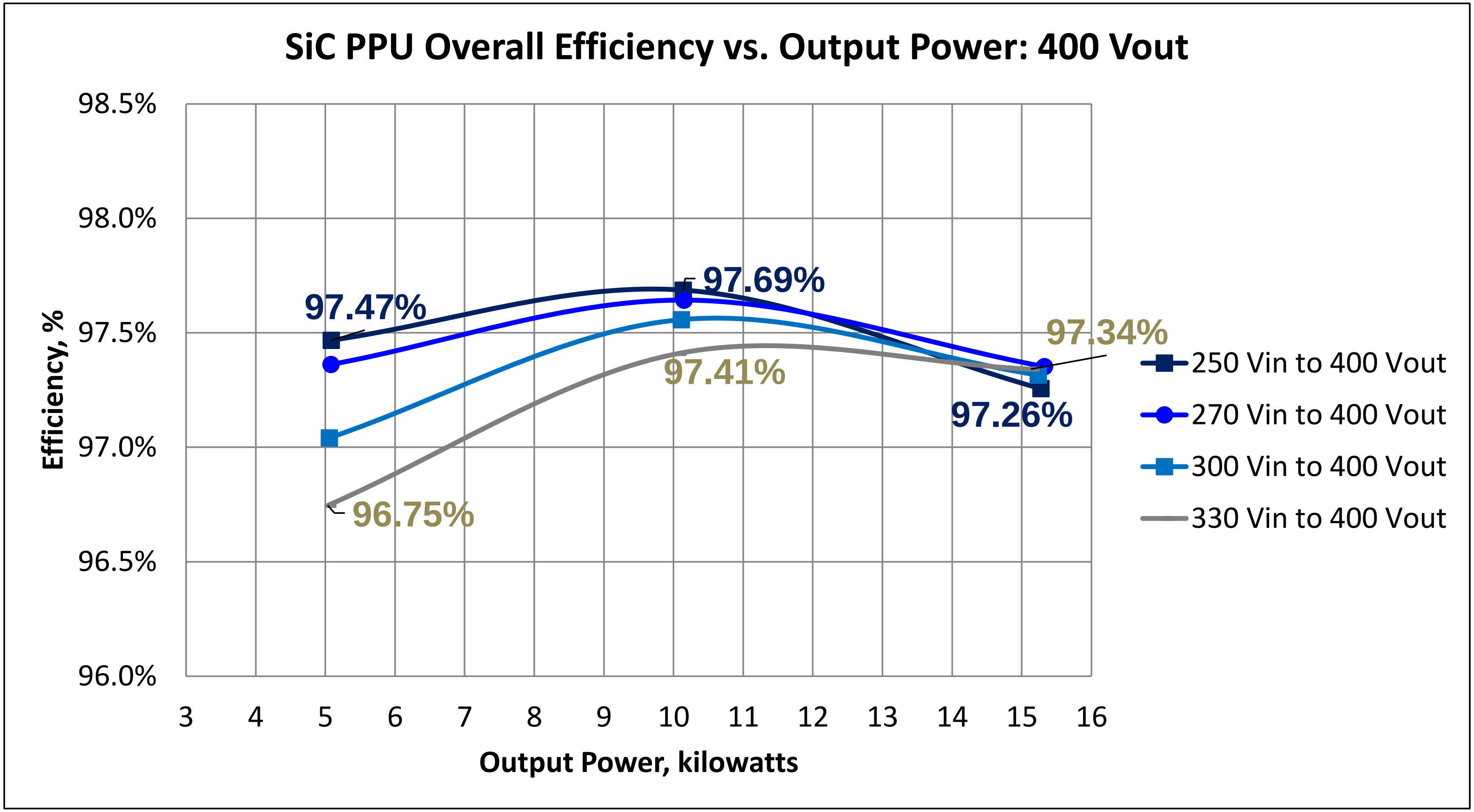
Performance Results



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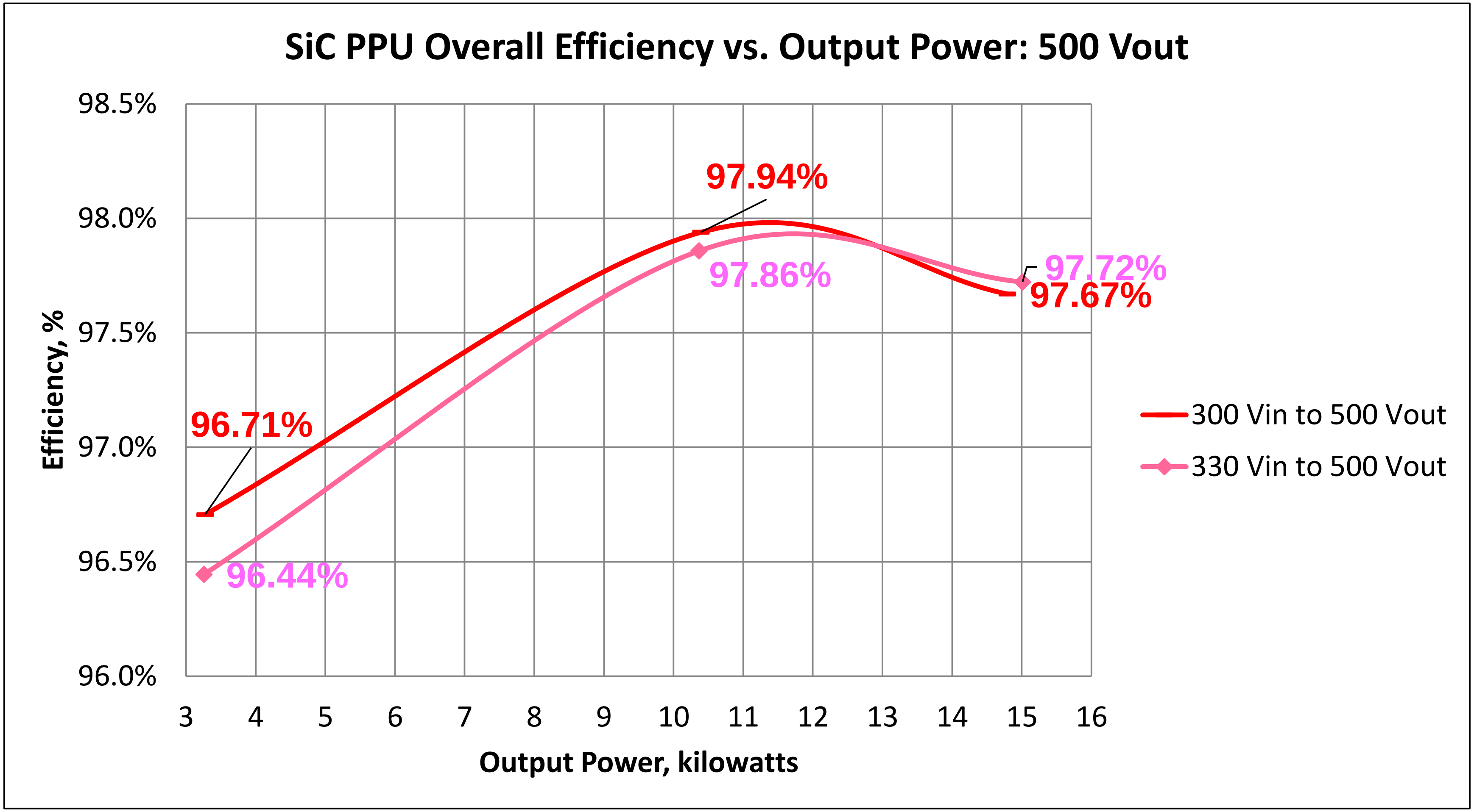
Performance Results



$$Efficiency = \frac{(Discharge\ Output\ Power + \sum Auxilary\ Output\ Power + Housekeeping\ Power\ )}{(Low\ Voltage\ Power\ Input + High\ Voltage\ Power\ Input)}$$

Performance Results

	Test Conditions (full-scale value)	Line Regulation, %	Load Regulation, %	Ripple, %
Discharge Supply	Vout = 400 VDC (400 VDC)	2.90%	0.74%	1.25%
Inner Magnet Supply	Iout = 5 ADC (10 ADC)	0.08%	0.08%	0.08%
Outer Magnet Supply	Iout = 5 ADC (10 ADC)	0.03%	0.02%	0.20%
Heater Supply	Iout = 5 ADC (9 ADC)	0.08%	0.04%	0.20%
Keeper Supply	Iout = 2 ADC (3 ADC)	0.01%	0.02%	0.80%

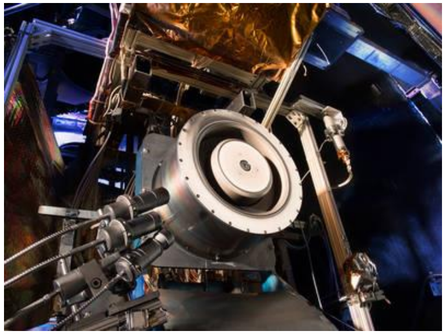
EQUATION	**VARIATION**
$Line\ Regulation = \frac{\Delta Regulated\ Output}{\Delta Input\ Voltage}$	For discharge supply, high voltage input varied from 250 – 330 VDC For auxiliary supplies, low voltage input varied from 23 - 36 VDC
$Load\ Regulation = \frac{\Delta Regulated\ Output}{Nominal\ Regulated\ Output\ Value}$	For each supply, load resistance was varied from 30% to 100% of the full load capability of the supply.

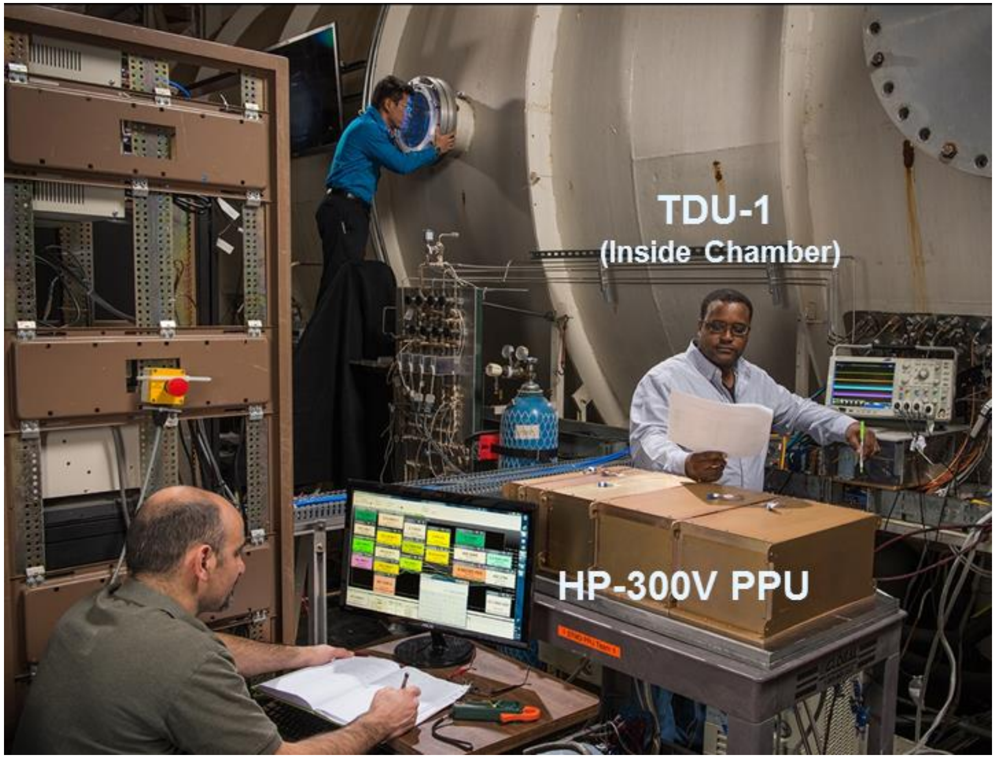
Performance Results

Brassboard SiC PPU Thermal Result Summary High Voltage Input: 300 VDC Low Voltage Input: 28 VDC Discharge Output Voltage Setting: 400 VDC, Discharge Output Power: 15 kW					
Component Temperature	**Ambient Steady State Temperature, C** *Baseplate at 25 C*	**Vacuum Steady State Temperature, C** *Baseplate at 25 C*	**Vacuum Steady State Temperature, C** *Baseplate at 50 C*	**Vacuum Steady State Temperature, C** *Baseplate at 5 C*	**ΔT (Vacuum-Ambient)** *Baseplate at 25 C*
Discharge Module 2, Inside Transformer Windings	54.6	67.3	97.2	61.4	12.7
High Voltage Bus Input Filter Differential Inductor	47.6	66.2	81.5	51.5	18.6
Housekeeping Power Supply, DC-DC Converter	38.8	53.8	73.2	36.5	15.1
Discharge Module 2 Transformer Case	45.9	52.5	74.8	35.2	6.6
Discharge Module 2 SiC MOSFET	33.3	35.3	58.8	16.3	2.0
Low Voltage Bus Total Input Current Sensor	33.1	45.6	64.8	27.7	12.4
Discharge Module 2 Gate Drive Board	35.9	42.2	64.3	24.3	6.4
Discharge Module 2 SiC Output Rectifier Diode	38.7	40.6	64.1	21.5	1.9
Discharge Module 2 Baseplate Temperature	25.6	26.7	50.1	6.9	1.1

Performance Results

- Integrated Thruster Demonstration





Forward Work

- NASA's Glenn Research Center with support from the Goddard Space Flight Center has investigated the ability of commercially available SiC devices to survive the space radiation environment.
  - ***To date, none of the SiC components under test have passed all of the required space environment radiation tests.***
- On-going research seeks to better understand and analyze the failure modes of SiC power devices in order to develop space-qualified devices for future NASA missions.

Conclusion

- SiC components and high voltage design contributed to the superior performance demonstrated by the 15 kW brassboard SiC PPU under ambient and vacuum conditions.
  - Peak PPU overall efficiencies in excess of 97% at full-power in ambient test environment
  - All component temperatures within 30C of baseplate in ambient test environment
  - Vacuum performance results consistent with ambient performance results
  - Integrated test demonstrated compatibility with a technology demonstration unit Hall Effect Thruster
- Future work is necessary to demonstrate that SiC power devices can withstand the space radiation environment.

Acknowledgements

- **Co-Authors**: Luis Pinero, Robert Scheidegger, Michael Aulisio, Marcelo Gonzalez, and Arthur Birchenough

- **Engineers**, **Designers**, and **Technicians** at NASA Glenn Research Center who contributed to the success of these development efforts.