Non-Contact Thermal Characterization of NASA's HERMeS Hall Thruster (AIAA-2015-3920)

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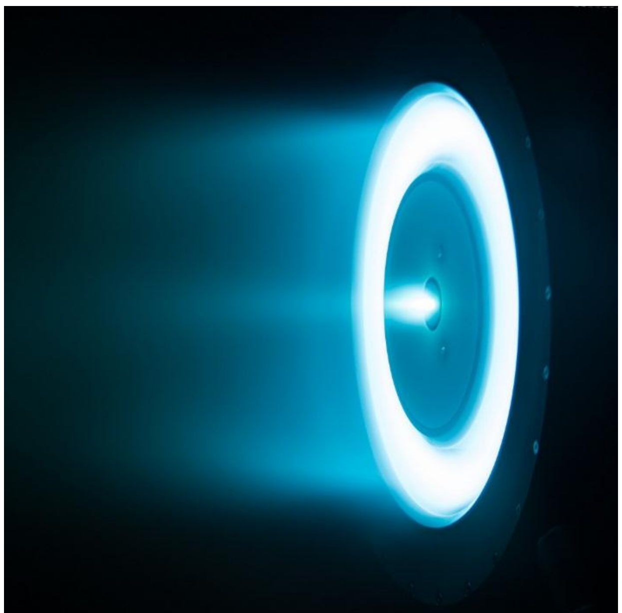
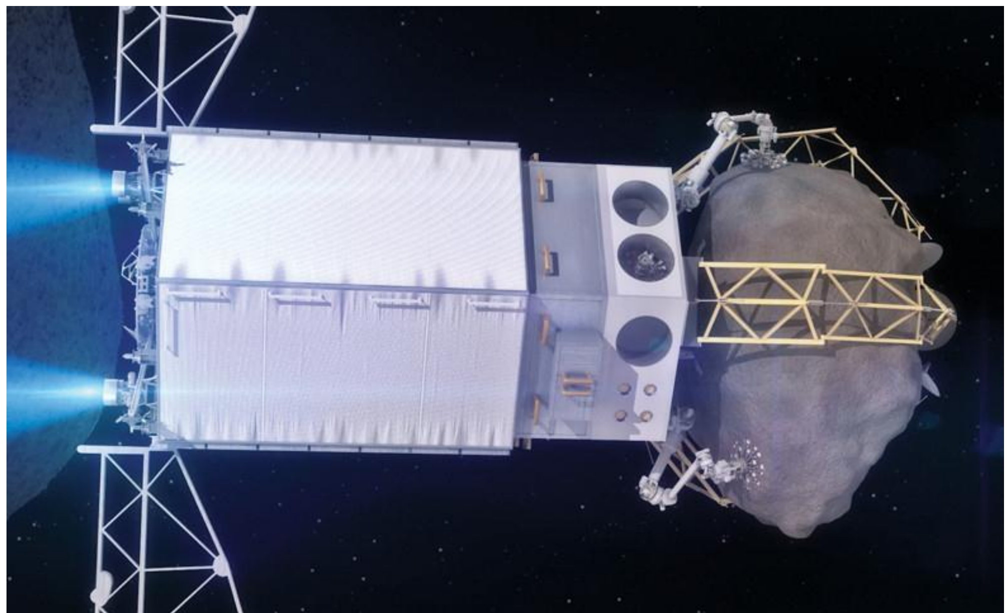
Introduction

- A NASA GRC and JPL team is developing a 12.5-kW, magnetically-shielded Hall thruster, called Hall Effect Rocket with Magnetic Shielding (HERMeS)
- Mission concepts utilizing HERMeS Technology Demonstration Unit (TDU) include Solar Electric Propulsion (SEP) Technology Demonstration Mission (TDM) and the Asteroid Redirect Robotic Mission (ARRM)
- This presentation will focus on the development of an infrared (IR) thermal imaging system deployed during the thermal characterization test

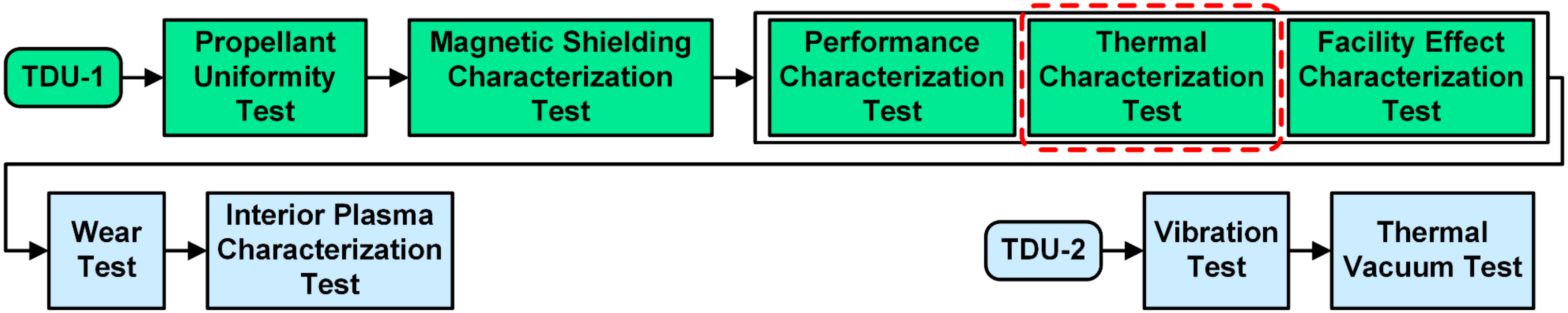


HERMeS TDU1 in operation



Notional Asteroid Redirect Vehicle

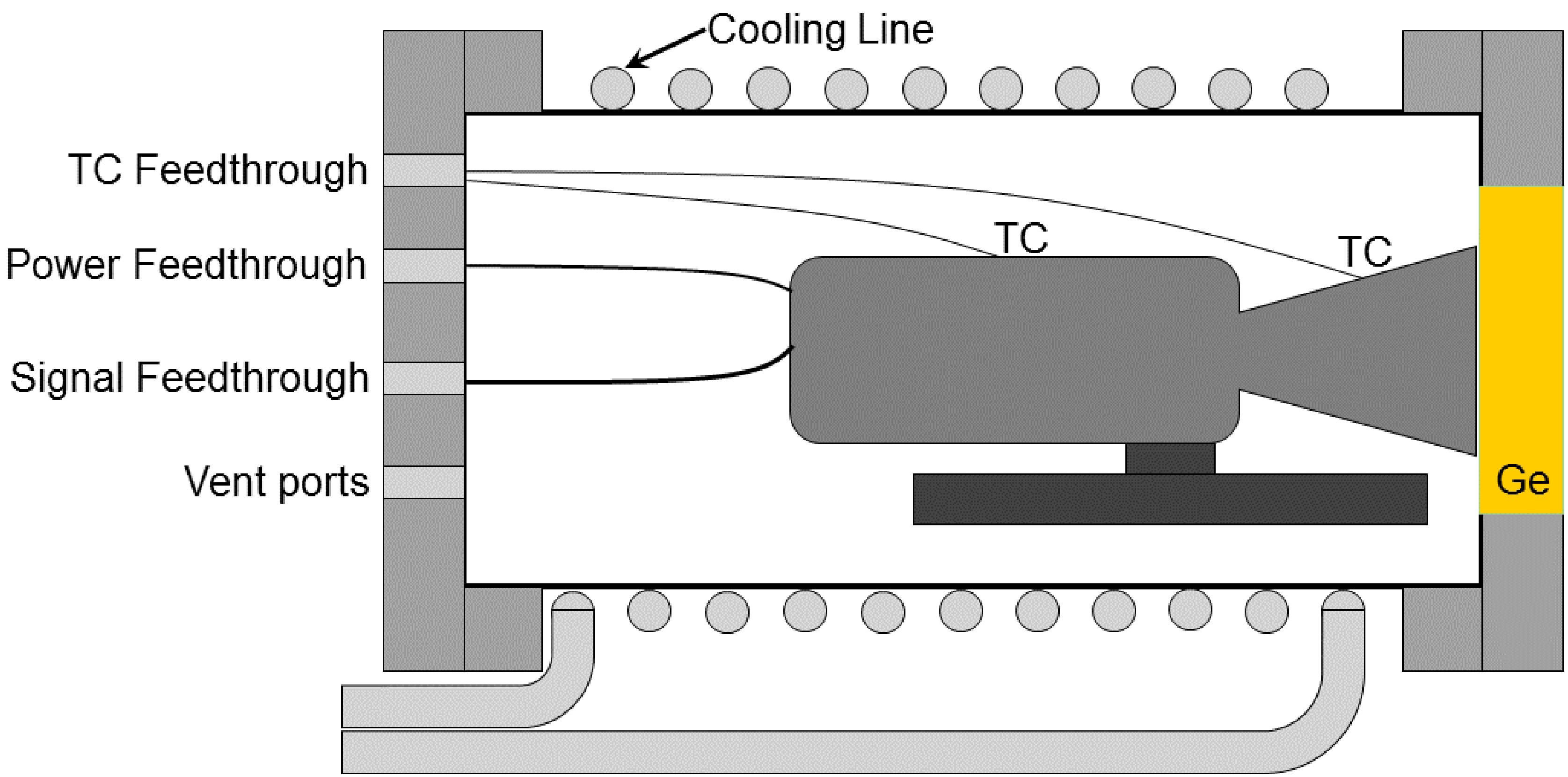
HERMeS Test Campaign Status



- Completed the following tests on TDU-1:
  - Propellant uniformity test (JANNAF-2015-3926, JANNAF-2015-3884)
  - Magnetic shielding characterization test (AIAA-2015-3919)
  - Performance characterization test (IEPC-2015-007)
  - Thermal characterization test (TCT)
  - Facility effect characterization test
- Additional overview found in: IEPC-2015-186, JANNAF-2015-3946, IEPC-2015-008
- TCT objectives:
  - Provide thermal data for validating the thruster thermal model
  - Find any non-uniformities in the thruster thermal distribution that may need to be addressed

Diagnostic Development: IR Camera and Enclosure

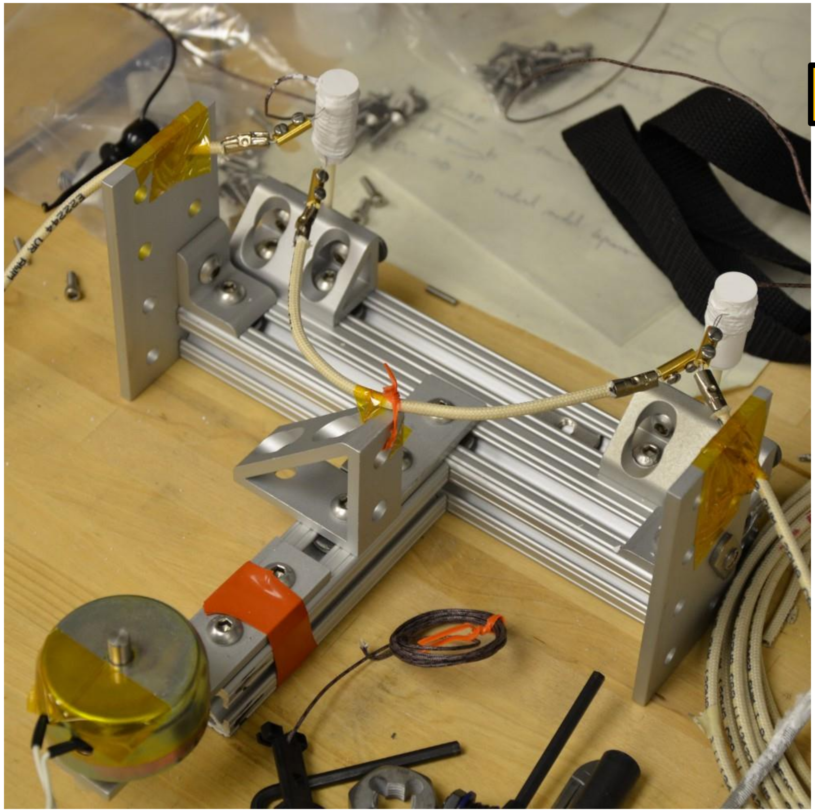
- Design is based on a similar system by Spektor and Beiting (IEPC-2013-452)



Cross sectional view of IR camera enclosure

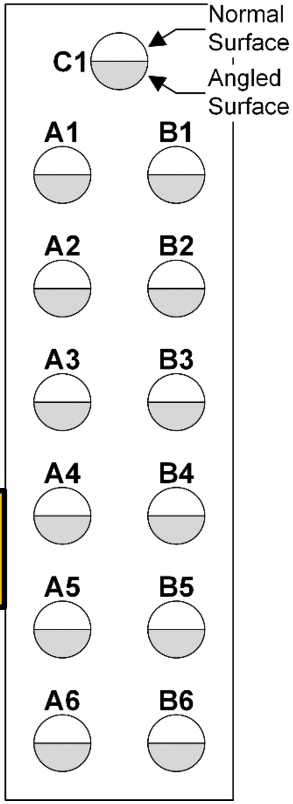
Diagnostic Development: IR Camera Calibration Array

- Transmission through Germanium window can change over the course of a test, need calibration array for accurate measurements
- Performed pilot test to determine number of turns on each heater
- 13 boron nitride (BN) samples at varying temperatures (up to 600 °C), each with a normal and an angled surface, and instrumented with a type K thermocouple



<-Pilot test rig

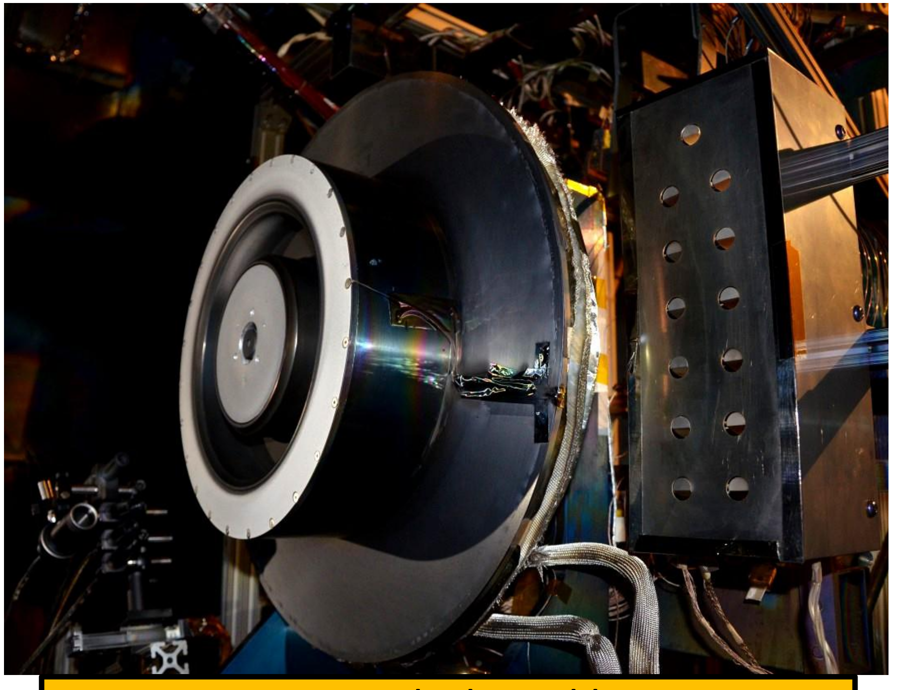
Calibration array diagram->



Test Setup: Test Article

- HERMeS TDU1 is a 12.5-kW, 3000 sec, magnetically-shielded Hall thruster
  - Demonstrated throttling from 0.6 to 12.5 kW, 2000 to 3000 sec
  - Magnetic shielding topology maintained throughout, magnetic field strength measured by peak radial magnetic field strength on channel centerline
  - Nominal magnetic field strength means optimized for best performance while maintaining >25 gauss margin against oscillation mode transition
  - Max magnetic field strength is about twice as large as nominal at 800 V, 12.5 kW
  - 7% cathode flow fraction

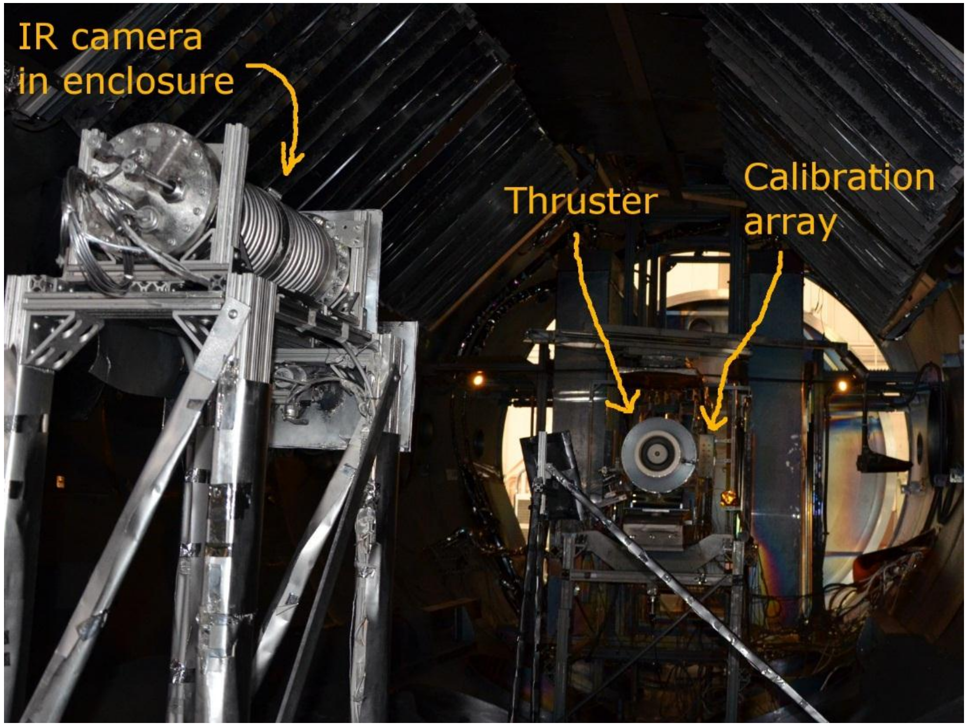
Label	Discharge voltage, V	Discharge power, kW	Magnetic field strength
30-094	300	9.4	Nominal
40-125	400	12.5	Nominal
50-140	500	14.0	Nominal
80-125	800	12.5	Nominal
80-125B	800	12.5	Max



HERMeS TDU1 with the calibration array

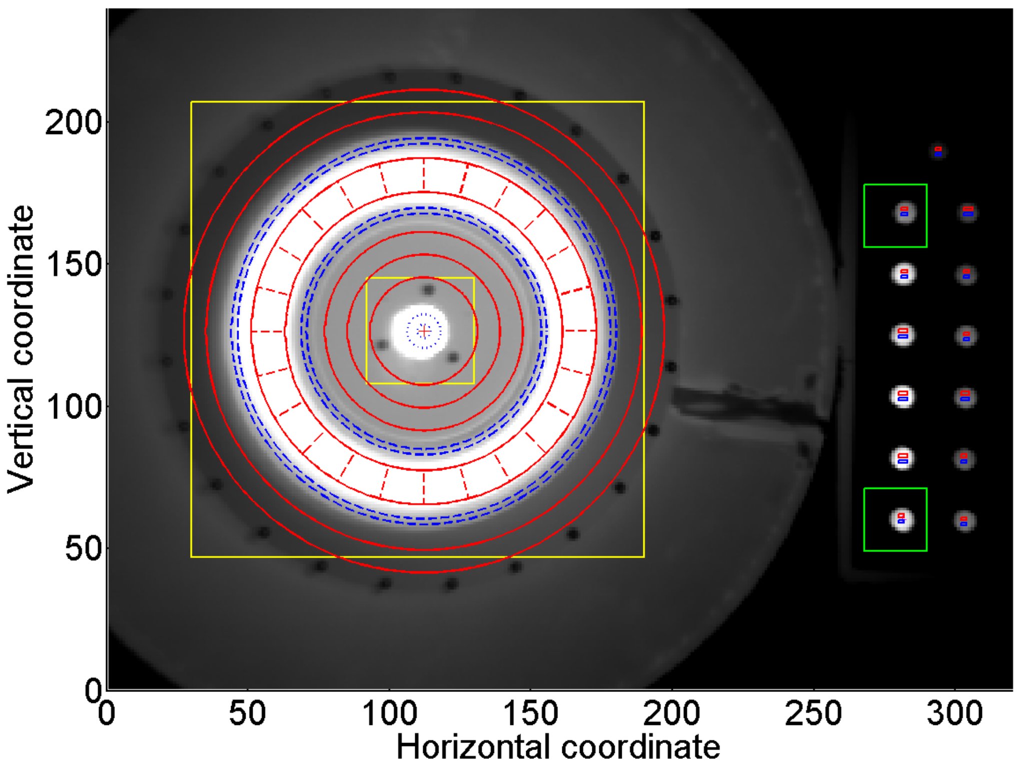
Test Setup: Test Facility

- GRC Vacuum Facility 5
  - Pressure by thruster varied from 3.8×10^{-6} to 6.7×10^{-6} Torr
- Calibration array located slightly behind the thruster radiator
- IR camera located 5.9 m downstream of the thruster exit plane on the firing axis
- Camera and calibration array signals routed to a data acquisition computer



Data Reduction

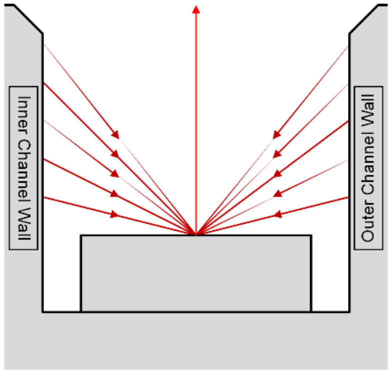
1. Curve-fit for the center of thruster and locations of A1 and A6
2. Use location of A1 and A6 to find remaining samples
3. Divide thruster image into concentric layers, in order from inner to outer:
   1. Inner front pole
   2. Inner chamfer of discharge channel
   3. Anode
   4. Outer chamfer
   5. Outer front pole
4. Divide each layer into 24 azimuthal slice and computer average intensity
5. Use cal. array data to construct calibration curve, convert intensity to temperature



Sample IR camera image with analysis boundaries overlaid

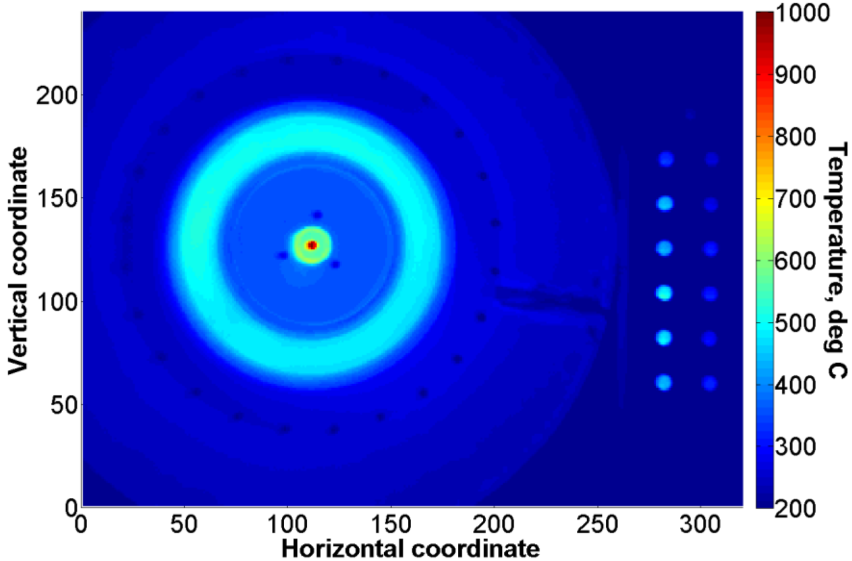
Correction Factors and Uncertainty

- Two issues increase uncertainty if not corrected
  - Reflected emission:
    - No thruster surface is perfect emitter. Anode has large view factors to the discharge chamber walls and reflect much of the radiation, causing anode temperature to be overestimated. Correction left for future work.
  - Variation in emissivity:
    - Front poles made with alumina coating and further coated by backsputtered carbon during test, emissivity may be different than the BN samples. Emissivity also change with temperature. Correction left for future work
    - Chamfer surfaces on discharge channel should be very similar to BN sample. IR reflectometry measurement show clean and carbon-coated BN samples have emissivity of 0.83 to 0.86

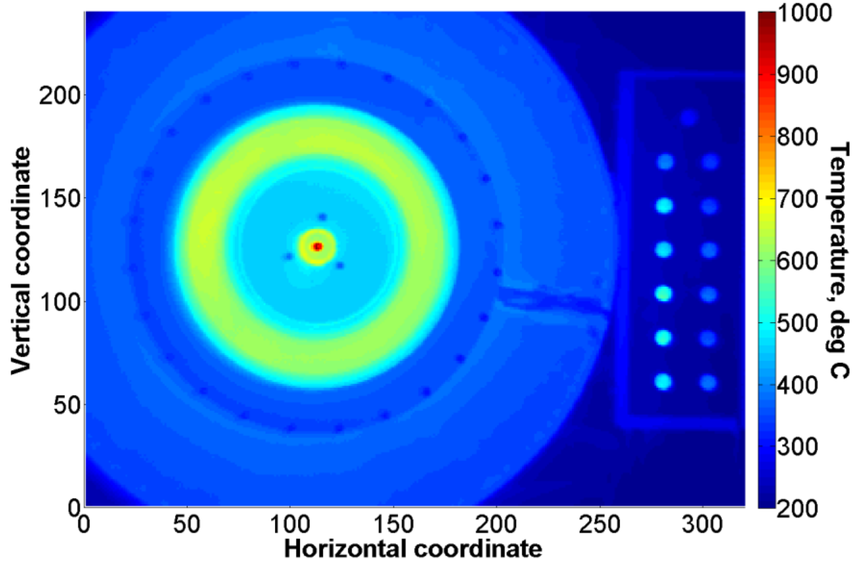


- Uncertainty
  - Inner and outer chamfer (angled BN surfaces): ±25 °C
  - Front pole (alumina surfaces coated with carbon): ±50 °C
  - Anode: only variation in radiance reported

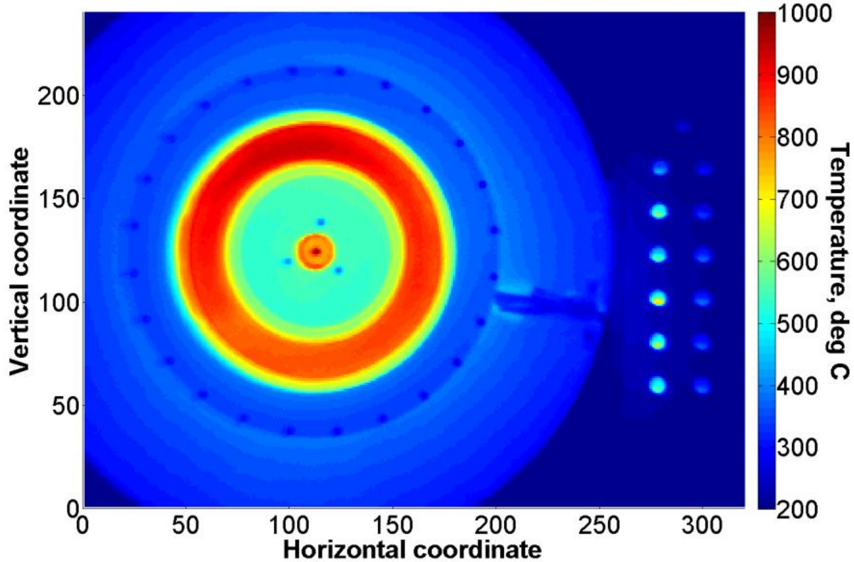
Results: Images



↑300 V, 9.4 kW

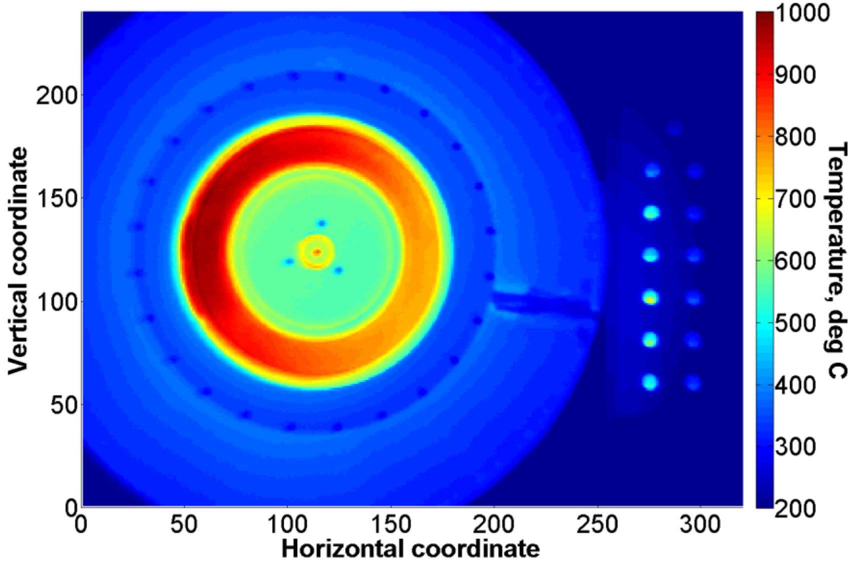


↑400 V, 12.5 kW

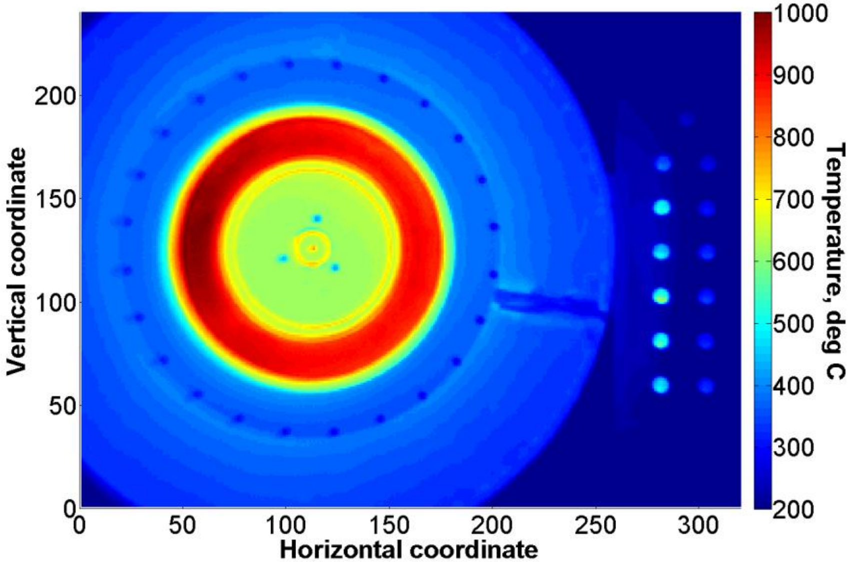


←500 V, 14.0 kW

Results: Images



800 V, 12.5 kW, nominal mag



800 V, 12.5 kW, high mag

- Note the non-uniformity in emission intensity from the anode on the left and the relatively better uniformity on the right

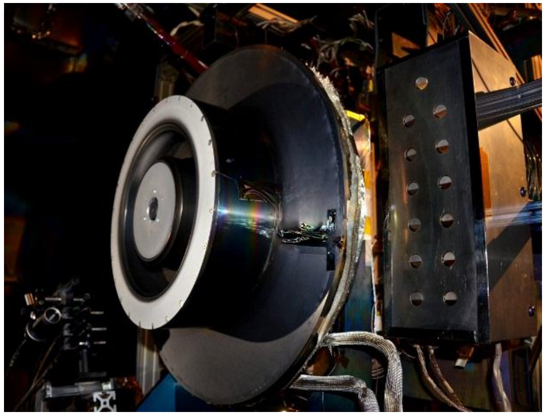
Results: Trends

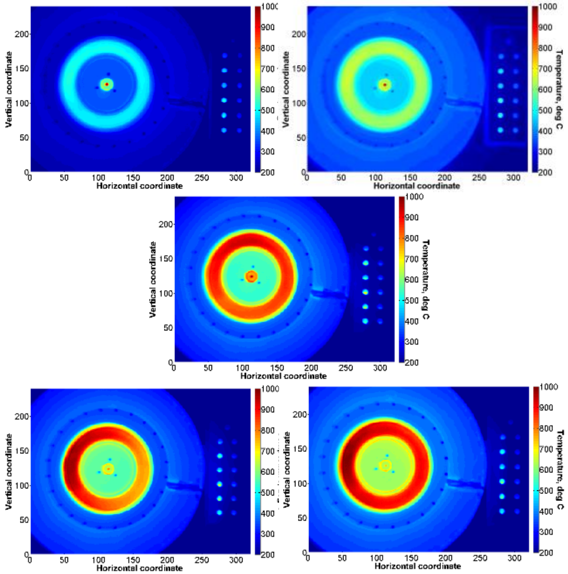
- Temperatures driven in part by discharge voltage in addition to discharge power (800 V, 12.5 kW shows higher temperature than 500 V, 14 kW)
- Azimuthal uniformity better for low discharge voltage operation than for high discharge voltage operation
- Increased magnetic field strength made temperature distribution on the anode more uniform

	30-094		40-125		50-140		80-125		80-125B	
	Avg.	pk-pk	Avg.	pk-pk	Avg.	pk-pk	Avg.	pk-pk	Avg.	pk-pk
Anode, radiance %		12%		9.5%		17%		35%		18%
Inner front pole, °C	355	6	459	6	539	14	567	20	623	15
Outer front pole, °C	252	30	358	12	359	17	354	24	377	15
Inner chamfer, °C	362	19	496	26	545	39	538	90	645	102
Outer chamfer, °C	349	34	494	32	553	85	580	~100	608	71

Conclusion

- Thermal characterization test of HERMeS completed and a non-contact thermal imaging system was deployed
- A pilot test was performed to help develop a calibration array, which was used to improve temperature measurement accuracy
- Three key findings:
  - Thruster temperature driven by both discharge voltage and power
  - Operations at low discharge voltages (300-500 V) yielded more uniform temperature distributions than at high discharge voltage (800 V)
  - At high discharge voltage, stronger magnetic field made the anode temperatures more uniform
- Future works: finite reflectivity correction and improve estimates for emissivity





Acknowledgment

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Question?