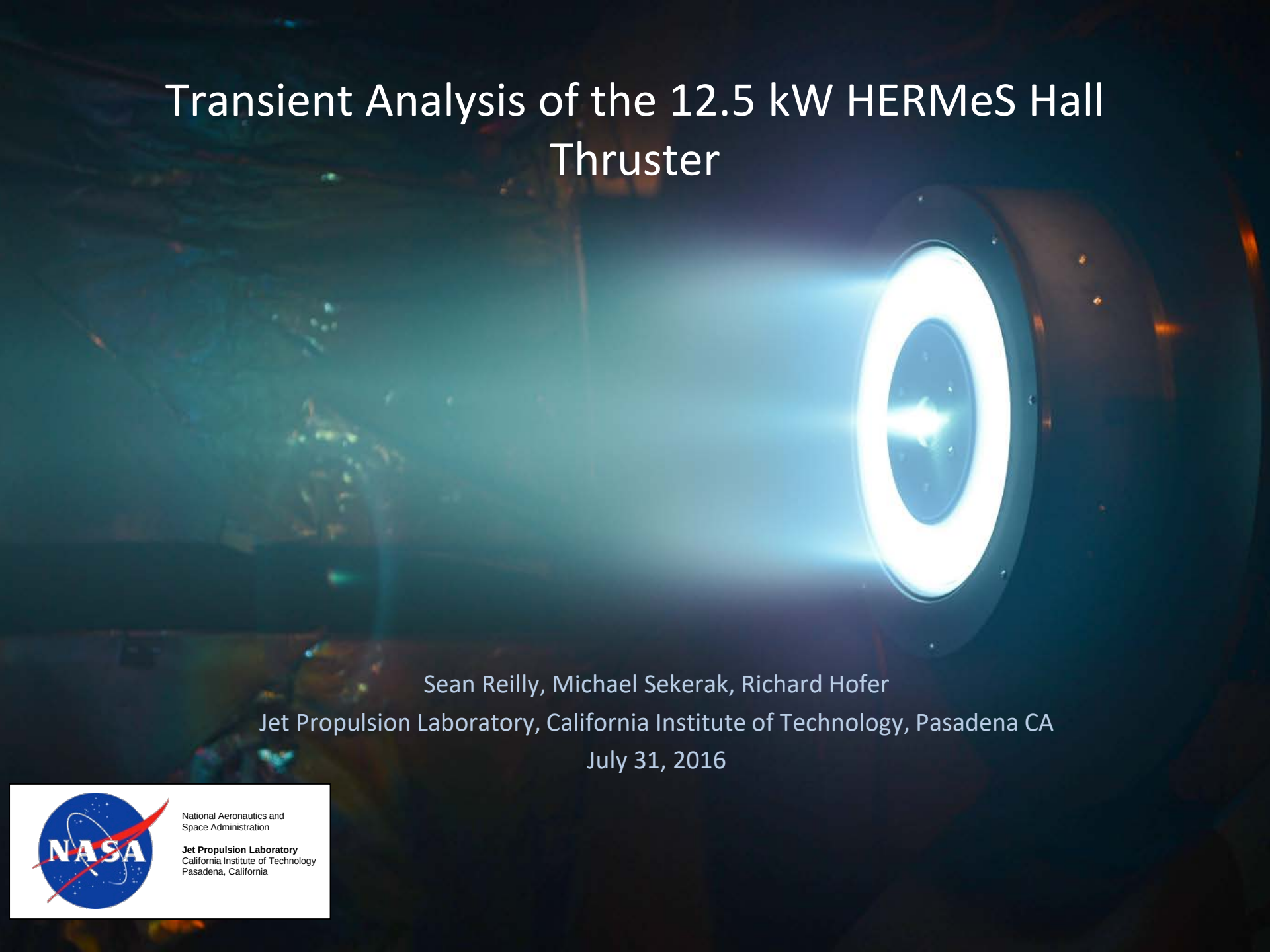
Transient Analysis of the 12.5 kW HERMeS Hall Thruster



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July 31, 2016

National Aeronautics and
Space Administration

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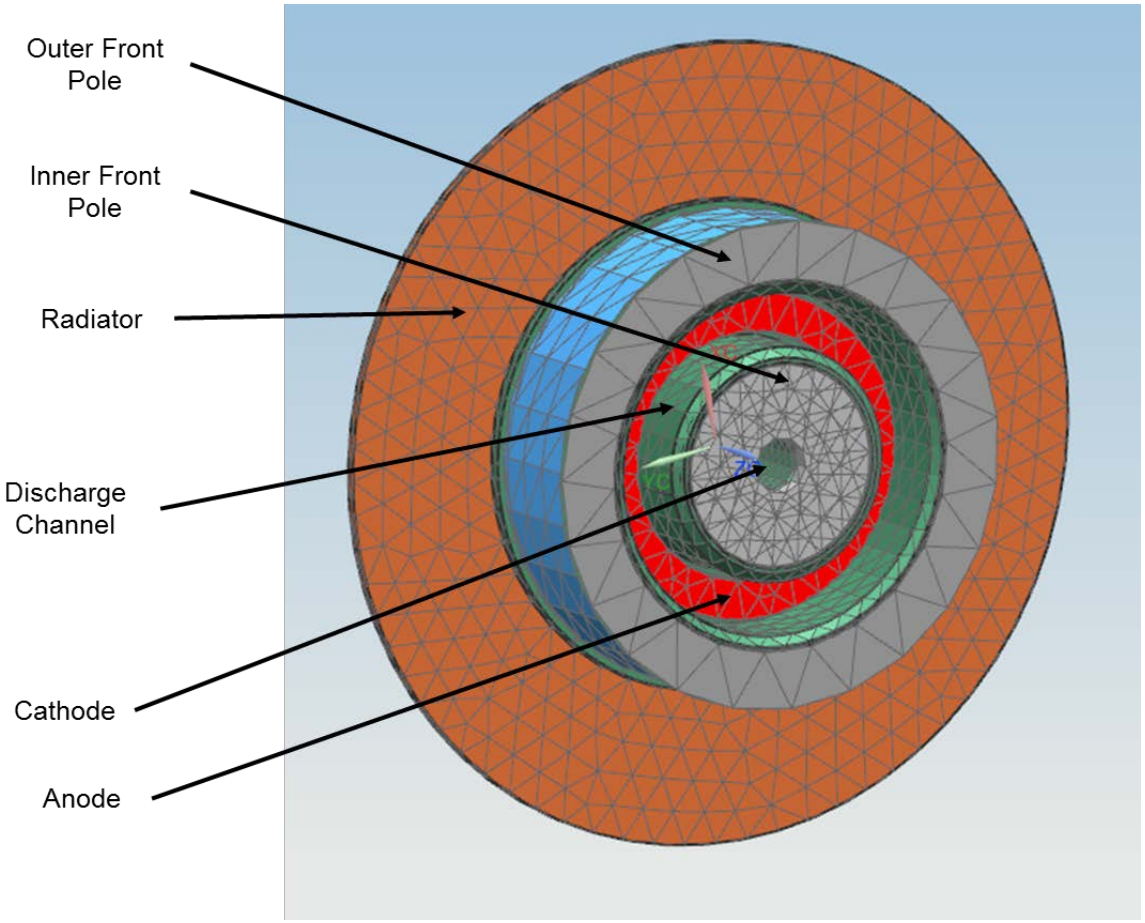
HERMeS

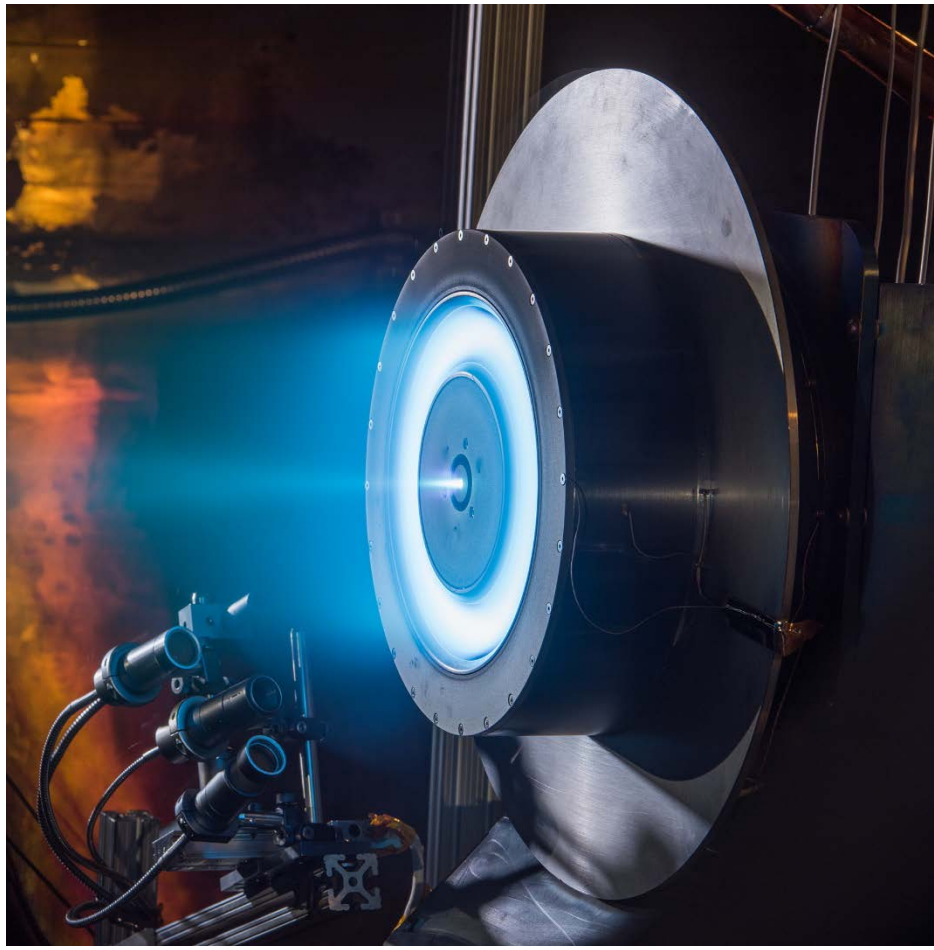
- **Goal:** Use a validated steady state model to predict the transient response of the HERMeS Thruster under environmental testing



12.5 kW Hall thruster (HERMeS)

Outline

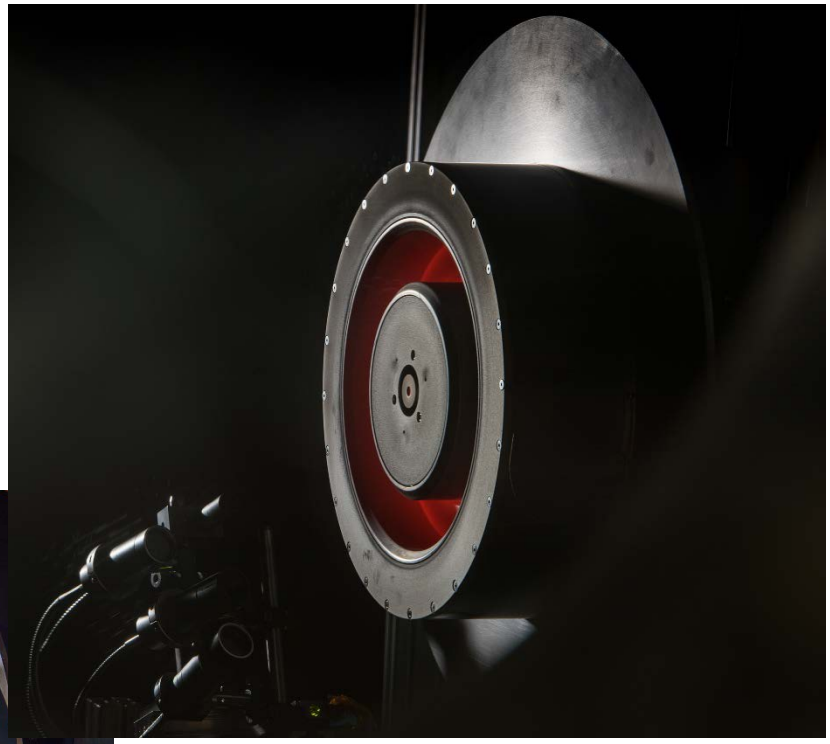
- Thermal issues considered
  - Discharge channel
  - Magnetic Coils
- Modeling Approach
  - Heat Flux
  - Flux Distributions
- Validation results
- Transient Predictions
- Preliminary transient results
- Future Work
- Conclusions

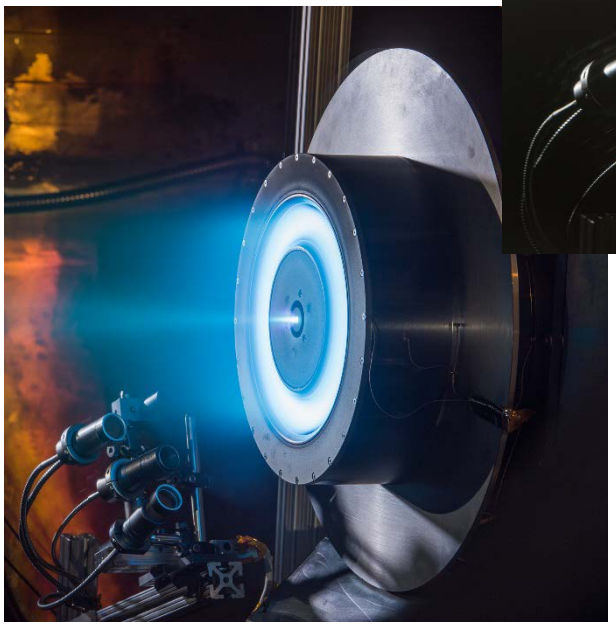


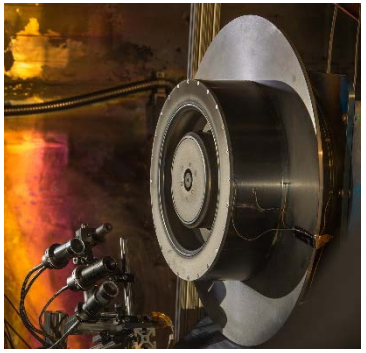
HERMeS TDU1 thruster at GRC
(radiator diameter ~20”)

Thermal Issues – High Temperatures, Unknown Limits!

- Large plasma loads (~1.4 kW) on thruster during typical firing condition (800 V, 12.5 kW, 130 G)
- HERMeS Cold
- HERMeS Firing
- HERMeS Shut off







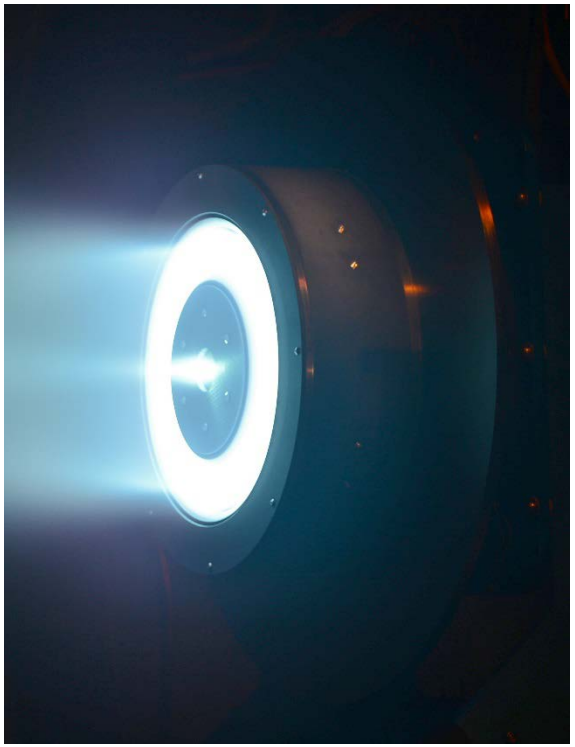
- TBD temperature requirements

High-Temperature Effects – Discharge Channel

- Hottest component measured is boron nitride (BN) discharge chamber
  - Anode does not have probes but is hotter (viewed using IR camera)

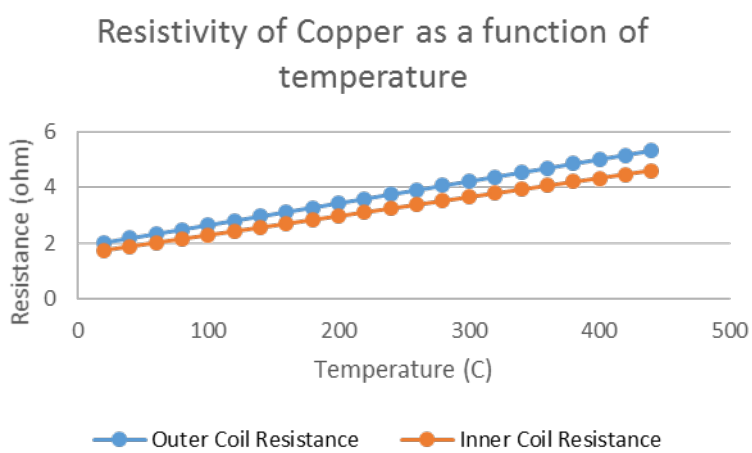
- Much energy emitted away but still need up-stream conduction out of channel for acceptable thruster temperature

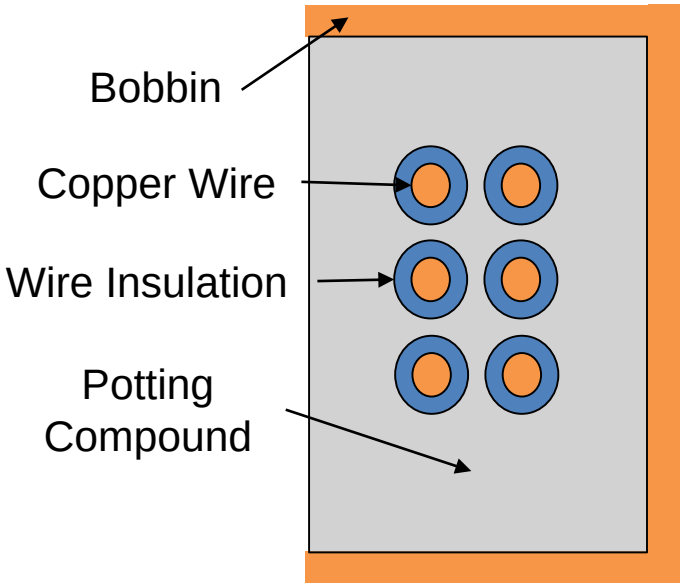
- Discharge channel is mated to an aluminum heat-sink with a bare I/F
  - Contact resistance is a big concern throughout thruster
  - High temps/voltages deter I/F material use



Thermal Issues - Magnetic Coils

- Magnetic coils have unique high temperature issues
  - Wires with high temp insulation, doped in a compound to keep them from contacting each other
  - Hard to determine thermal conductivity of coils
  - Emissivity is not well understood
  - Temperature gradients are extremely important to EP engineers since they are critical to maintaining the "magnetic circuit"





Schematic of coils
Note: not to scale, many more wires, less space

HERMeS Modeling Approach

- What was the progression and reason behind this model?
- Built steady state/transient thermal model for task Temperature dependent properties generally negligible relative to contact conductance and optical property degradation, first order
  - Thruster has many CTE mismatches at the numerous mechanical I/Fs
  - In-test sputtered carbon deposition on exterior surfaces affects ext T-O properties
- Used TMM to compare to 3/2015 GRC test with/without radiator
- Initial task was to understand relative importance of detailed plasma associated heat flux
  - Initially, discharge channel assumed to be uniform % of thruster dissipation
    - 10% of 12.5 kW (1.25 kW) into discharge channel
  - Heat sources
    - Plasma: 1.25 kW; Cathode: 14 W; Inner/Outer coil: 20 W(140 G), 100 W (300 G)

HERMeS Modeling Approach

- Heat Flux distribution is a complicated function of Thruster voltage, magnetic field strength, Xenon flow rate
  - Primarily heat flux as a function of mag. field str, $f(B_{max})$
  - DC: Discharge channel heating from plasma loading (variable parameter)
  - P_{in} and P_{out} : Inner and outer coil heat load (from experimental values)
  - Cathode: Loading from cathode (from previous analysis by J. Polk)
  - Spool: Optional parasitic Loss from back of experimental setup, representing loss through thruster mount
- All modeled power loads based on Mikellides' distribution
  - Modulated magnitude to better fit GRC test data by $\leq$ 10% typically

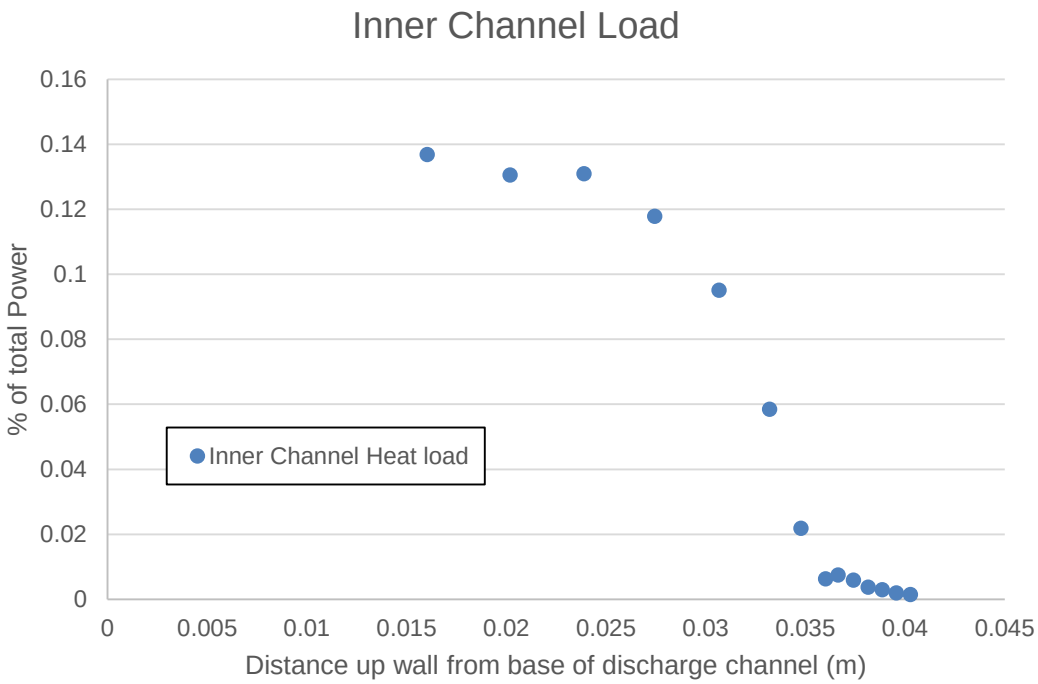
Bmax	Yiangos	DC	Pin	Pout	Cathode	Spool	Radiator	%
	DC	(model)						
(G)	(W)	(W)	(W)	(W)	(W)	(W)		
130	1444	1180	22	19	14	0	N	9.44
250	1945	1550	83	71	14	0	N	12.4
300	1895	1485	119	107	14	0	N	11.88

HERMeS Modeling Approach

- How are flux distributions typically modulated?
- Dr. Mikellides provides these distributions and they are based on the conditions of GRC tested HERMeS
  - Discharge power varies, but ~10%-15% of 12.5 kW power
- These flux distributions were the reason for switching to NX-SST, much easier to handle spatially varying heat loads
  - 6000 elements (TD) to ~65k elements (NX)
  - Model assumes uniform sink temperature surrounding thruster (~-20°C shroud)
- Used model to iteratively check the magnitude of Mikellides' profiles to validate his modeling

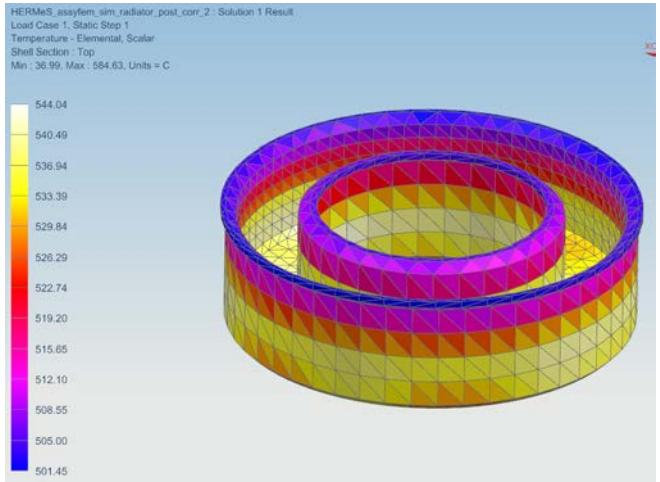
HERMeS Modeling Approach

- Typical heat flux distribution deliverable:
  - Heat load on wall starts above the top boundary of the anode
  - Since discharge channel is radially symmetric, independent variable is the distance along the discharge channel wall, as measured from the base of the channel



Comparison to Mikellides' Distribution

- Results of Heat flux modulation
- In practice, using full power of calculated distribution is too much heat flux
- It is not possible to match the full power of Mikellides' distribution without using unrealistic thermal parameters elsewhere in the model
  - Only way to fix the no-radiator case is to reduce overall load going into the BN
  - Plasma loading should not change with the addition or subtraction of components so same distribution should be used for cases with and without radiator
- In practice, most cases I correlated ended up ~90% of Mikellides' magnitude



Case	Magnitude Multiplier
130 G – Radiator	0.92
130 G – NO Radiator	0.85

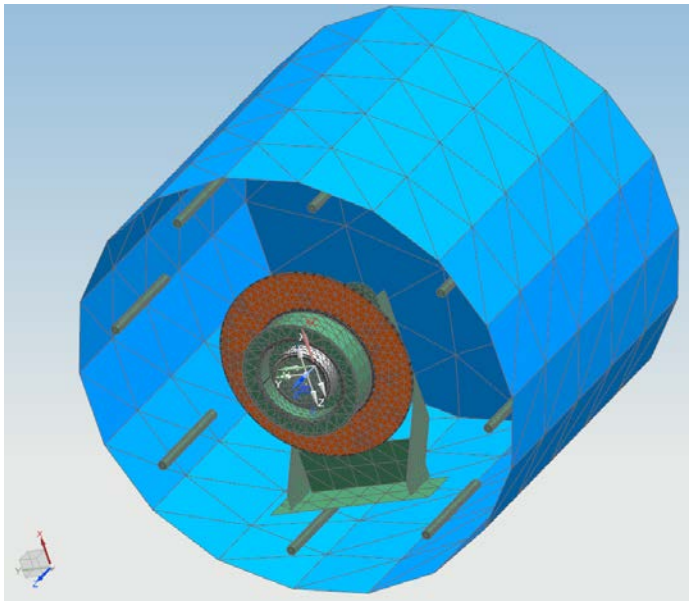
TMM Predictions (Key Nodes, 130 G)

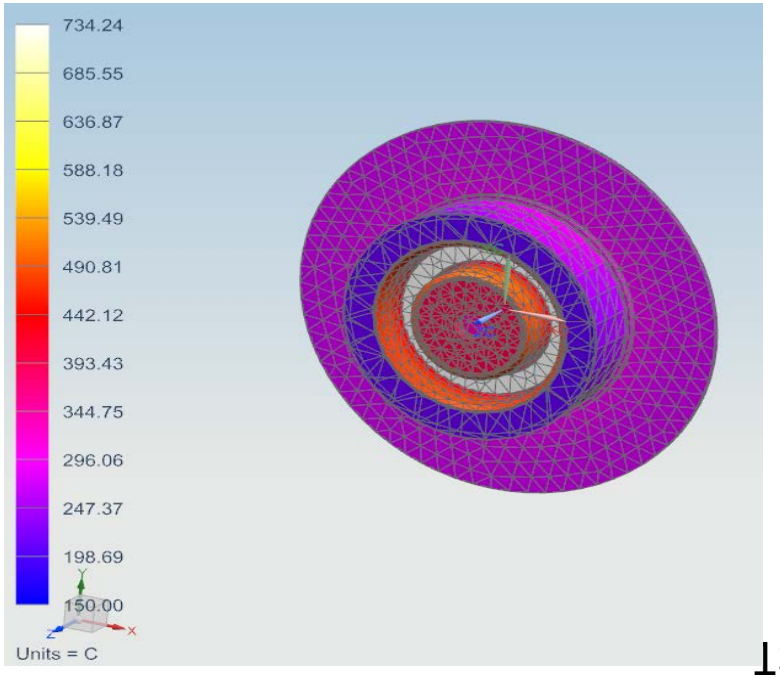
Node	GRC Test Data [°C]	JPL TMM [°C]	$T_{Test} - T_{JPL\ TMM}$ [°C]
Discharge Channel (avg)	540	524	16
Inner Coil – UP	356	360	4
Outer Coil - UP	257	256	1
Radiator OD	233	228	5
Backpole Inner	309	320	11

- JPL TMM predictions within 20°C of GRC test data, generally
  - Seems like big offset, but correlation done almost blind (all testing at GRC)
  - Many property values intuited since thruster is such a complex system
  - Also some issues with test consistency
  - Hope to shrink 20°C offset with 2016 JPL testing
    - Should yield better control over TMM variables and known test TC locations

Environmental Test Profile

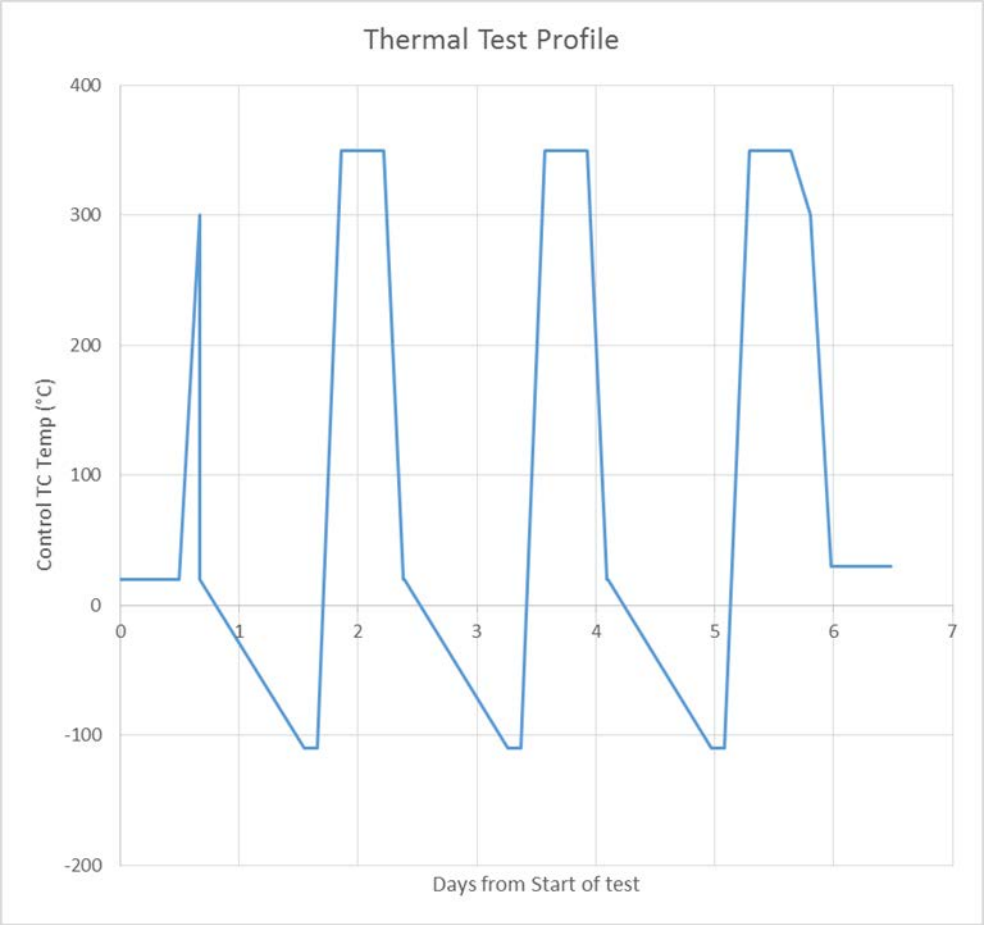
- Environmental test based on thruster temperatures at 0.8 AU
- Validated model used to predict temperatures in space environment at 0.8 AU
  - Resulted in control tc temperature of approximately 350°C, ~22°C > thruster at same firing condition with no environmental loads
  - Model used to estimate lamp power required to drive to elevated temperature and predict final temperature of thruster when shroud cooled with LN2 (garage door closed)
  - Environmental loads fed into transient model to predict thruster behavior





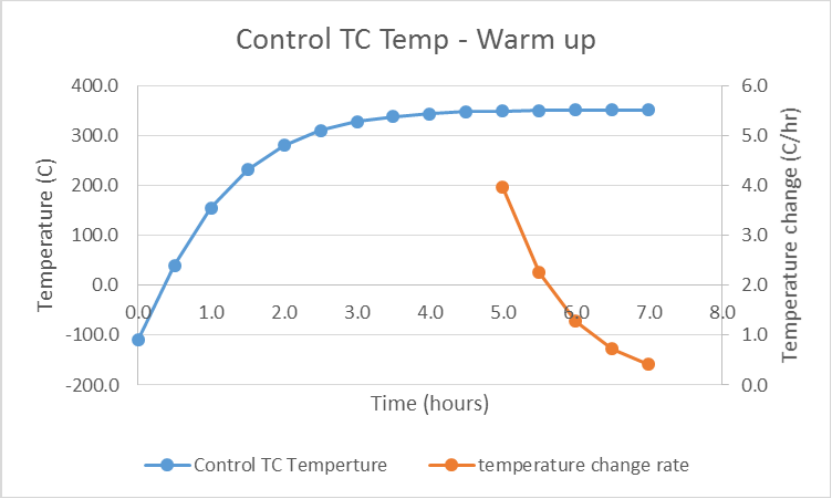
Environmental Test Profile

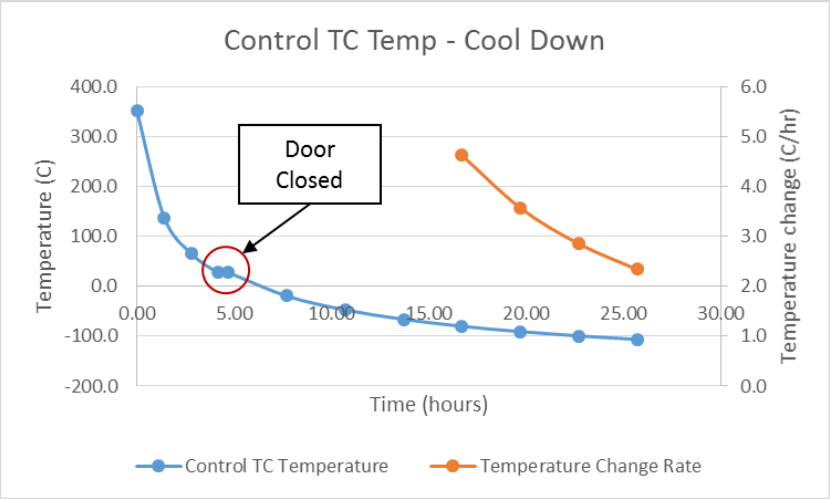
- Determining environmental loads lead to the development of the Environmental Test profile
- Three thermal cycles preceded and concluded by a functional test
- Thermal cycle includes a cold start at cold environment, hot soak at hot environment, and a hot start from the hot environment
- In order to speed cooling, after shroud is flooded with LN2, garage door is left open until thruster temperature approaches sink temperature, then closed so that the sink doesn't heat thruster



Transient Prediction results

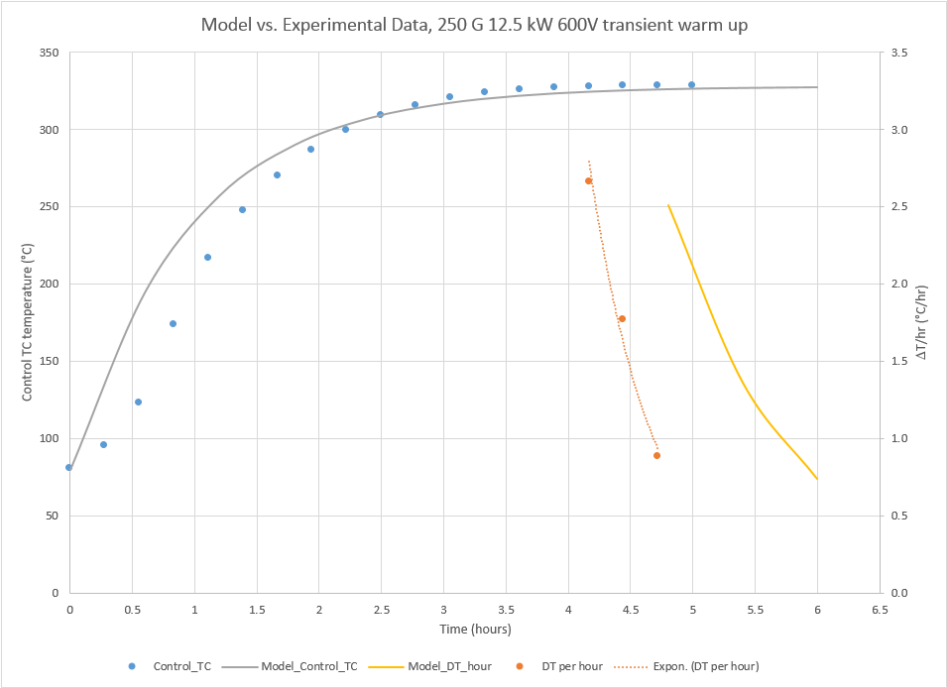
- Transient results show that thruster warms up in approximately 5.5 hours and takes more than 27 hours to cool
- Steady state is assumed to be $\Delta T<2°C/hr$
- Hot soak temperature is 352°C
  - Lamp power is automatically controlled to maintain this temperature at hot soak
- Cold soak minimum temperature is -120°C
  - Lamp power is applied to maintain thruster temperature above this temperature
- Cooling is primarily radiation driven, which leads to slower predicted cooling time
- Note that thruster is not quite at steady state when thruster reaches -120°C, implying survival power will be needed





Preliminary Results: Model vs. Experimental

- Preliminary results have been obtained by running a thruster functional test (no environmental loads) to thermal steady state and seem to agree well with model prediction
- Prediction within 2°C of steady state temperature of control TC
- Transient model over predicts steady state time by approximately 45 minutes
- However, model used two simplifications
  - Initial temperature uniform at 81°C, in reality other thruster components warmer
  - Assumed constant power, in reality power was ramped up from 0 to 12.5 kW in stages



Future work and Conclusion

Future work

- Preliminary results are encouraging but the real work is just beginning
- Conduct environmental test
- Use environmental test data to finish validation of HERMeS TDU-2 model

Conclusions

- **Goal:** Use a validated steady state model to predict the transient response of the HERMeS Thruster under environmental testing
- A model and the methodology for validating it was presented using data obtained by GRC
- The validated model was used to predict the steady state behavior of the thruster in flight at 0.8 AU to inform the environmental loads needed for a terrestrial environmental test
- Model with environmental loads used to predict transient performance of thruster during environmental test
- Model results compared with preliminary results from first functional test of TDU-2 at JPL
  - Model compares favorably with experimental data

Backup Slides

Transient Prediction Results

- Bulk of heat into thruster is plasma loading and majority of heat is radiated to environment by discharge channel/anode

Thruster Heat Loads	Power (W)
Plasma Loading	1732
Inner Coil	83
Outer Coil	71
Heat Dissipation to environment	**Power (W)**
Discharge Channel/anode	-751
Inner & outer front pole	-229
Outer Guide	-193
Radiator	-479
Mount Spool	-66
Heat Conducted to mount	**Power (W)**
Mount Spool	-168

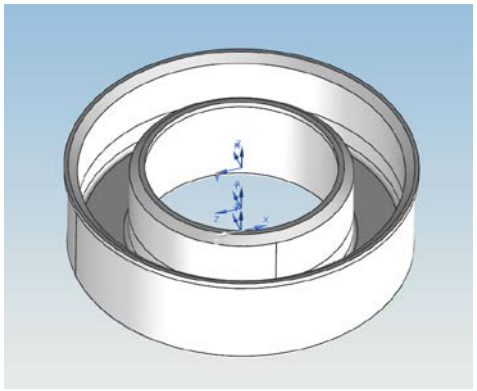
References

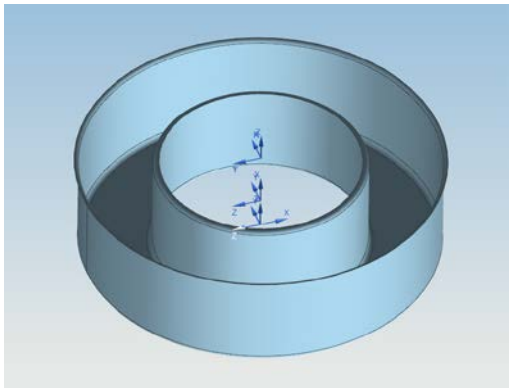
- [1] https://en.wikipedia.org/wiki/Hall_effect_thruster
- [2] https://en.wikipedia.org/wiki/Specific_impulse
- [3] http://www.rocket.com/article/aerojet-rocketdyne%E2%80%99s-modified-xr-5-hall-thruster-demonstrates-successful-orbit-operation
- [4] http://pepl.engin.umich.edu/thrusters/X3.html
- [5] http://www.space.com/28732-nasa-dawn-spacecraft-ion-propulsion.html
- [6] http://dawn.jpl.nasa.gov/mission/ion_prop.asp
- [7] http://www.nasa.gov/centers/glenn/technology/Ion_Propulsion1.html
- [8] Hofer, R. et al. 2012. "Design of a Laboratory Hall Thruster with Magnetically Shielded Channel Walls, Phase II: Experiments". Proceedings of 48th AIAA/ASME/ASEE Joint Propulsion Conference. AIAA 2012-3788

HERMeS Modeling Approach/Issues

- Began modeling thruster natively in NX-SST last April
  - NX-SST advantages
    - NX captures thruster's 3D effects easier (e.g., heat sink) + CAD geometry in NX
    - Easier to work with heat flux distributions in NX
    - Meshing, importing geometry and setting up radiation requests is very intuitive
  - NX-SST drawback
    - Had to add in additional meshed surface to simulate MLI or surface with different optical properties on various sides (e.g., discharge channel)
    - Time consuming switching changing model settings to different magnetic field strengths (case manager in TD is superior in this regard)
    - Longer run times (~25 min NX vs. ~1 min in TD)

Discharge Channel - Solid

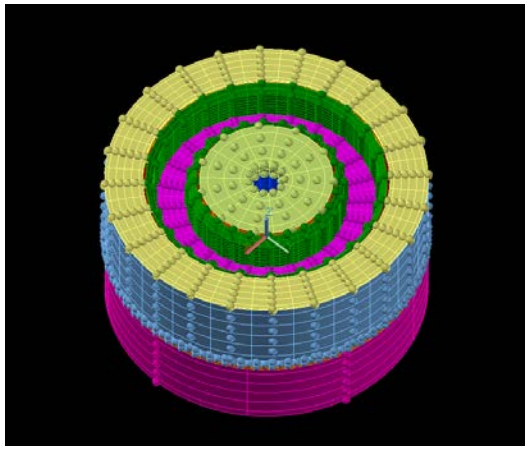




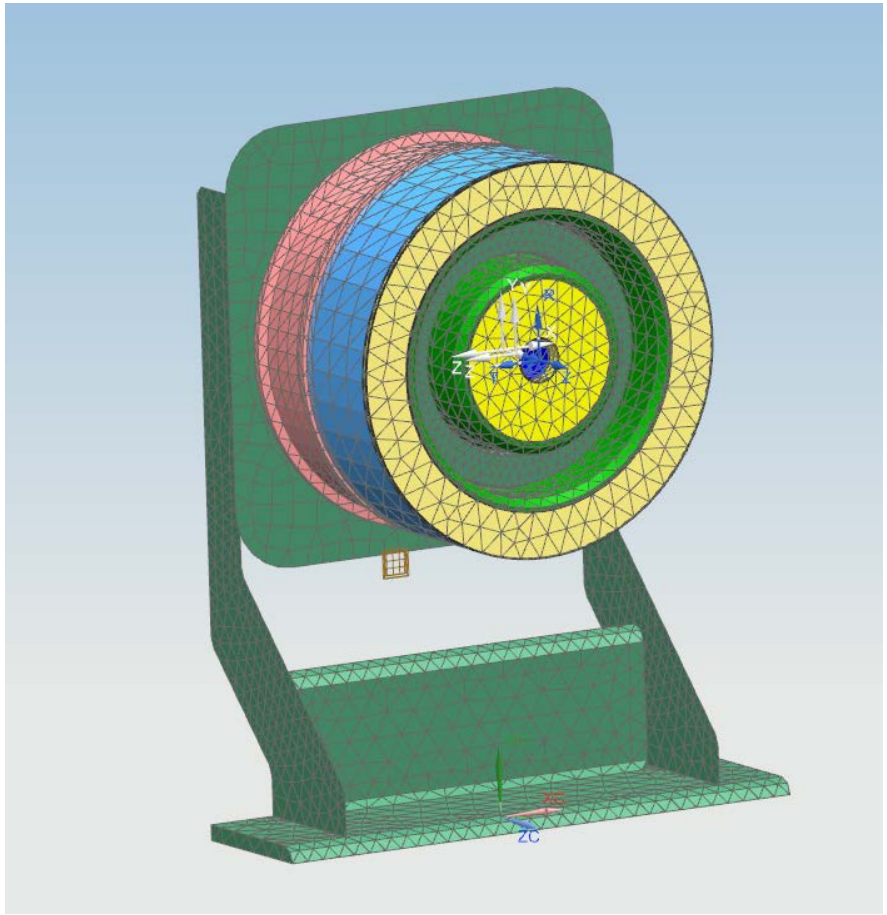
Discharge Channel – Interior facing surface

NX-SST Thermal Model

- Comparison images of two models (radiator plate removed)
- Note increased elements in NX as well as addition of test stand
- EP engineers are concerned about test stand temperatures since heat soak-back into bus is a big concern



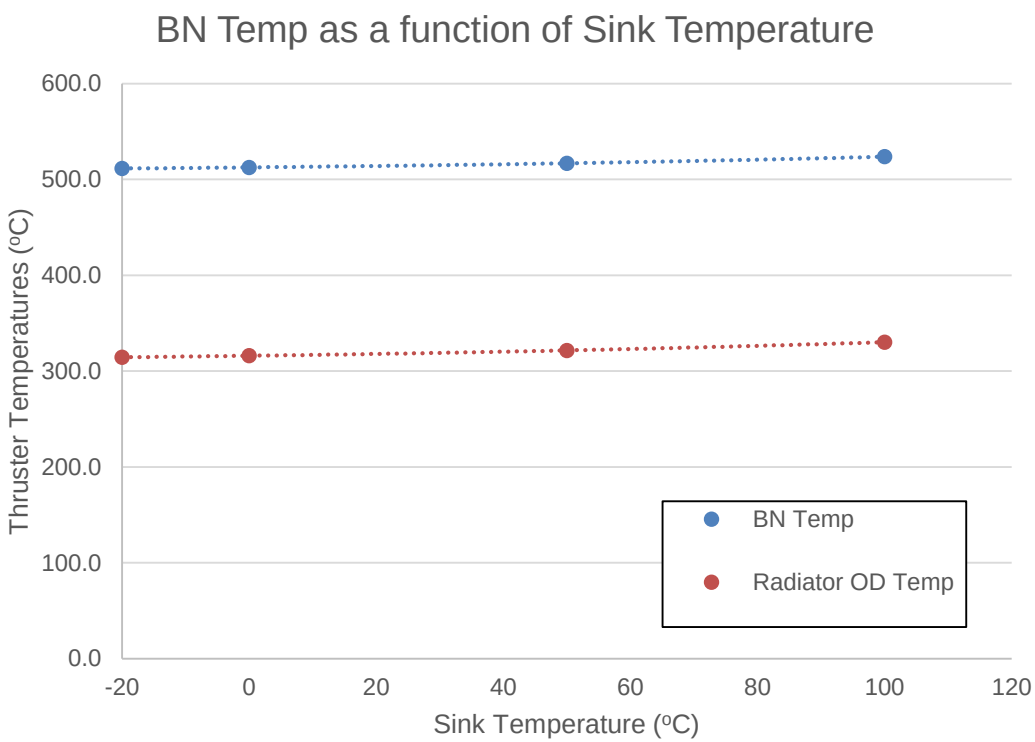
TD model (04.2015)



NX SST model (07.2015)

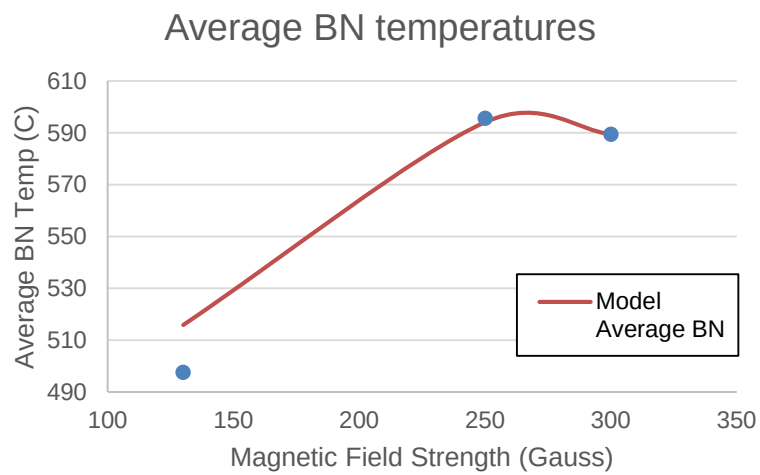
Sensitivity To Sink Temperature

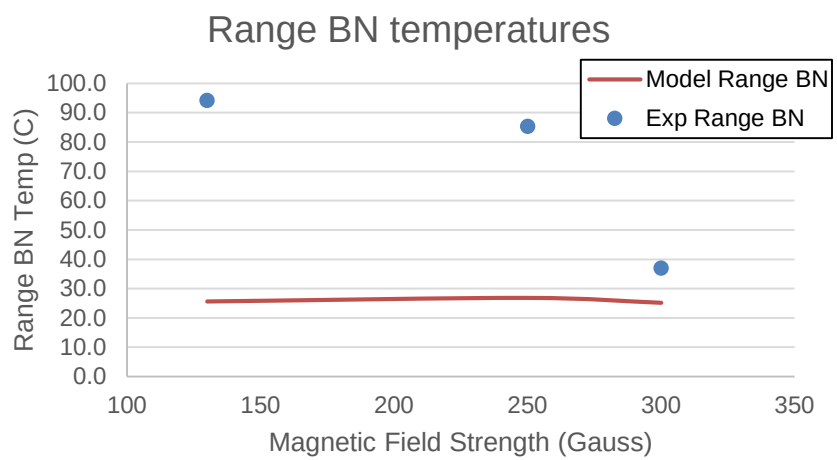
- Model assumes a uniform sink surrounding the thruster
- Varied Sink temperature to assess thruster temperature sensitivity to sink temperature
  - Discharge Channel temperatures not very sensitive to sink temperature
  - Increasing sink temperature from -20 C to 100 C results in only a 13 C increase in average discharge channel temperatures



Modeling Results – Discussion, BN

- Key observations
  - Average BN temperatures vary most from experiment in the 130 Gauss case
    - Almost 500W less than other 2 cases
  - Experimental BN Temp ranges MUCH higher than model prediction, also a strong function of magnetic field strength
    - Model predicts fairly constant temperature gradient across BN
    - Likely due to heat load distribution being mostly constant





Average BN Temps

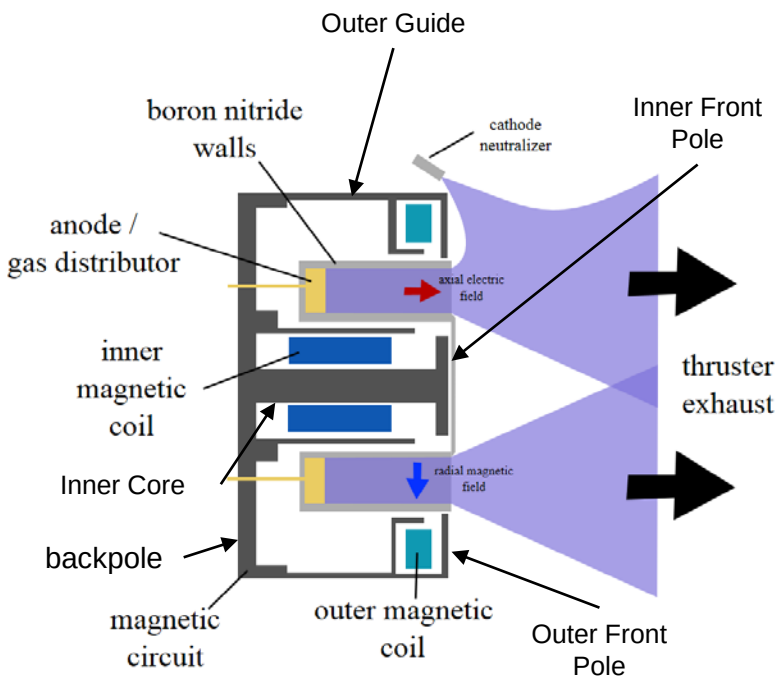
497.6	130 average measured BN
515.8	130 average model BN
595.5	250 average measured BN
594.2	250 average model BN
589.4	300average measured BN
589.5	300 average model BN

BN Temp ranges

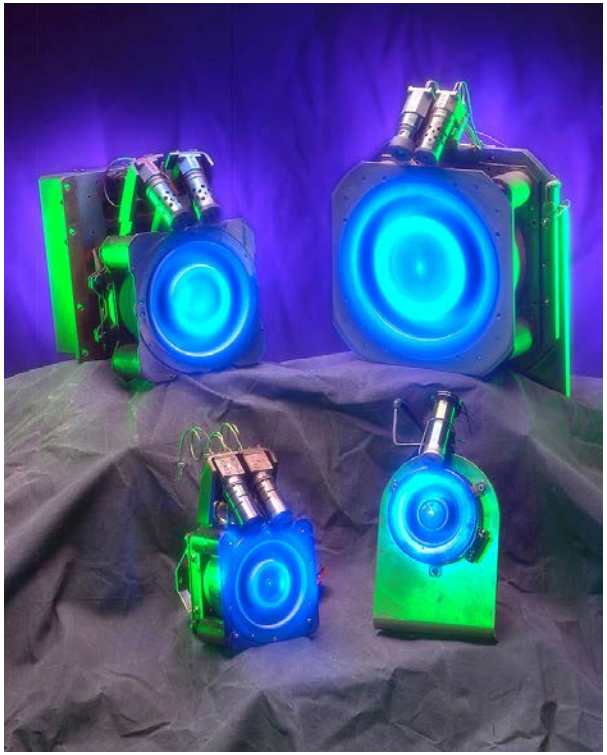
94.2	130 measured range BN
25.2	130 model range BN
85.4	250 measured range BN
26.8	250 model range BN
37.0	300 measured range BN
25.6	300 model range BN

What is a Hall thruster?

- Hall thruster is simply an ion engine, electric (or magnetic) field + xenon
  - Generates thrust by accelerating charged particles (ions)
  - Ions are accelerated in electric field



Cross section, Hall thruster

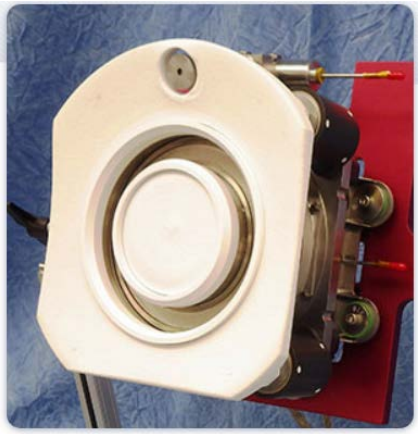


Soviet Hall Thrusters

Characteristics of Ion engines

- Ion engines are low thrust by definition
  - Supplies 40-600 mN thrust (weight sheet of paper)
- High specific impulse
  - ~1600 s for Hall thrusters (SSME* only ~450 s)
  - For rockets, specific impulse defined as exhaust velocity divided by Earth gravity
  - Hall effect exhaust velocities ~ 29,000 m/s (SSME 4423 m/s)
- Discharge (relatively) enormous electrical power
  - Up to 100 kW
- Discharge of long time scales, relative to chemical rockets
  - 50,000 hrs vs. a few minutes

UM PEPL X-3

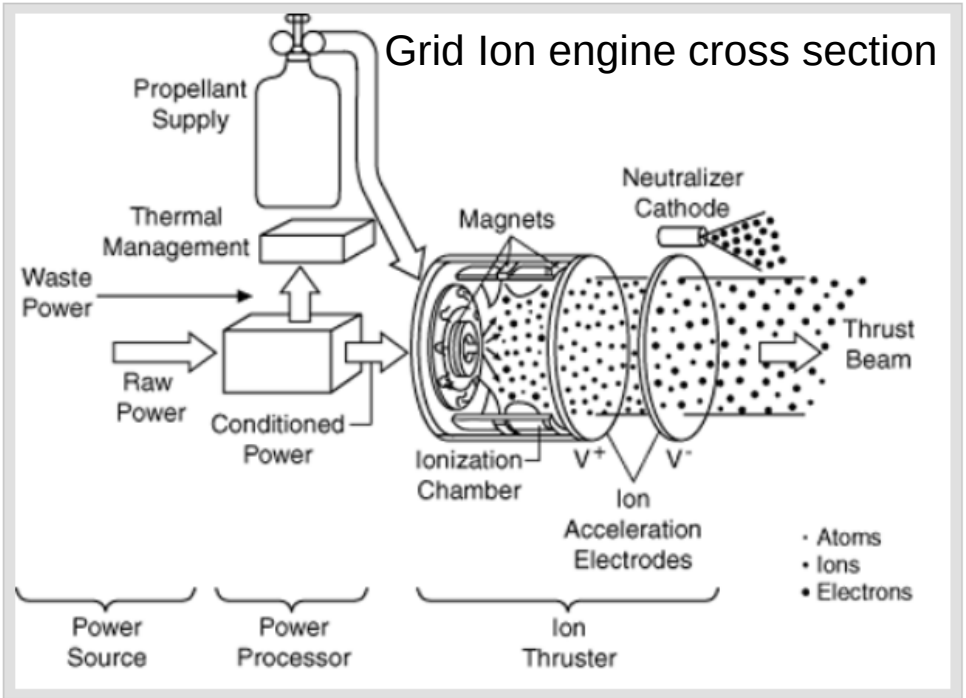


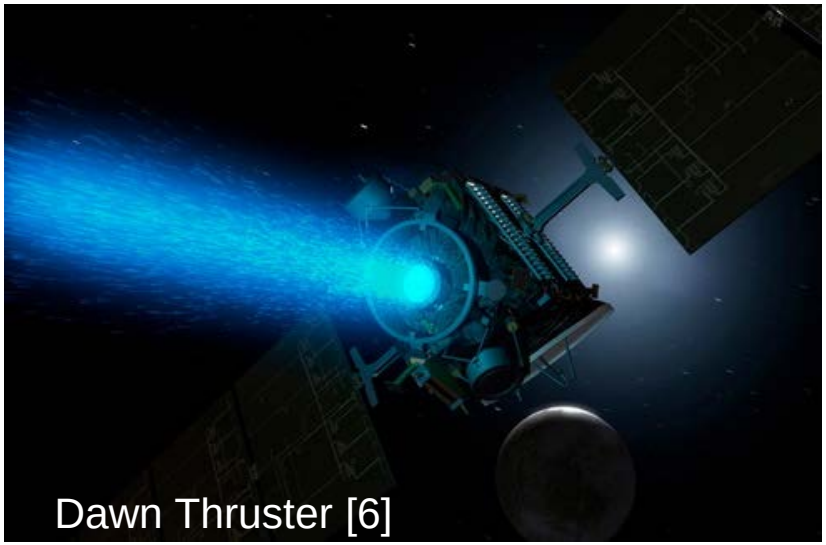
Rocketdyne XR-5

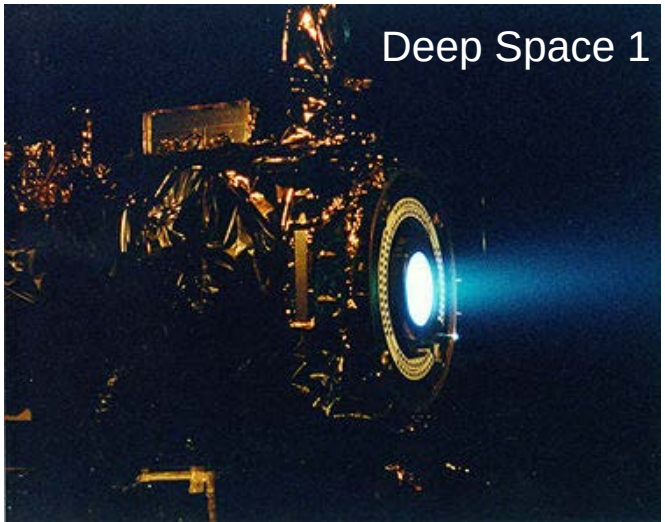
* SSME = Space shuttle main engine

Flight Heritage

- NASA flew ion engines with screen cathode, no Hall thrusters yet
  - NM Deep Space 1 (1999-2001 mission)
  - Dawn (2007-present)
- Soviets used them for long time
- ESA SMART-1 (2003-06, moon)
- JAXA Hayabusa (2003-10, asteroid)

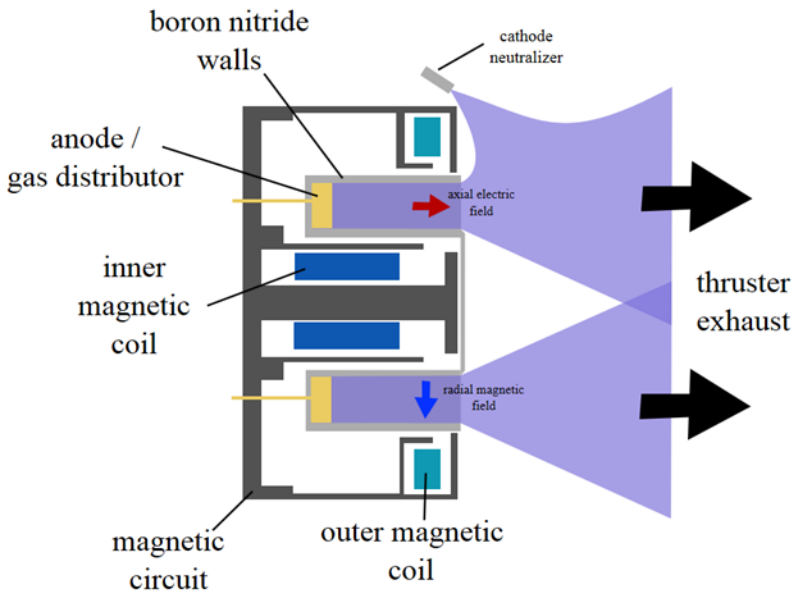




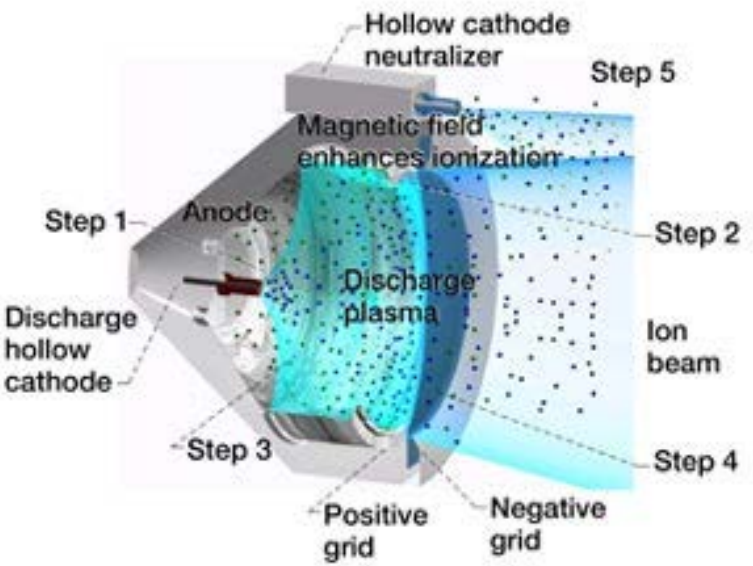


So Why Hall Thruster?

- Why do we care about Hall thrusters if we're already flying successful gridded ion thrusters?
  - Name of the game in ion engines is extending lifetime
  - Grids damaged over time by high energy particles, unavoidable degradation
  - Even generic Hall thrusters are subject to this damage
- What if we could get around this problem?



Grid Ion engine cross section



Grid Ion engine cross section

Why does a thermal engineer care?

- JPL is aggressively pursuing Hall effect thrusters for future missions
  - HERMeS (Hall Effect Rocket with Magnetic Shielding) on ARRM (12.5 kW)
  - Several mission proposals included Hall effect thrusters (4 of 7? past yr)
  - Big push to get these engines rated for deep space missions NASA in general is very interested in this technology
  - JPL proposed plan for human exploration of Mars includes Hall thruster powered cargo tugs making regular trips to Mars to supply missions
- These thrusters and their associated issues could start popping up all over the place on future missions
- <u>Maintaining appropriate temperatures is crucial for ensuring thruster operation on long duration missions</u>