ITERATIVE METHOD FOR THERMAL MODELING OF HALL THRUSTERS GUIDED BY HIGH FIDELITY PLASMA SIMULATIONS

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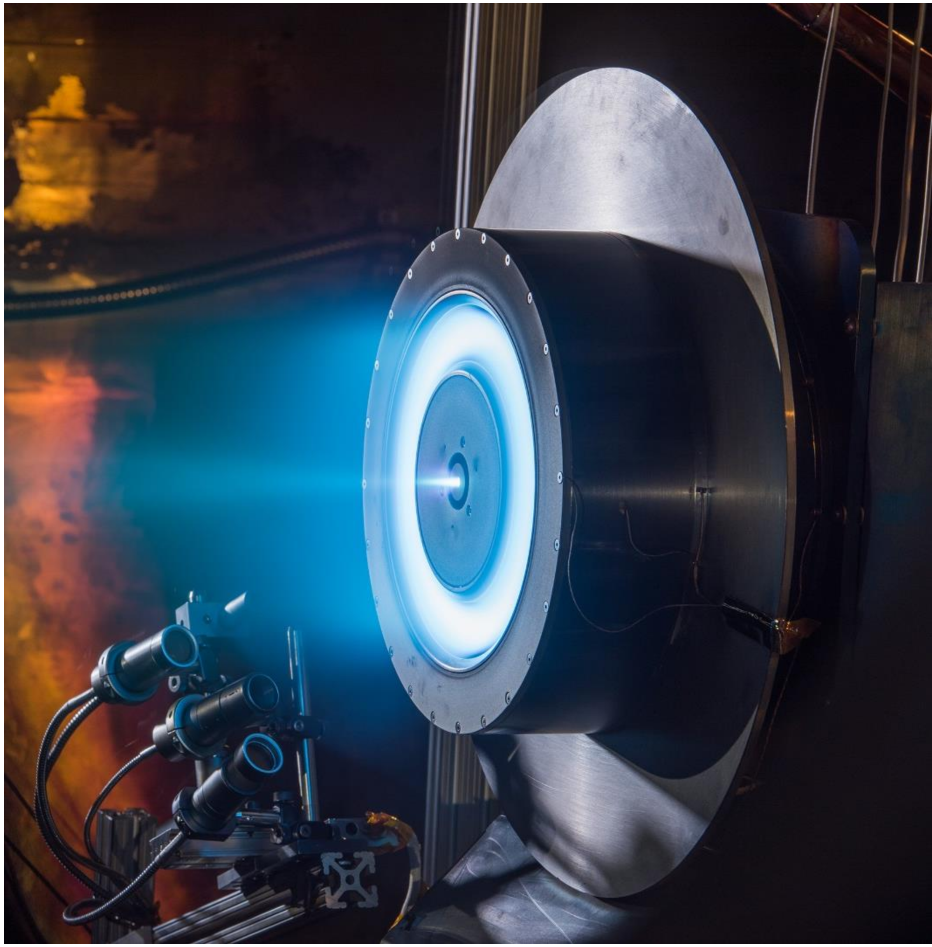
Outline

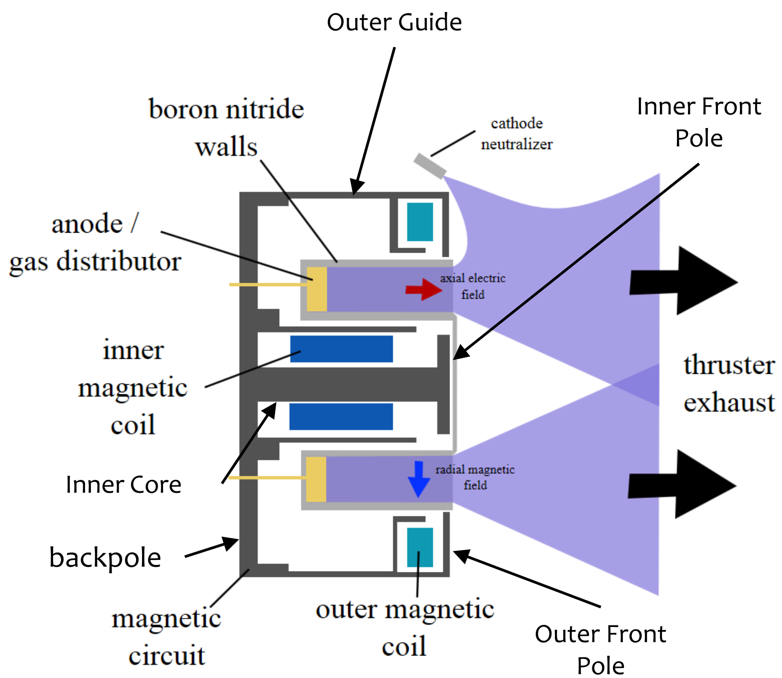
- What is a Hall Thruster?
  - What is an ion engine?
- Characteristics of Ion engine
- Flight Heritage
- So why Hall thruster?
  - Why hall current is important?
- Why does a T/E care?
- Thermal issues
  - High discharge channel temperature
  - Contact conductance issues
- Future work/conclusions



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

What is a Hall thruster?

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



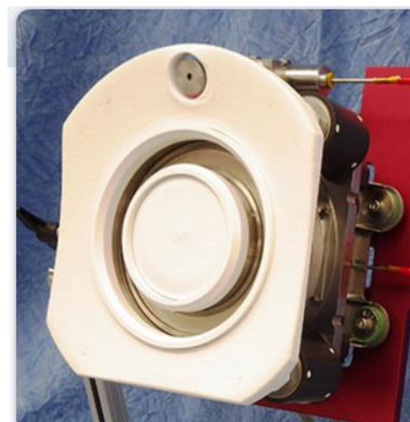
Cross section, Hall thruster

Soviet Hall Thrusters

Characteristics of Ion engines

- Ion engines are low thrust by definition
  - Supplies 40-600 mN thrust (weight of a sheet of paper)
- High specific impulse
  - ~1200-3000 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)
- Relatively high electrical power consumption
  - 10’s to 100’s of kW
- Long operation time scales, relative to chemical rockets
  - 50,000 hours vs. a few minutes

UM PEPL X-3

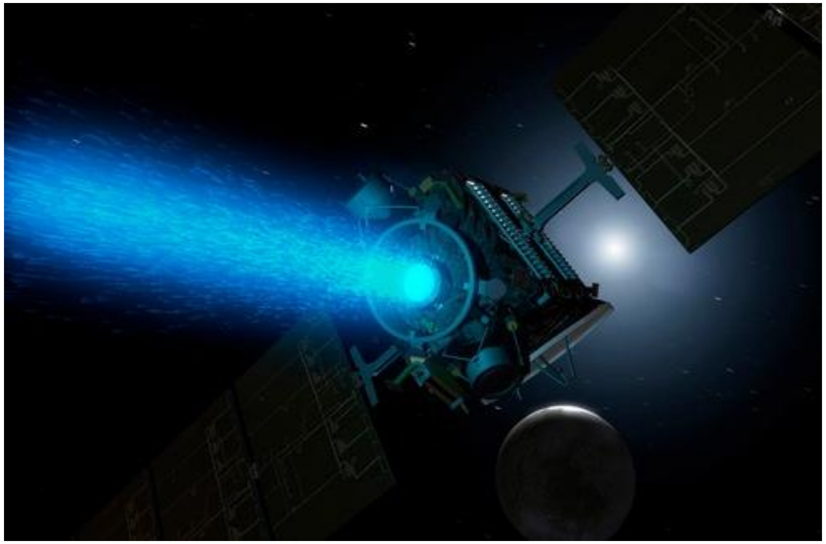


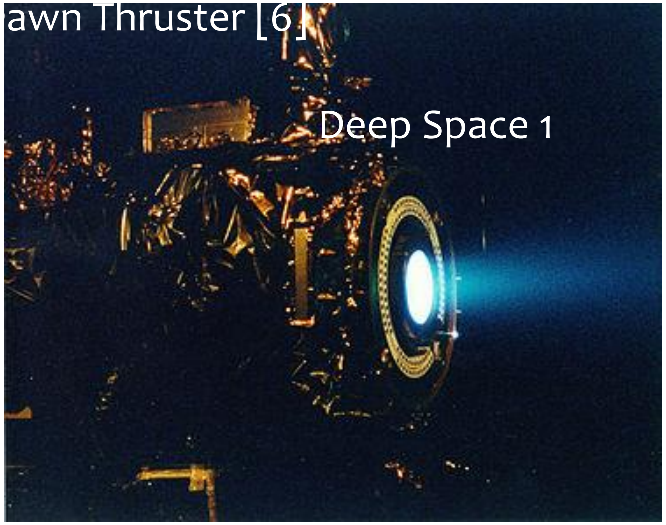
Rocketdyne XR-5

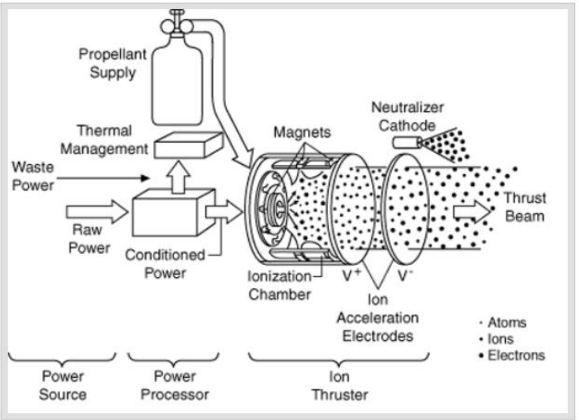
* SSME = Space shuttle main engine

Flight Heritage

- NASA flew ion engines with screen grids, no Hall thrusters yet
  - NM Deep Space 1 (1999-2001 mission)
  - Dawn (2007-present)
- Soviets have used hall thrusters
- ESA SMART-1 (2003-06, moon)
- JAXA Hayabusa (2003-10, asteroid)
- Used on commercial and military satellites for decades





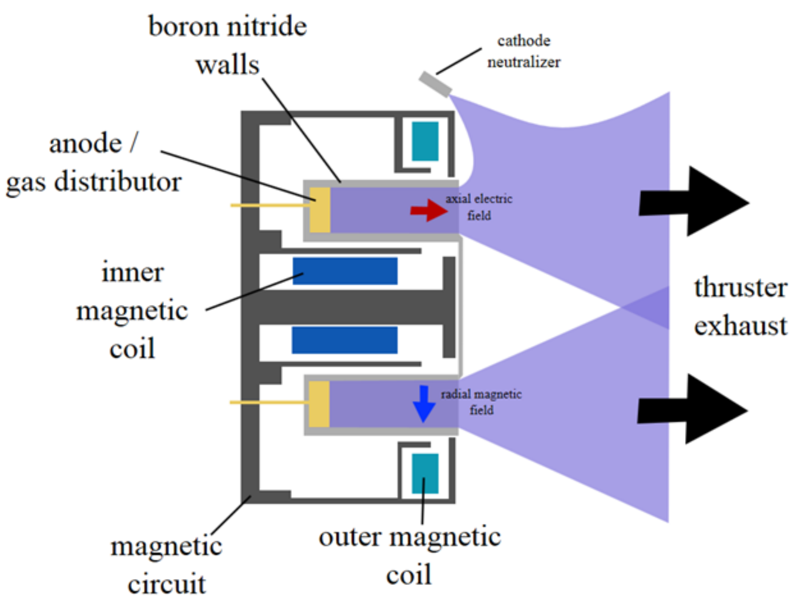


JPL Current/Future Work

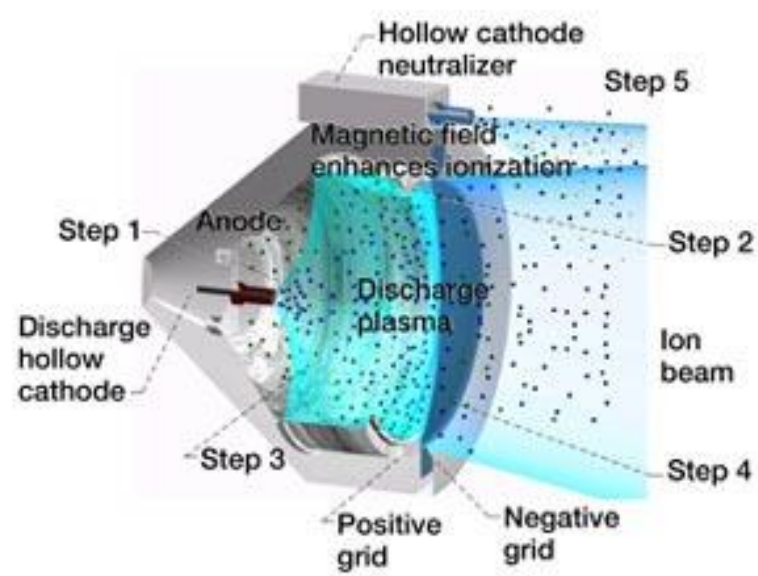
- 100 kW XR-100 system, X3 thruster (w/ Aerojet/U Michigan/AFRL)
  - 3 channel nested thruster
  - Each channel's plasma and magnetic fields impact each other
- 0.325 kW MASMI
  - Small size creates unique challenges
- 12.5 kW HERMeS (w/GRC and Aerojet)
  - Hardware now being developed for ARRM, trying to get it flight qualified presents extra set of challenges

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 mitigate this problem?



Hall Thruster cross section



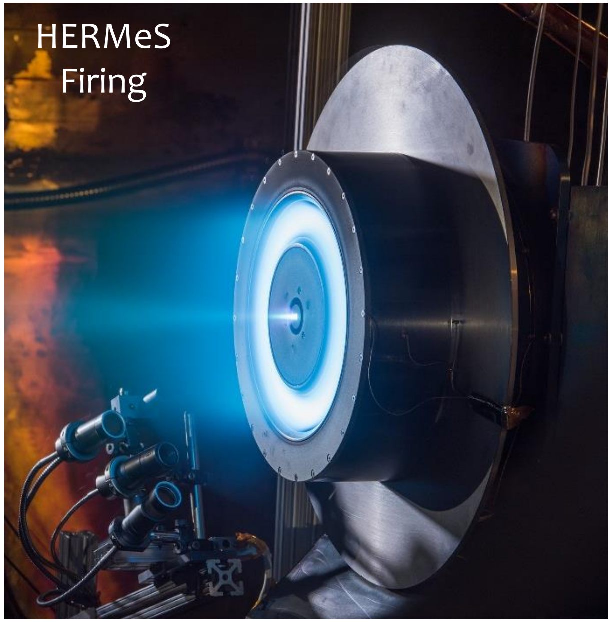
Grid Ion engine cross section

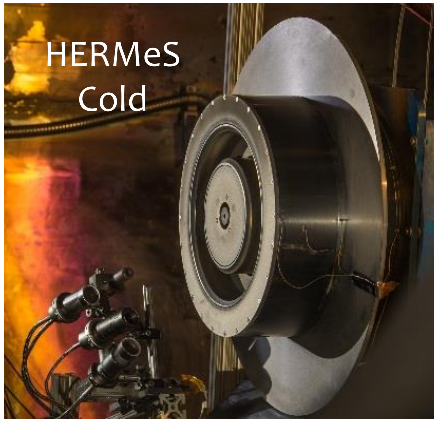
Why does a thermal engineer care?

- NASA and JPL are aggressively pursuing Hall effect technology for future missions
  - HERMeS (Hall Effect Rocket with Magnetic Shielding) proposed for 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 mission concepts for NASA in general is very interested in this technology
  - JPL "minimal architecture" concept for human exploration of Mars includes Hall thruster powered cargo tugs making regular trips to Mars to supply missions
  - JPL has been pursuing the use of commercial Hall thruster systems since 2006
    - The recently selected Discovery mission proposal Psyche would use 4.5 kwW SPT-140 Hall thrusters
    - Many more proposals for competed missions in the works
- <u>Maintaining appropriate temperatures is crucial for ensuring thruster operation on long duration missions</u>

Thermal Issues – High Temperatures, Unknown Limits!

- Large plasma loads (~8-9% of total discharge power deposited as heat load) on thruster during typical firing condition





High-Temperature Effects – Discharge Channel

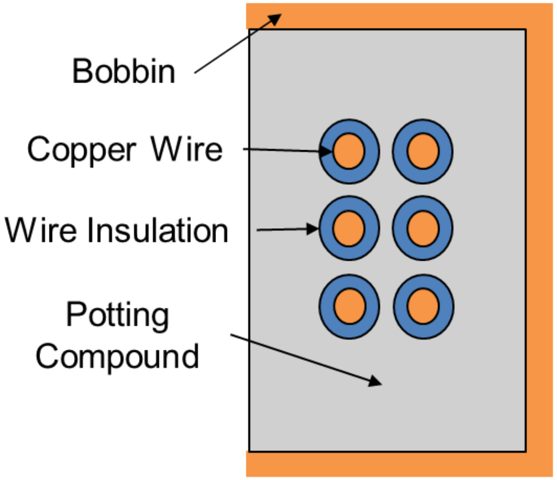
- Hottest component measured is generally discharge channel
  - Anode does not have probes but is hotter (viewed using IR camera)

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

- Discharge channel is mated to thruster body 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 are 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

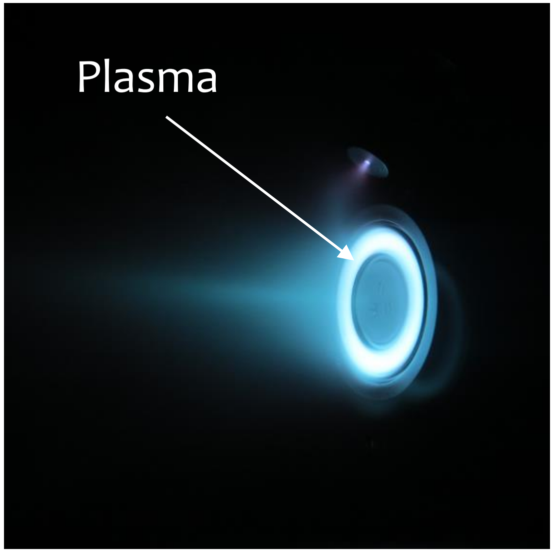
Thruster Modeling Approach

- Plasma Heat Flux distribution is a complicated function of temperature, thruster voltage, magnetic field strength, Xenon flow rate
  - Primarily T/E will see heat flux as a function of mag. field str, $f(B_{max})$
  - DC: Discharge channel heating from plasma loading (variable parameter)
  - Coil heat load (from experimental values)
- Plasma modeling makes assumptions about temperature, which affect distribution and magnitude
  - Plasma models fed to thermal model, thermal model modulates magnitude of plasma loads, feeds temperatures and multiplier back to plasma model

Thruster Modeling Approach

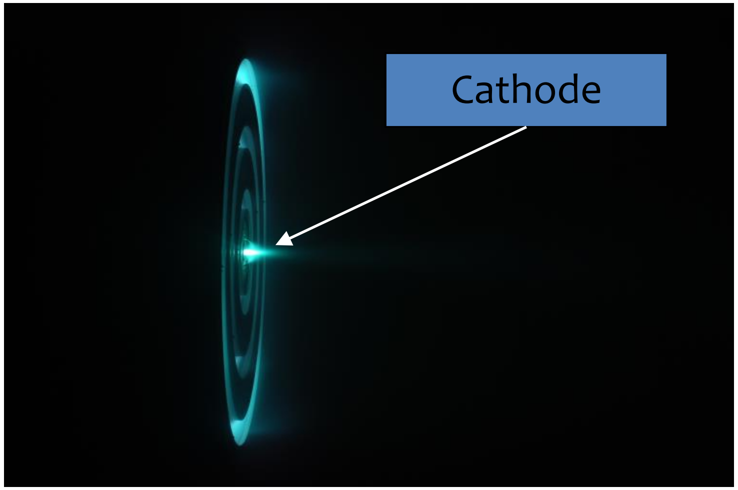
- Plasma modelers provide these distributions and they are based on the test conditions
  - Plasma heat load varies, but typically < ~ 10 % of discharge power

- Used model to iteratively check the magnitude of plasma model profiles to validate plasma modeling

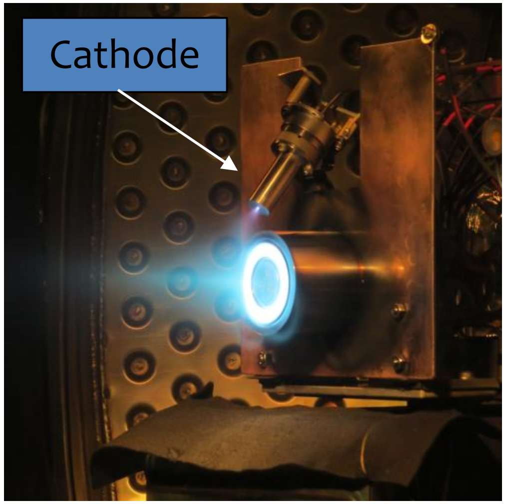


Cathode Examples

- This method is also used for cathode specific modeling
  - Process is really the same, though cathode structure differs slightly from thruster configuration
  - Loads are concentrated in the emitter of the cathode
- Cathode can typically be modeled independently
  - Cathode is designed to contain heat for emission purposes so cross talk between cathode and thruster is generally minimal



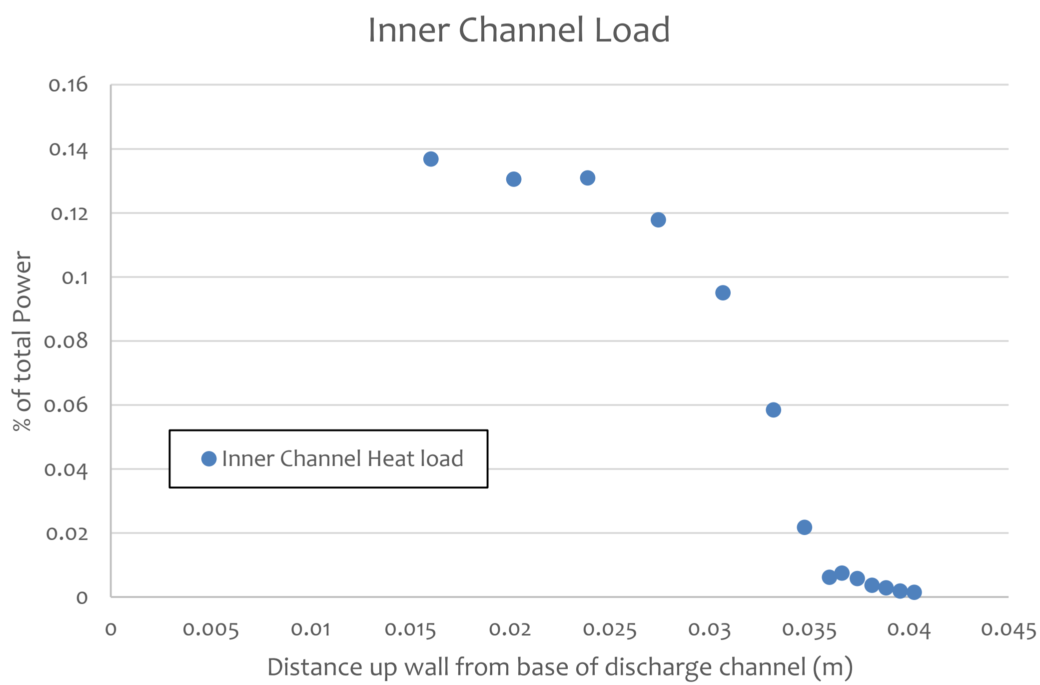
X3

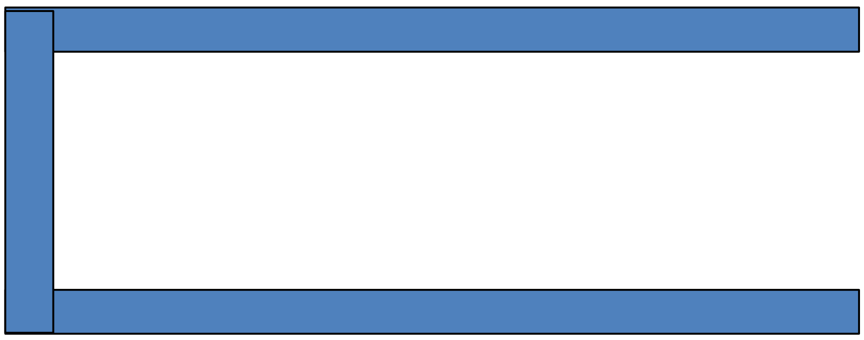


MASMI

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

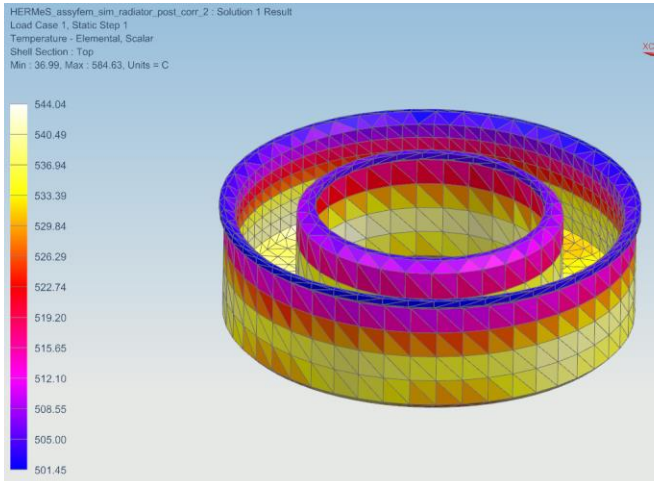




Cross-section of Discharge Channel

Comparison to Plasma Model Distribution

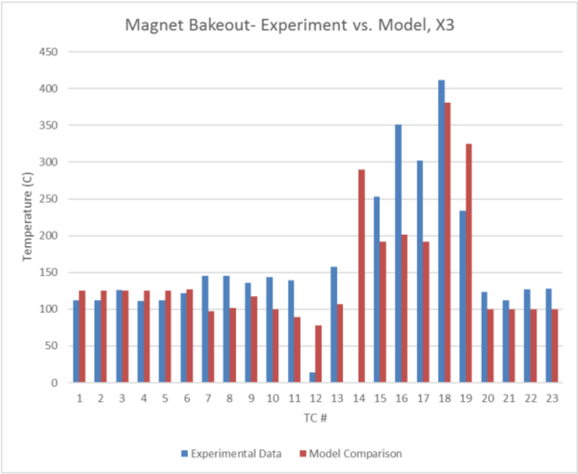
- In general, using full power of calculated distribution is too much heat flux
- Model usually has to be checked across multiple thruster configurations and throttle conditions
- Most cases were correlated to around ~90% of initial plasma model magnitude



Case	Magnitude Multiplier
HERMeS – Radiator	0.92
HERMeS – NO Radiator	0.85

Results of TMM Predictions (HERMeS/X3)

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 average within 30°C of test data generally
  - Dealing with relatively high sustained temperatures
  - Many property values represent best estimates, since thruster is such a complex system
  - Also some issues with test consistency
  - Hope to shrink offset with 2017 JPL testing
    - Should yield better control over TMM variables and known test TC locations

Conclusions (1 of 2)

- Plasma physics is very complicated but building EP thruster model is not as bad
  - Mostly routine except for a few challenges such as exotic materials, discharge chamber heat flux and lots of new EP nomenclature
  - Firing EP thruster (plasma loading) dominates environmental loading
  - Key conduction path via “the stack”: anode/dischge channel/heat sink/backpole/radiator
  - Plasma loads inform the thermal model and the thermal model informs the plasma model until difference are minimal

Conclusions (2 of 2)

- Plasma physics is complicated… (continued)
  - Ensure EP test personnel used flight-calibrated torque wrench at key test I/Fs to achieve advertised joint pressure/contact conductance for used fasteners
    - Because contact conductances are so critical to accurate thermal modeling, it is important to make sure thruster reassembled same way after each disassembly
  - When scoping EP thruster work, determine criticality of plasma loading accuracy and critical component temperature requirements

Questions?
(So long as it's not about plasma physics)

References

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- [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