THERMAL ANALYSIS OF THE 100-KW CLASS X3 HALL THRUSTER

ICES 345

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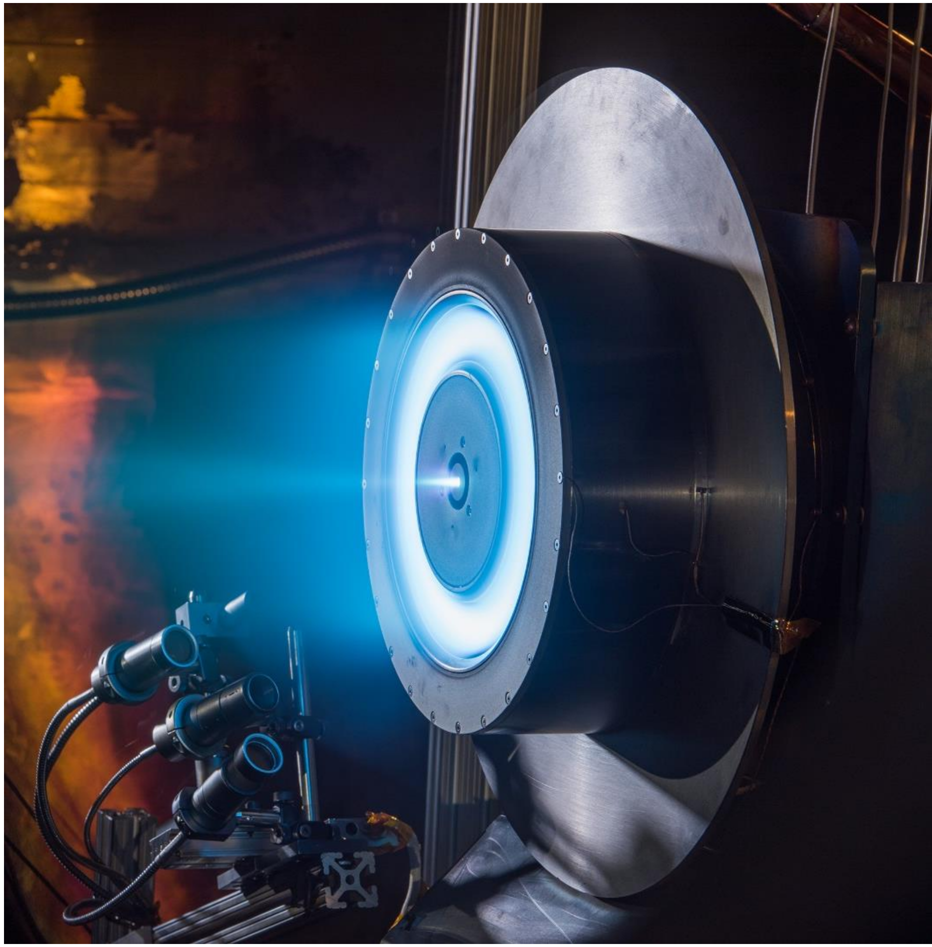
Outline

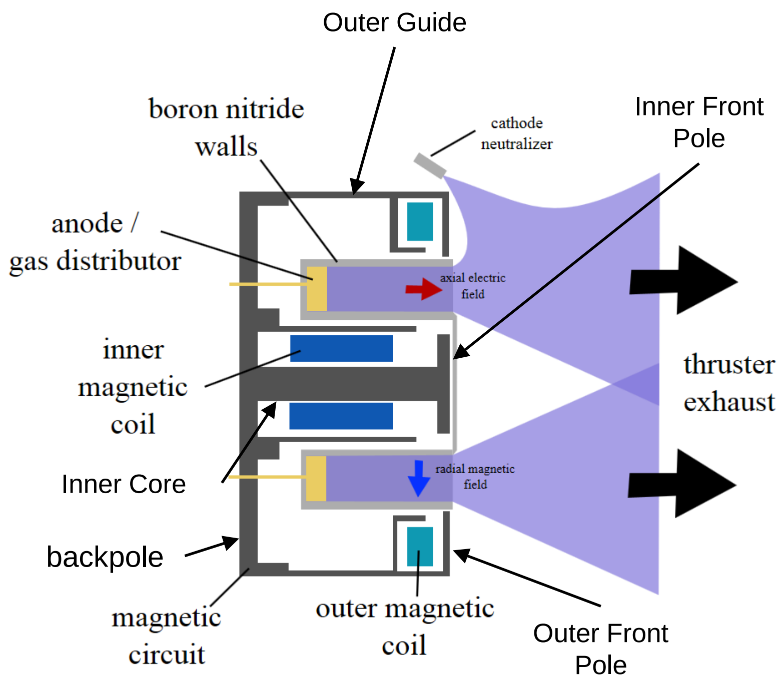
- Goal: Present on the current status of thermal modeling of the X3 thruster
- What is a Hall Thruster?
- Characteristics of Hall Thruster
- Flight Heritage
- So why Hall thruster like the X3 for small body missions?
- Why does a T/E care?
- Thermal issues of the X3
  - High discharge channel temperature
  - Contact conductance issues
  - Configuration
- Future work/conclusions



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

What is a Hall thruster?

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



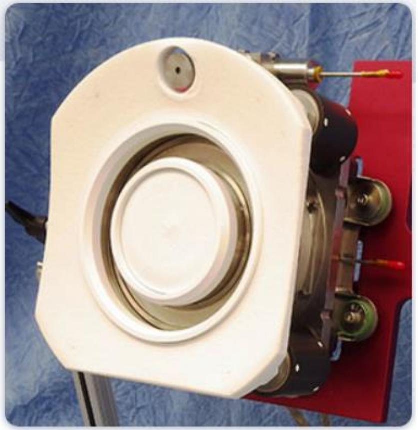
Cross section, Hall thruster

Soviet Hall Thrusters

Characteristics of Ion engines

- Ion engines are low thrust by definition
  - Supplies 40-600 mN thrust (weight 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

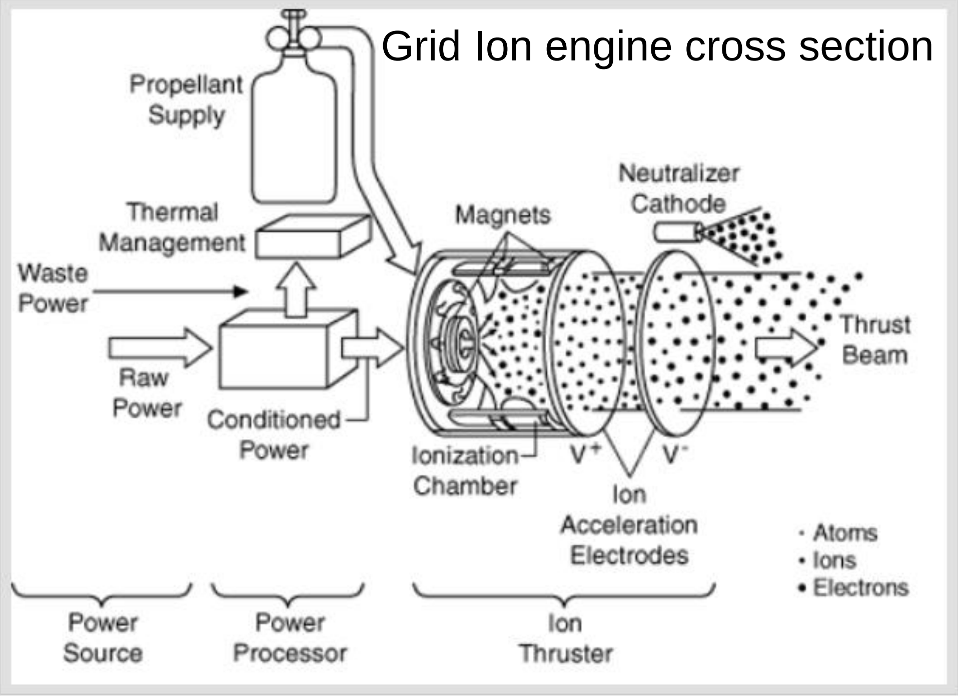
UM PEPL X-3



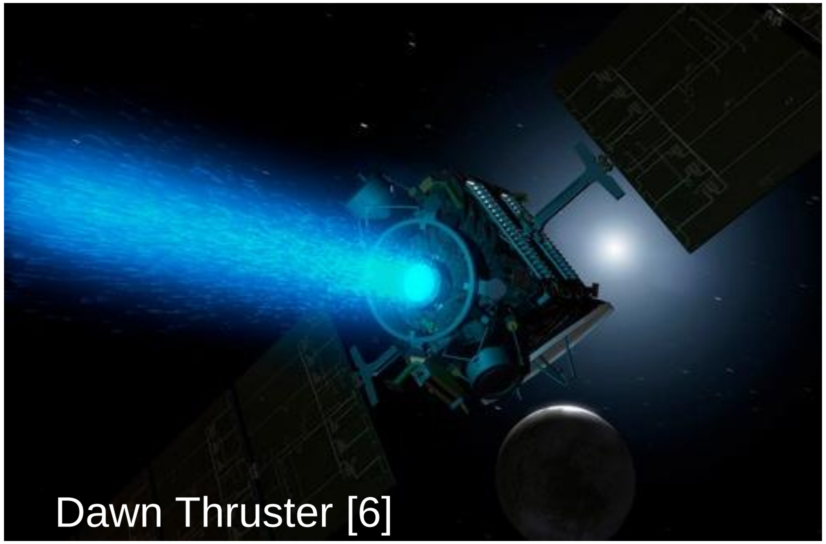
Rocketdyne XR-5

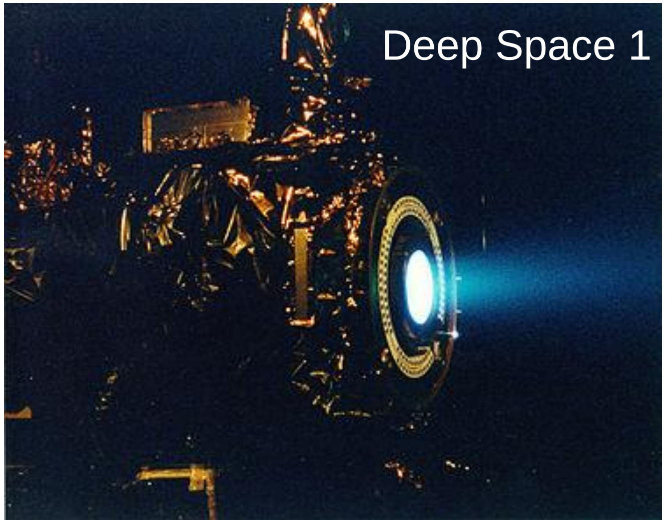
* SSME = Space shuttle main engine

- 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)



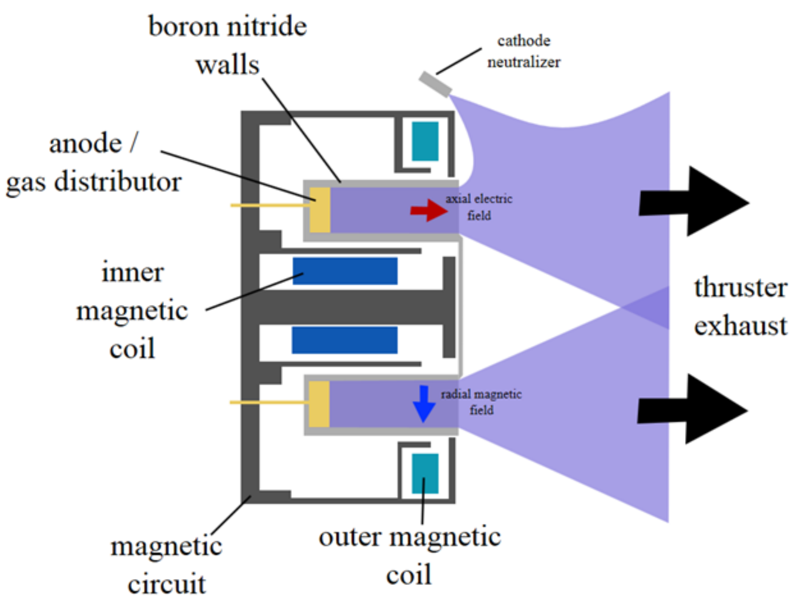
Grid Ion engine cross section


Dawn Thruster [6]

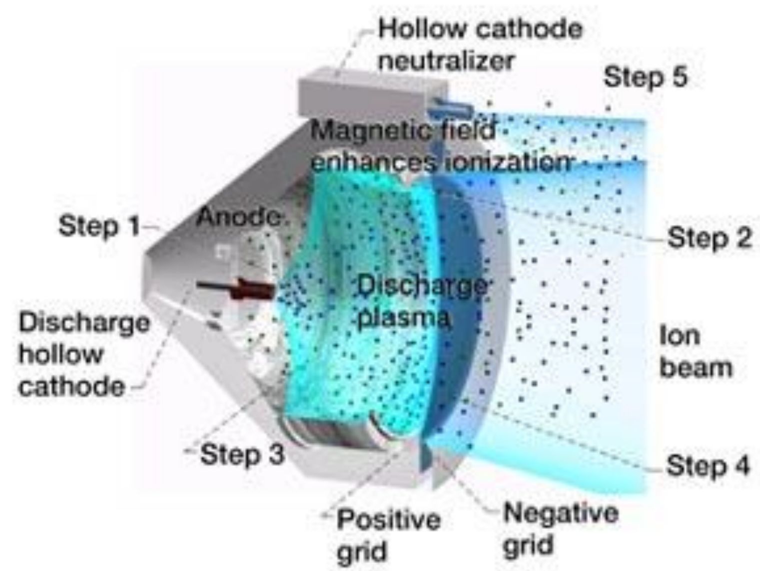

Deep Space 1

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
  - Magnetic shielding has shown promise for extending Hall thruster life



Hall Thruster cross section



Grid Ion engine cross section

Why does a thermal engineer care?

- JPL is aggressively pursuing Hall effect thrusters for future mission concepts
  - DAWN proved the viability of exploring multiple small bodies in the same mission
  - HERMeS (Hall Effect Rocket with Magnetic Shielding)
  - Several mission proposals included Hall effect thrusters
    - Psyche, a recently selected Discovery class mission, uses hall thrusters
  - 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 and sample return
- <u>Maintaining appropriate temperatures is crucial for ensuring thruster operation on long duration missions</u>

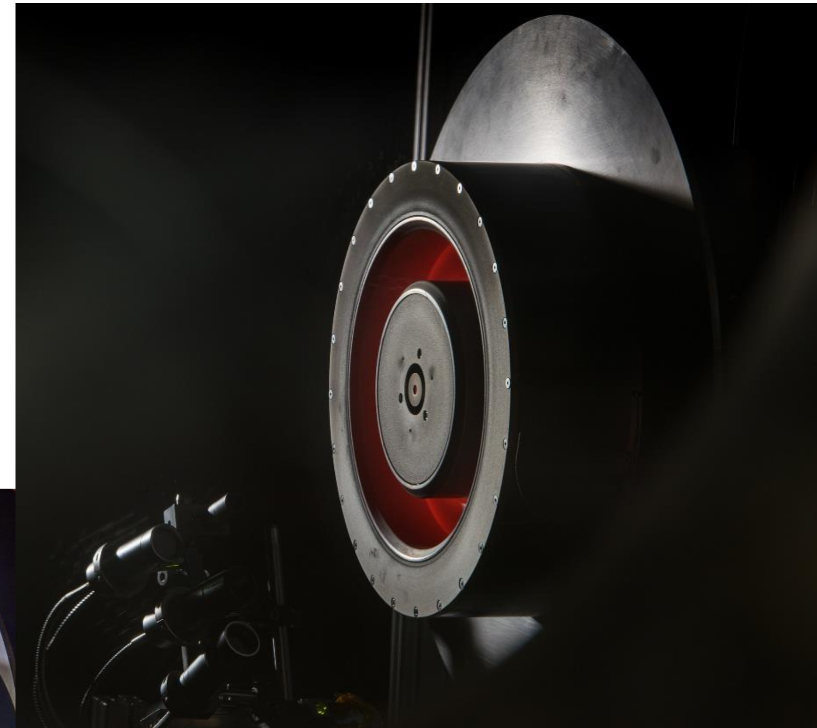
JPL Current/Future Work

- XR-100 system, X3 thruster (this talk)
  - 100 kW, 3 channel nested thruster
  - Each channels plasma and magnetic fields impact each other
  - 3 year research and development project
  - Currently in year 2
  - In year 1, we built a thermal model with data that was obtained before and during Y1
  - JPL did not have control over test parameters for data presented here
  - This presentation details the efforts to this point to build a predictive model of the X3 thruster
  - Limitations on detail available for X3

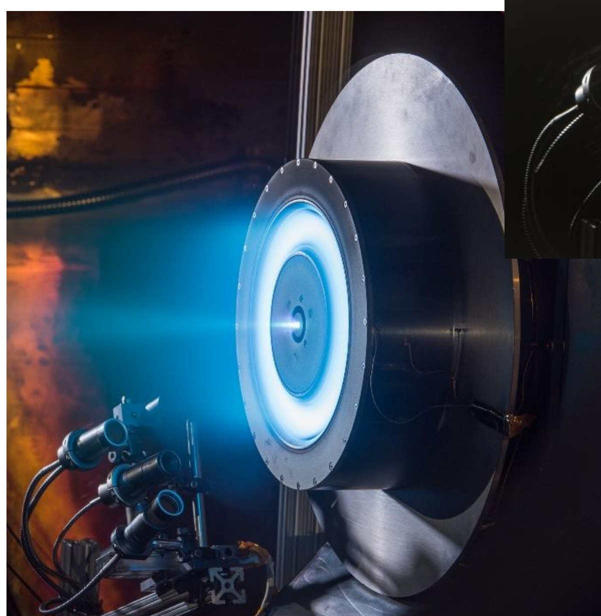
UM PEPL X-3

Thermal Issues – High Temperatures, Unknown Limits!

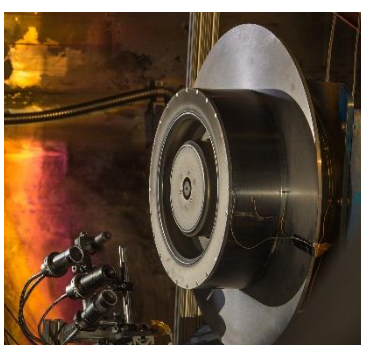
- Large plasma loads (X3~10 kW) on thruster during typical firing condition



HERMeS Shutoff



HERMeS Firing



HERMeS Cold

High-Temperature Effects – Discharge Channel

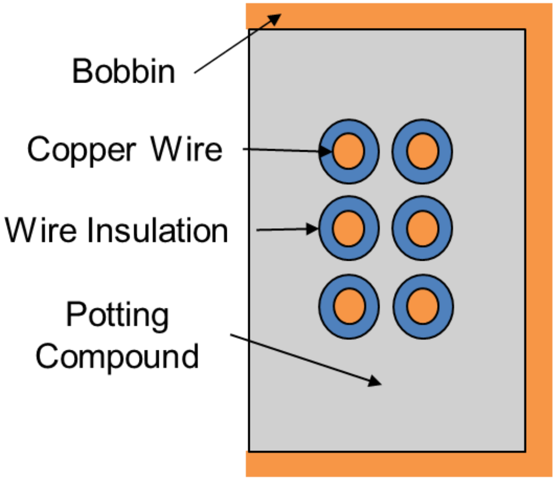
- Hottest component measured is generally discharge channel
  - Anode does not have probes but is hotter (viewed using IR camera)

- Much energy emitted away but some up-stream heat transfer is possible and must be understood

- 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, encased in a potting compound
  - 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

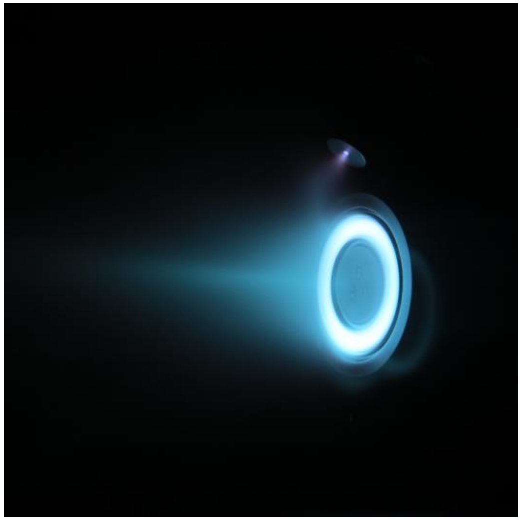
Thruster Modeling Approach

- Plasma Heat Flux distribution is a complicated function of temperature, thruster voltage, magnetic field strength, fuel 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)
  - Cathode: Loading from cathode Spool: Optional parasitic Loss from back of experimental setup, representing loss through thruster mount
- 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
  - Discharge power varies, but +/-~10%-15% of total discharge power

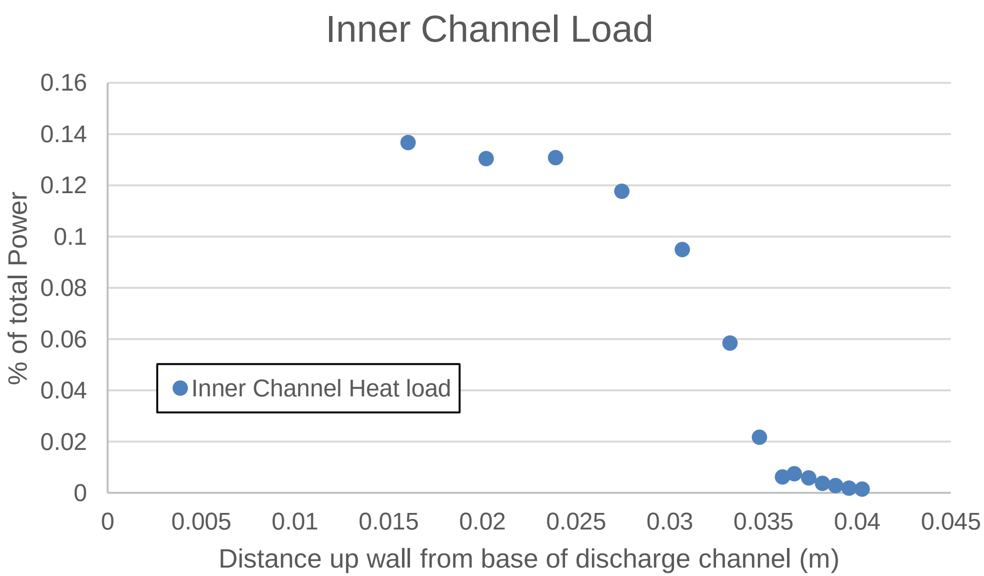
- Used model to iteratively check the magnitude of plasma model profiles to validate plasma modeling

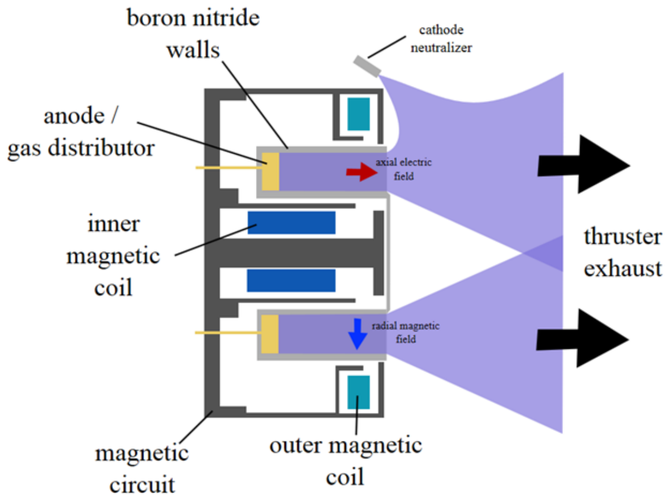


Hall thruster, firing

Discharge Channel 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

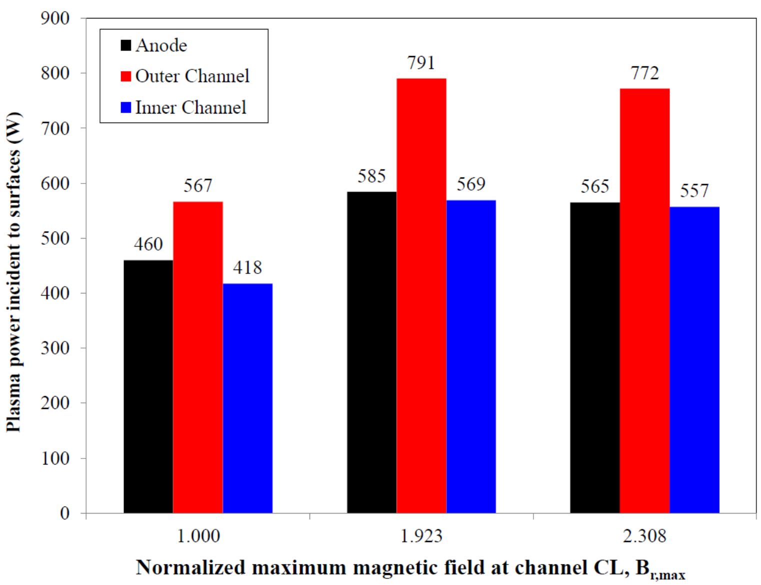




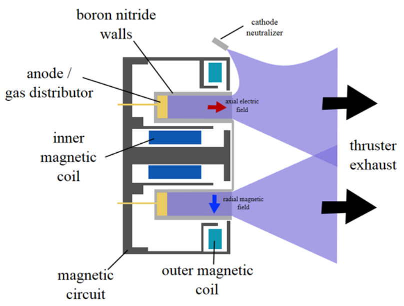
Hall Thruster cross section

X3 Thruster Thermal Model Status

- X3 is a 3 year program, we are in Y2
- Thruster plasma loadings are currently based on estimates scaled from previous Hall thrusters
  - Scaled using recommendations from Yiangos Mikellides (JPL)
  - Assume 11% of total discharge power is assumed to be incident thermally on the thruster
    - Ex. Outer Channel only 40A*400V = 16 kW*0.11 = 1760 W (thermal incident)
    - Adjacent Front Poles = 160 W (1%)
    - Anode and inner channel wall = 485 W
    - Outer channel wall = 630 W
- Will use more accurate thermal plasma models as they become available
- Cathode is assumed to impose 20 W of power onto thruster (gross estimate)



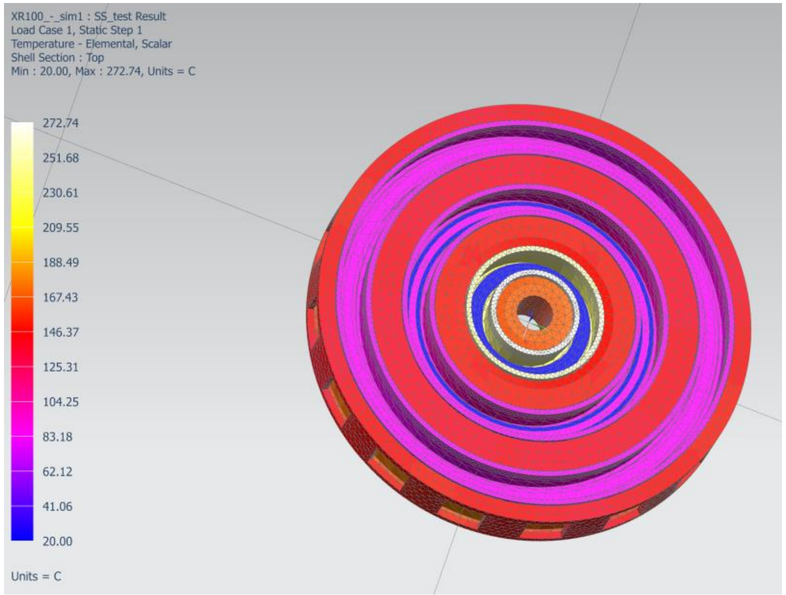
Channel Plasma Loading for HERMeS [1]



Hall Thruster cross section

X3 Thruster Thermal Model Status

- Thruster Data comparisons are for 3 operating points and one bakeout
  - Inner Channel Only
  - Middle Channel Only
  - Outer Channel Only
  - Magnet bakeout
- TC anomalies in the experimental data were detected
  - Led to discovery that all runs except magnet bakeout were not at steady state
- Model tends to undershoot wire turn temperatures
  - Led to discovery that magnet coils had covers installed that were not previously disclosed
- Thermal loads and properties need to be investigated in the discharge channels to increase accuracy



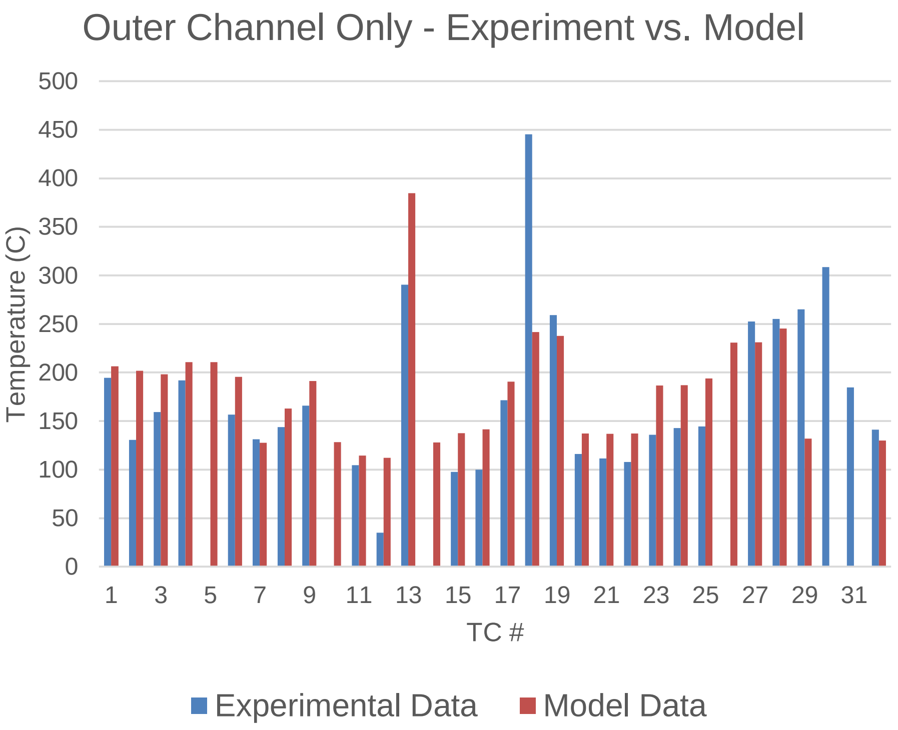
Thruster Thermal Model Status

- Temperature measurement issues:
  - Steady state in the thermal data was assumed to be DT < 10 °C/hr in the backpole for 30 minutes
  - This resulted in places where there were still very large gradients when any of the channels were running, which led to discovery that magnet bakeout was only true steady state run
    - This needs to be addressed in thruster testing in Year 2
  - Further study will be necessary to verify but for Thermal steady state runs in the future, tighter steady state criterion will likely be necessary

TC #	TC Description
1	Outer Front Pole 6:00 connector Top
2	Outer Front Pole 6:00 connector outisde
3	Back Pole 6:00 connector
4	OFP 6:00 top
5	OFP 6:00 outside
6	Back Pole 6:00
7	Back Pole inner 4:00
8	Back Pole inner face outer ring 6:00
9	Back Pole inner face 6:00 outer ring
10	Back Pole back face 6:00 inner ring
11	Inner Cup
12	Mid Cup
13	Outer Cup
14	AAI-I wire turns
15	AAI-O wire turns
16	AAM-I wire turns
17	AAM-O wire turns
18	AAO-I wire turns
19	AAO-O wire turns
20	AAI-O bobbin
21	AAI-O Bobbin
22	AAI-O Bobbin downstream
23	AAM-O bobbin upstream
24	AAM-O bobbin midline
25	AAM-O bobbin downstream
26	AAO-O bobbin upstream
27	AAO-O bobbin midline
28	AAO-O bobbin downstream
29	Front Pole Cathode Channel BP interface AAI
30	Front Pole Cathode Channel Midline 1" from int
31	Front Pole Cathode Channel Midline 0.5" from int
32	Back Pole Cathode Channel midline

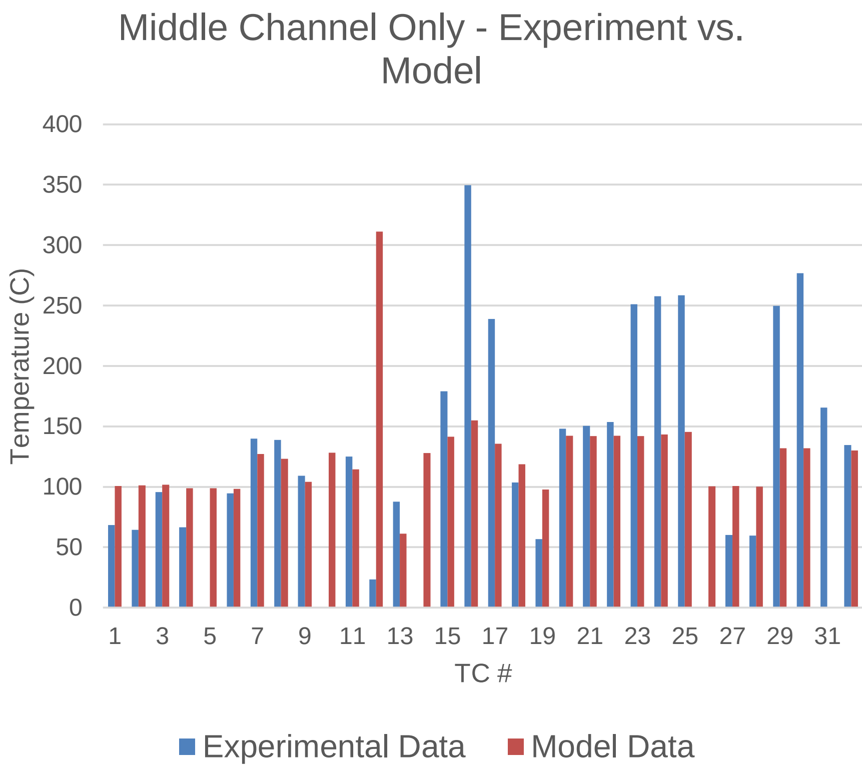
Thruster Thermal Model Status

- Outer Channel only case
- Largest Anomalies
  - TC 13 – Outer Cup, Model overshoots outer cup temperature
  - TC 18 – AAO-I wire turns, model undershoots wire turns
  - Note that Gradient on TC 29 through 31 is in 0.5” increments on a solid iron part, this seems physically unrealistic and is ignored
  - Note, model does not report TC30/31



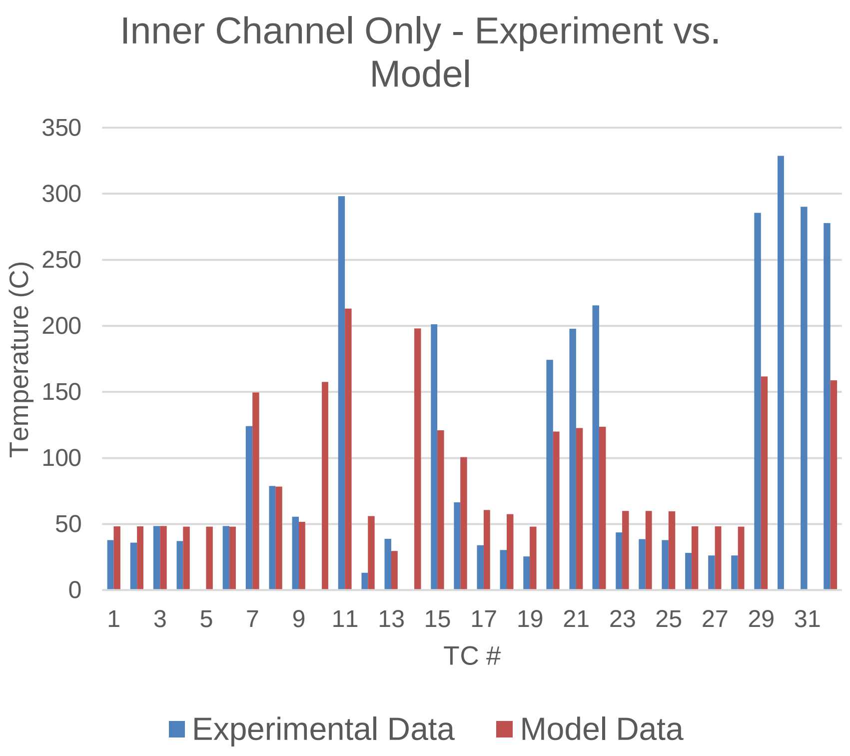
Thruster Thermal Model Status

- Middle Channel only case
- Largest Anomalies
  - TC 12 – U of M reported that TC 12 experienced an anomaly in this case and did not return appropriate values, should be ignored in this analysis
  - TC 16, 23-25 – AAO-I wire turns, model undershoots wire turns
  - Note that Gradient on TC 29 through 31 is in 0.5” increments on a solid iron part, this seems physically unrealistic and is ignored
  - Note, model does not report TC30/31



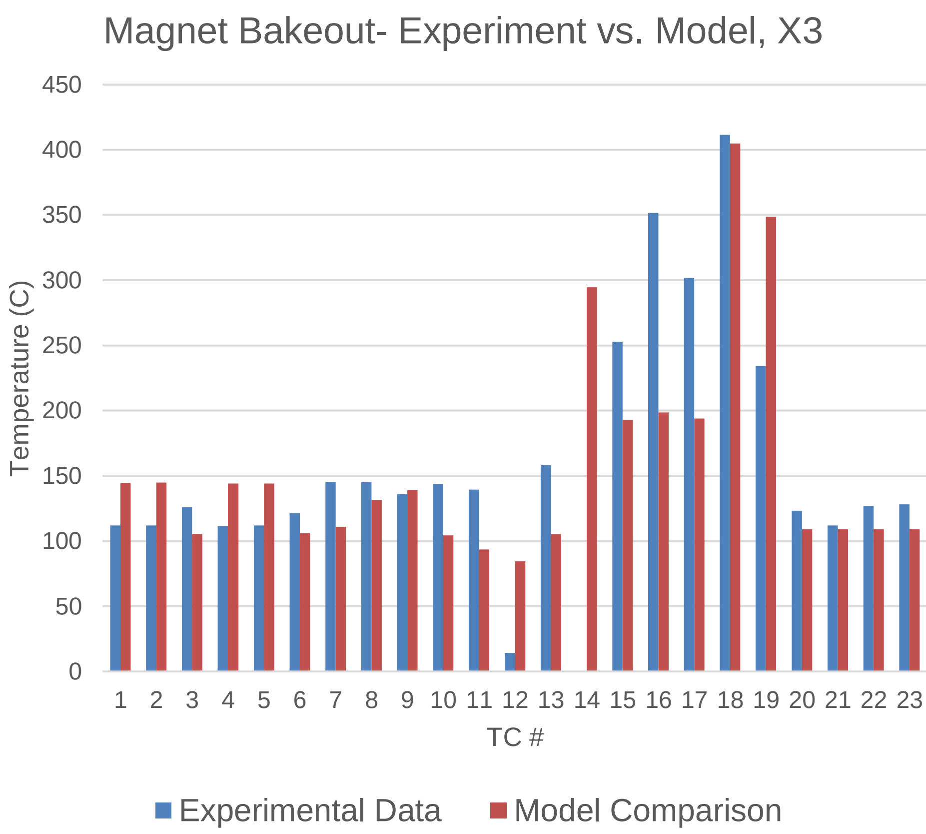
Thruster Thermal Model Status

- Inner Channel only case
- Largest Anomalies
  - TC 11 – Inner Cup, Model undershoots outer cup temperature
  - Note that Gradient on TC 29 through 31 is in 0.5” increments on a solid iron part, this seems physically unrealistic and is ignored
  - Inner Front pole gradients are much lower than other channel cases, but still very high, also absolute temperature is high
  - TC20-22 – AAI-O coils, Model undershoots coil temperatures
  - Note, model does not report TC30/31



Thruster Thermal Model Status

- Magnet Bake out case
- Largest Anomalies
  - TC16 and TC17, AAM-I and AAM-O coil temperatures
    - Model under predicts but this is likely due to presence of coil covers not previously accounted for
  - Data taken after 17 hours of operation
- Magnet bakeout temperatures likely closer to thermal steady state than other coil load cases
  - Most useful for comparison
  - Case with closest results between experiment and model, outside of coils



Conclusions (1 of 1)

- Plasma physics is very complicated but building X3 thruster model is not as bad
  - Firing EP thruster (plasma loading) dominates environmental loading
  - Plasma loads inform the thermal model and the thermal model informs the plasma model until difference are minimal
  - With the X3 thruster, the key has been to fully understand the configuration status of the thruster as it is modeled
    - Supporting the testing of the X3 remotely led to a few “gotcha” moments regarding whether the thruster was at steady state and the mechanical configuration of the coils
  - We are on the right track for validation, despite issues with Magnet bakeout case and other load cases
    - Plan is to incorporate the issues discovered in Y1 testing into Y2 testing
  - Overall, X3 thermal model is progressing in year 2 and we hope to get more data to validate against in the future

Acknowledgements

- I'd like to thank my co-author's, Richard Hofer and Scott Hall as well as the JPL and University of Michigan electric propulsion teams for their support. Additional thanks to NASA's AES and NextSTEP programs for funding this effort

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

References

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