WORKSHOP ON ELECTRIC PROPULSION OPERATION IN THE SPACE ENVIRONMENT AND FACILITY INTERACTIONS (EPOSE)

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Investigations of Background Pressure Effects in the SPT-140 Hall Thruster for the Psyche Mission

66th JANNAF Propulsion Meeting
Programmatic and Industrial Base Meeting
13th Modeling and Simulation Meeting
11th Liquid Propulsion & 10th Spacecraft Propulsion Meetings
Tampa Bay, FL, Dec 9 – 13, 2019

Mechanism Behind the Dependence of Thrust on Facility Backpressure and Implications on the Operation of the SPT-140 Onboard the Psyche Mission

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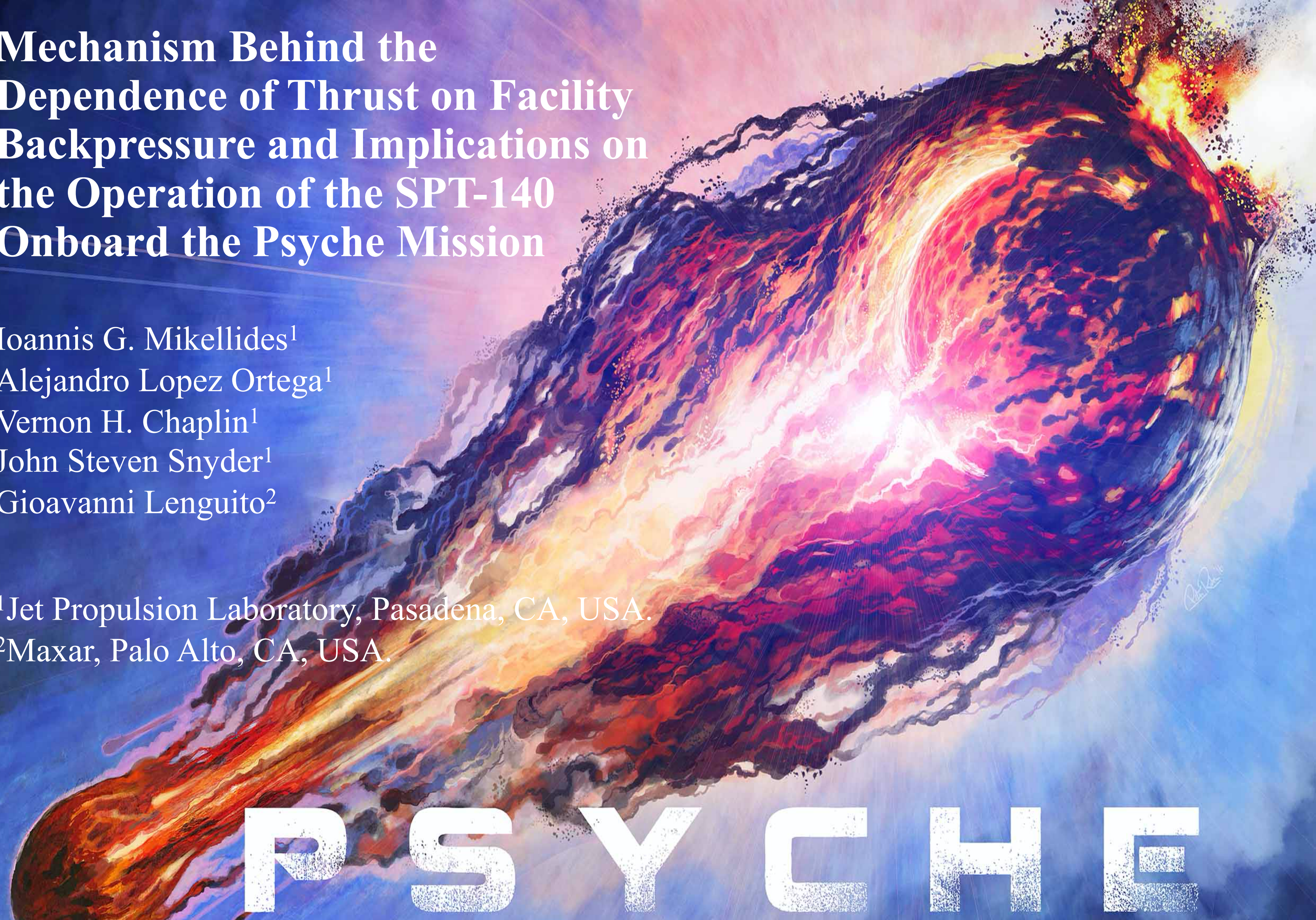
Vernon H. Chaplin[1]
John Steven Snyder[1]
Gioavanni Lenguito[2]

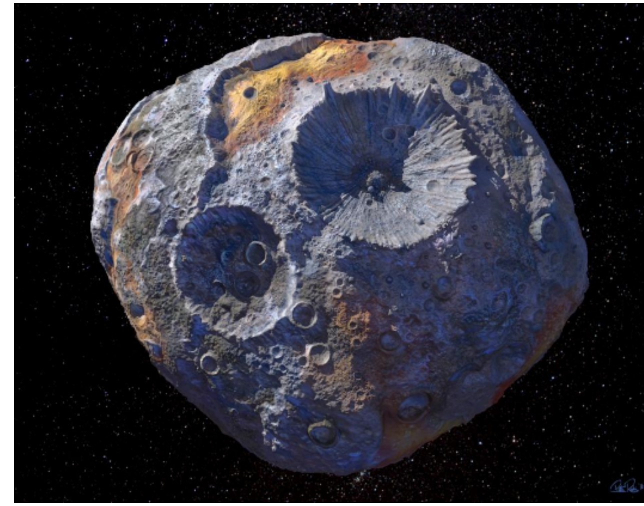
[1]Jet Propulsion Laboratory, Pasadena, CA, USA.
[2]Maxar, Palo Alto, CA, USA.

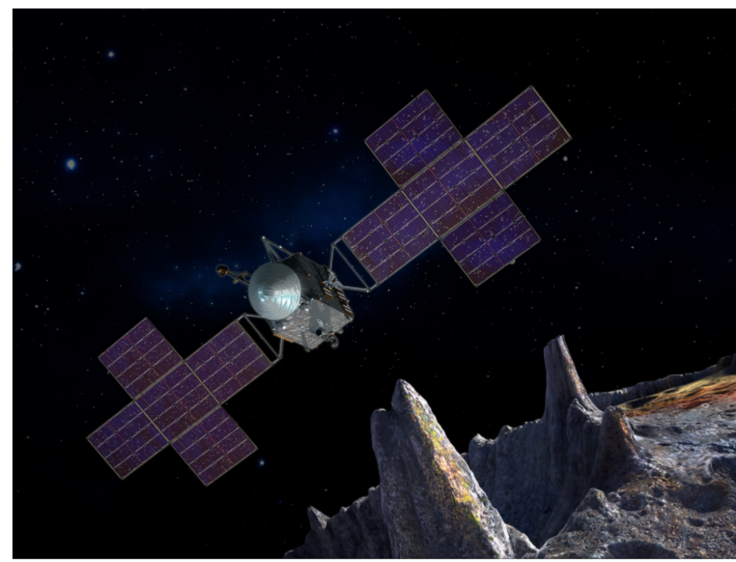


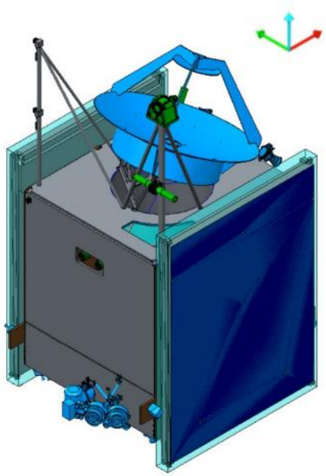
36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria. September 15-20, 2019.

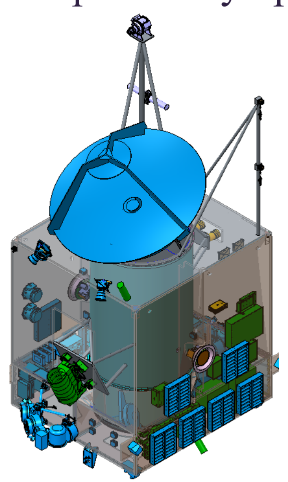
Psyche is the First Mission to Employ Hall Thrusters Beyond Lunar Orbit

- Launch: August 2022
  - 3.5 year cruise
  - 21 months orbital science operations
- Target: Metallic Asteroid Psyche
  - Is it the core of a planet interrupted by impacts during formation?
- JPL-Maxar hybrid spacecraft
  - Maxar provides the SEP Chassis
  - JPL provides command and data handling, fault protection, flight software, autonomous operations
- SPT-140 Electric Propulsion System
  - Used for cruise and asteroid proximity operations





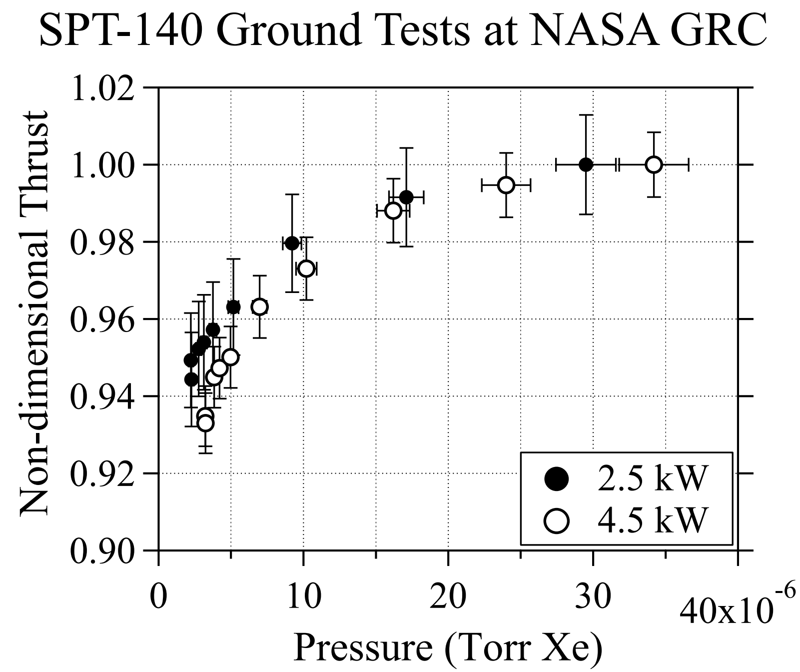




More information about the mission will be presented by S. Snyder, IEPC-2019-XXX (XXX-day).

Motivation Behind the Modeling and Simulation Work

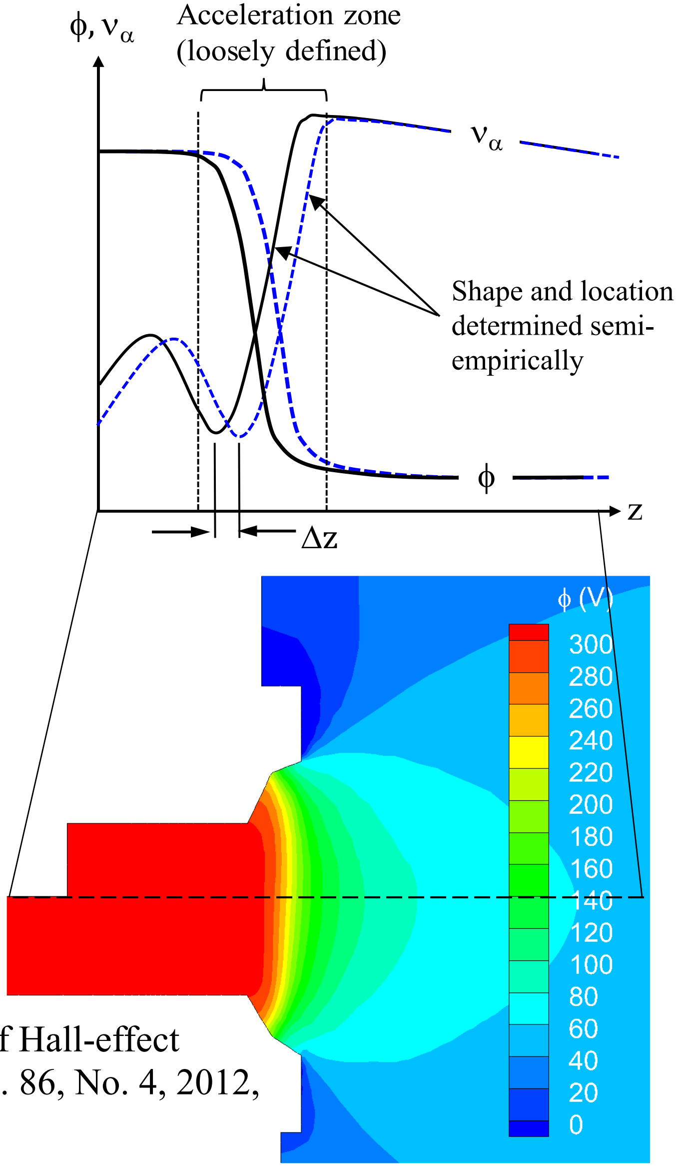
- Increase of thrust with facility backpressure well-known for decades in Hall thrusters
  - occurs most prominently with externally-mounted cathodes
  - limited understanding prohibits performance predictions in space



- Uncertainty on effects of backpressure affects adversely performance and lifetime margins
- Significant differences between operating conditions in ground tests and Psyche further increase uncertainty
  - throttle profiles different
  - magnet current higher than in ground tests

Modeling, Supported by Experiments, Reduces Risk in Performance and Lifetime Predictions for Psyche.

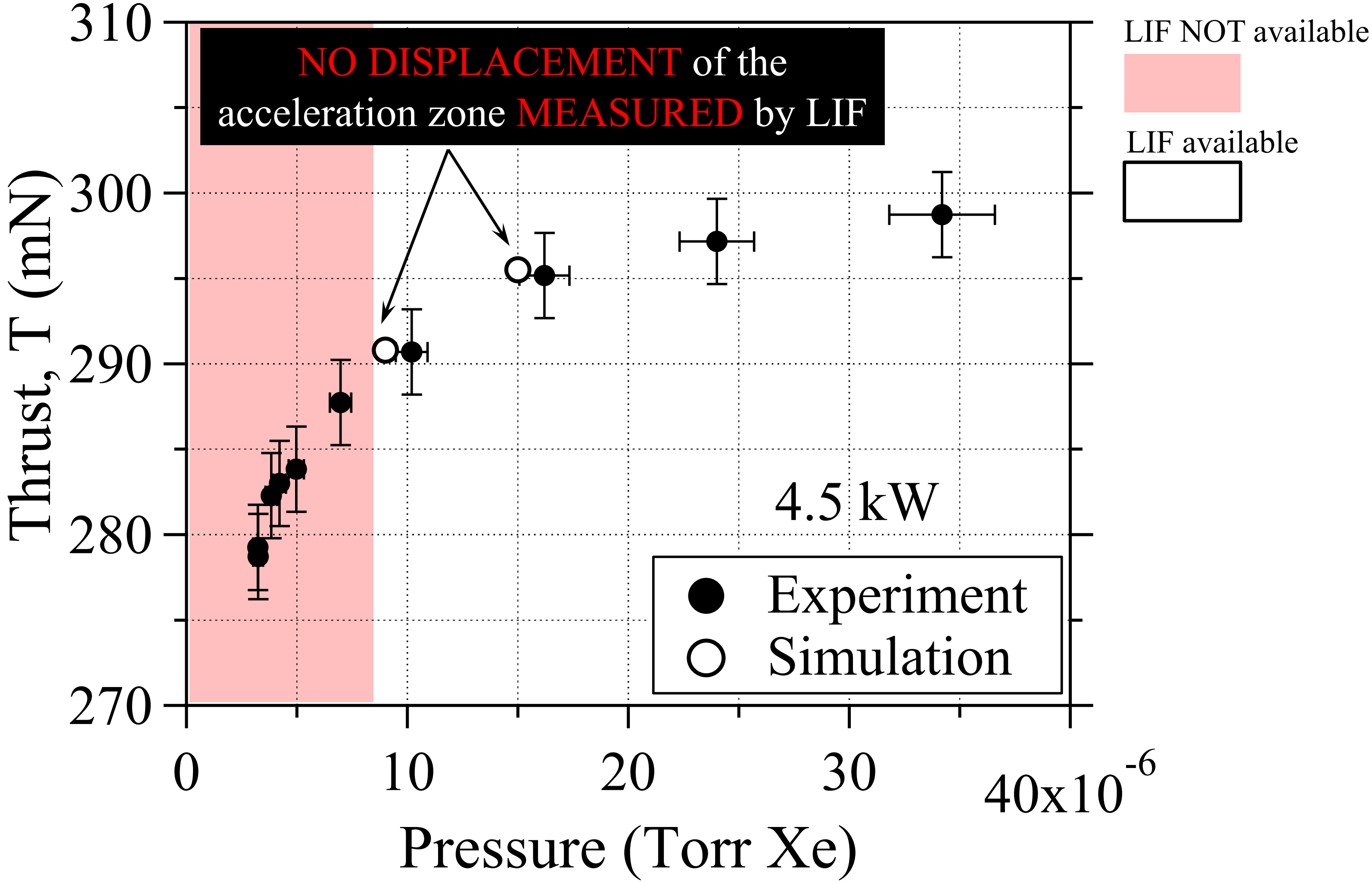
- Hall2De [1] employed for the numerical simulations
  - 2-D (r-z) axisymmetric domain
  - conservation laws discretized on a magnetic field-aligned mesh (MFAM)
  - **all physics models based on first principles except for the anomalous collision frequency (ν_α), which is usually empirically defined**
  - LIF diagnostics [2] used to specify ν_α in the SPT-140 simulations



[1] First journal article on Hall2De: Mikellides, I. G., and Katz, I., "Simulation of Hall-effect Plasma Accelerators on a Magnetic-field-aligned Mesh," Physical Review E, Vol. 86, No. 4, 2012, pp. 046703 (1-17).

[2] LIF diagnostics performed by V. Chaplin, IEPC-2019-XXX (XXX-day).

Understanding Gained from 2-D (r-z) Axisymmetric Simulations [1] with the Hall2De Code



[1] Hall2De simulations performed by A. Lopez Ortega, IEPC-2019-XXX (XXX-day).

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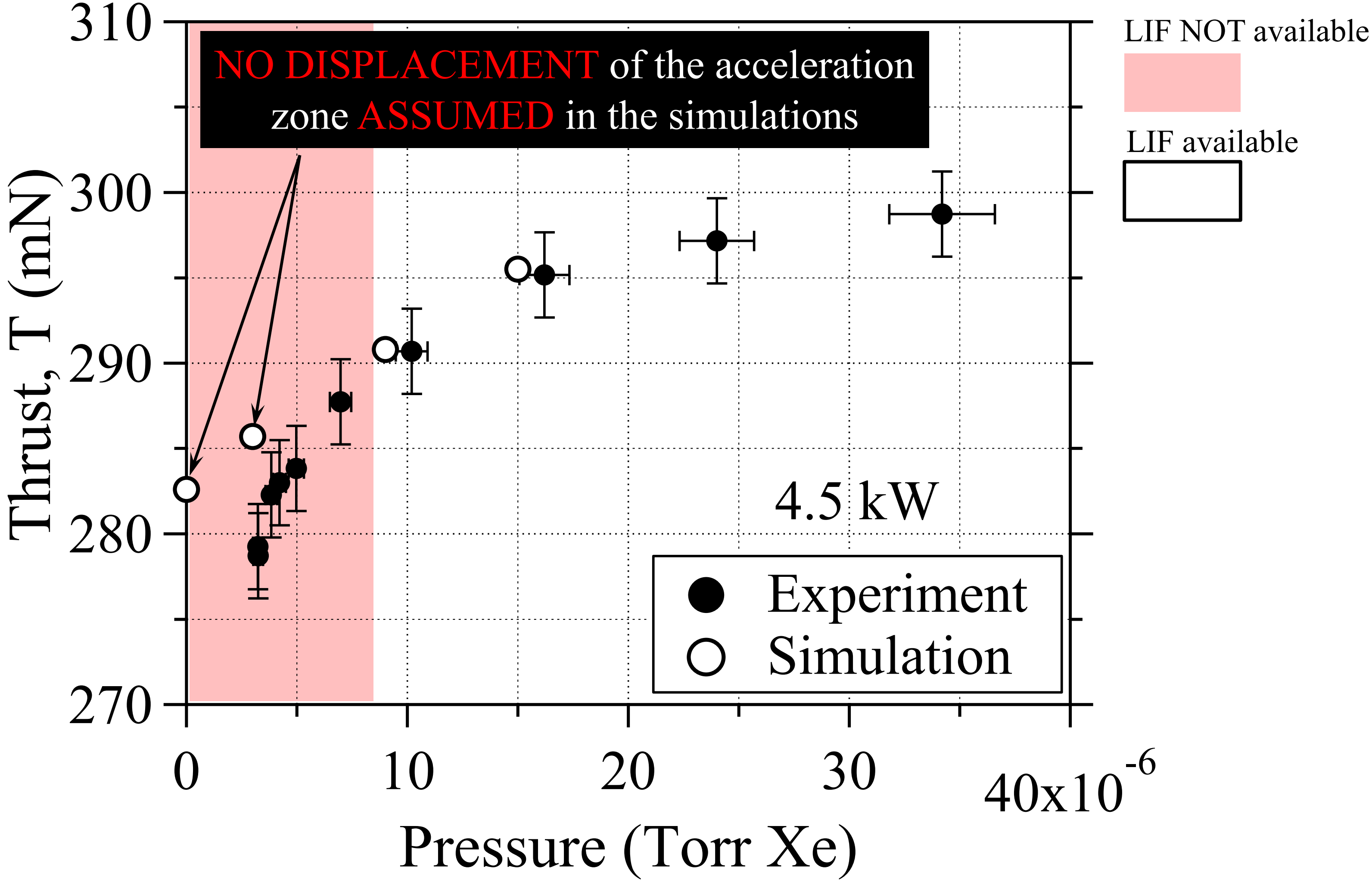

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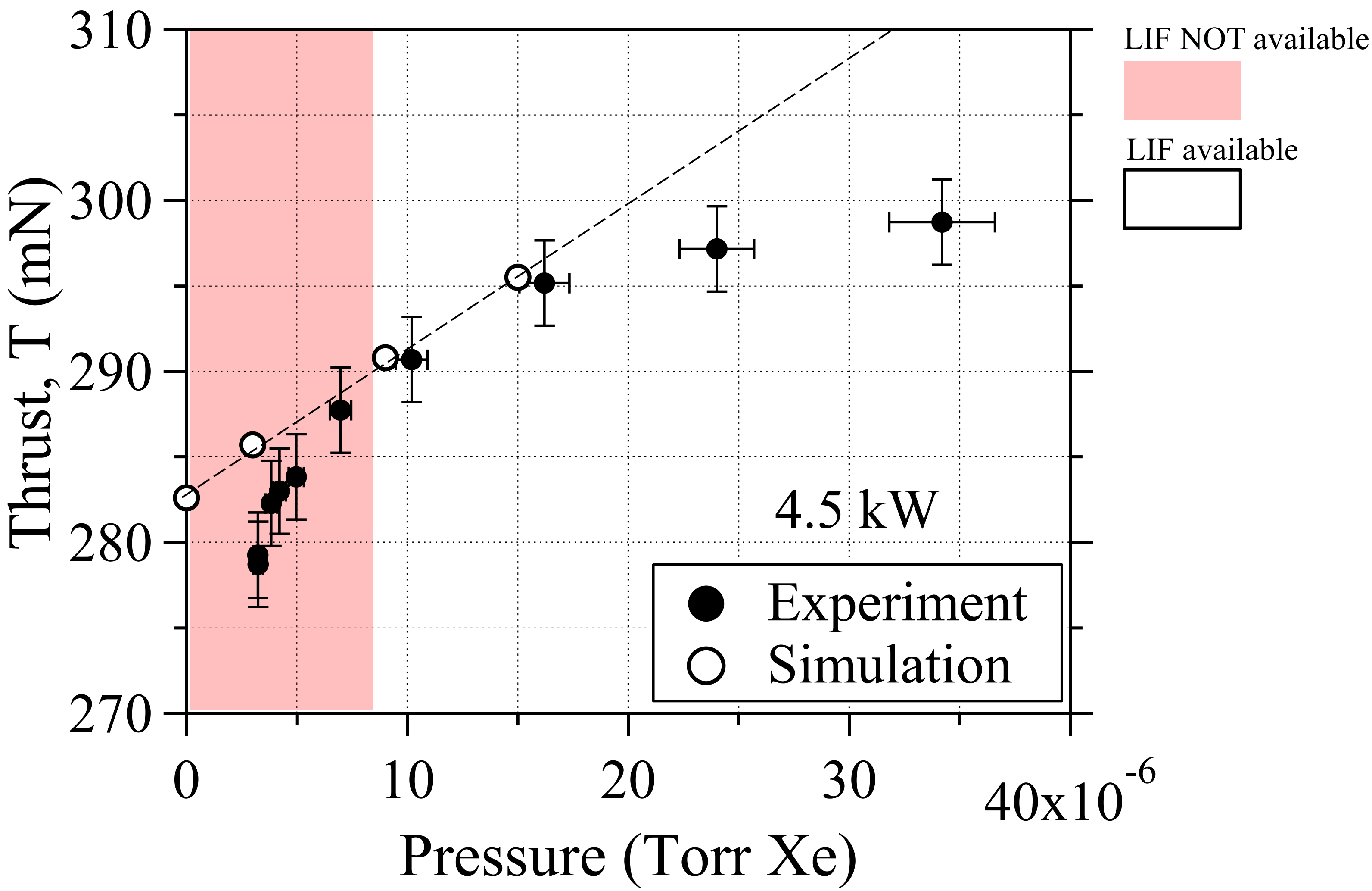

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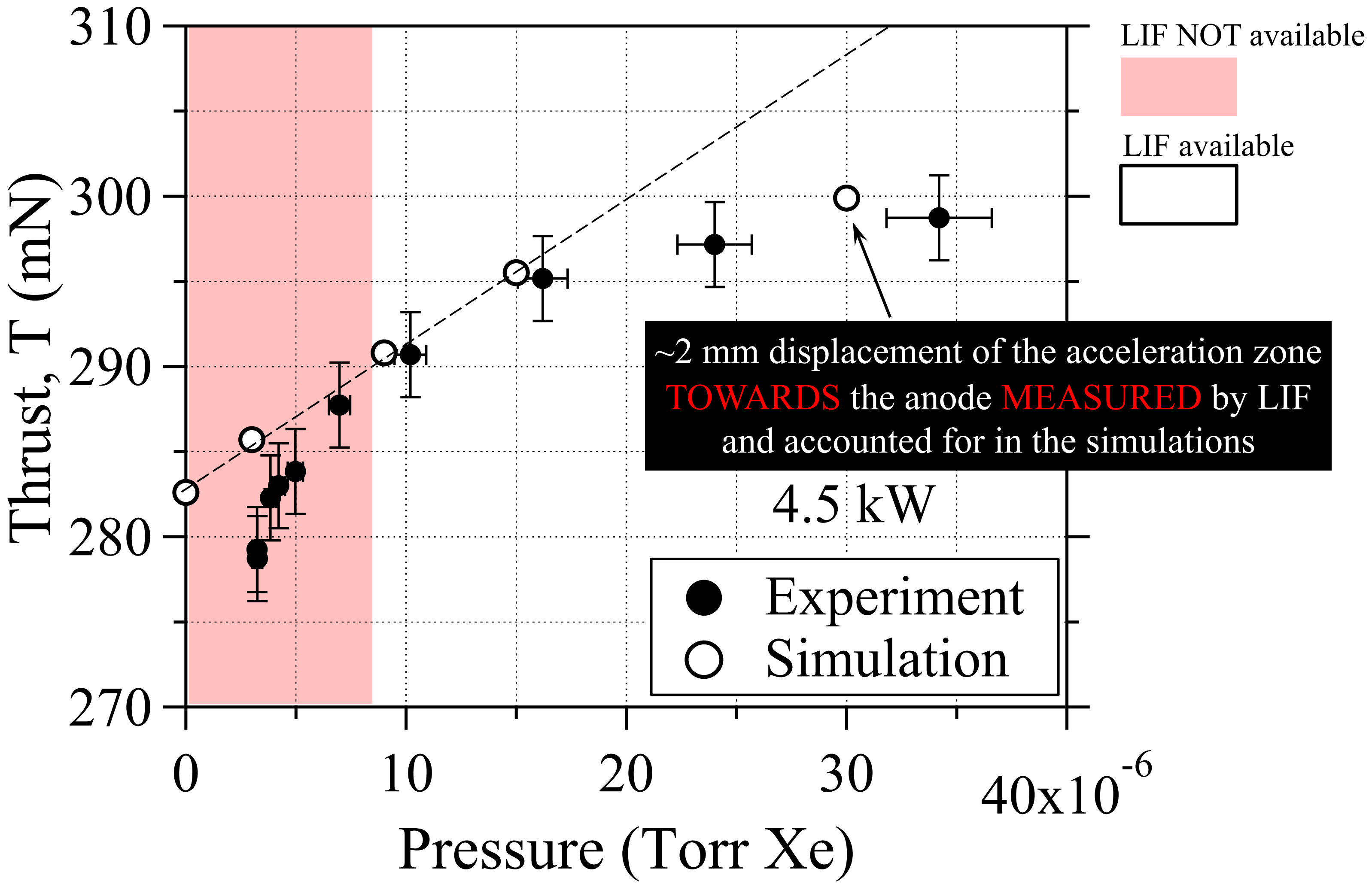

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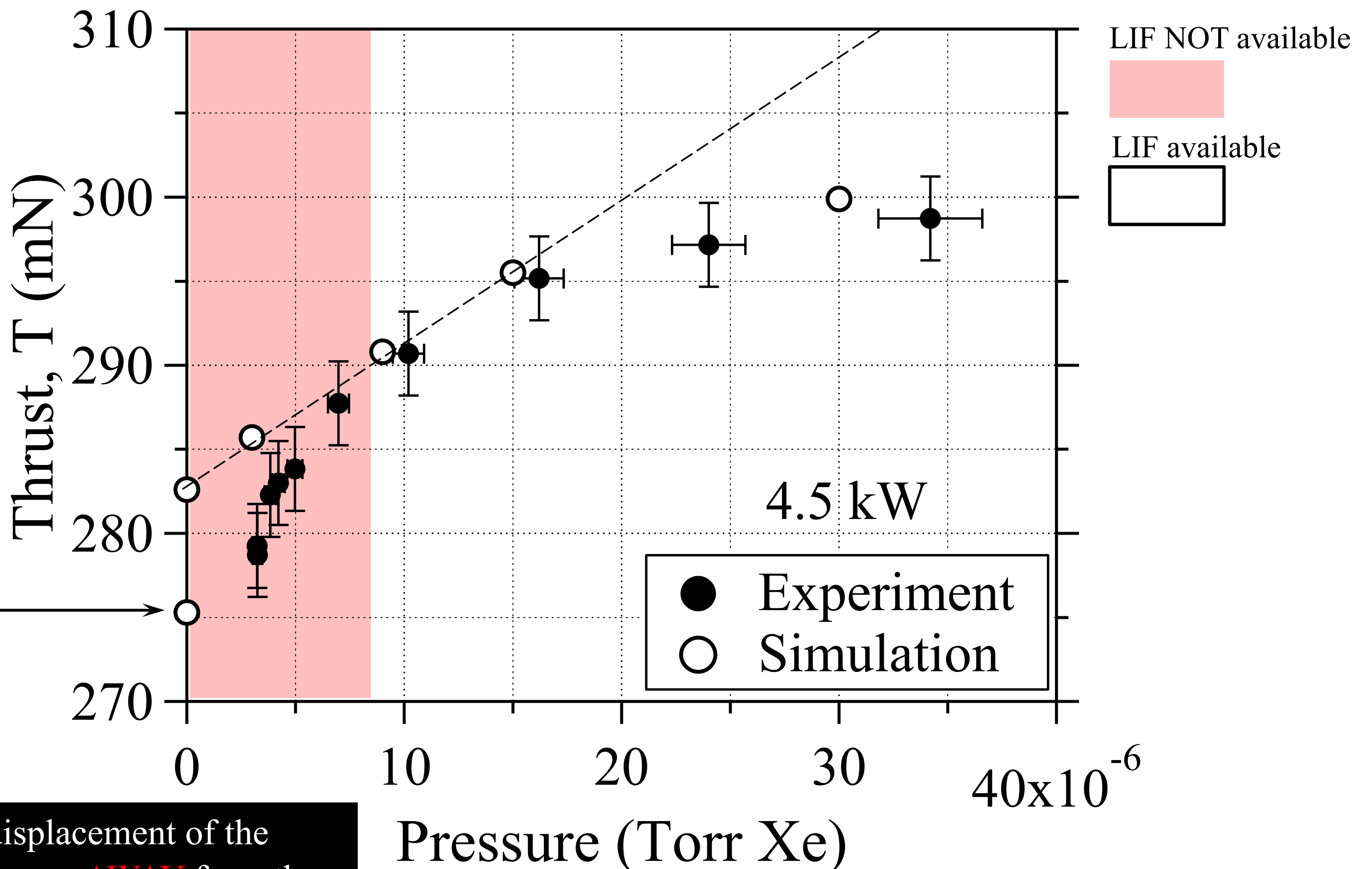


~2 mm displacement of the acceleration zone AWAY from the anode ASSUMED in the simulations

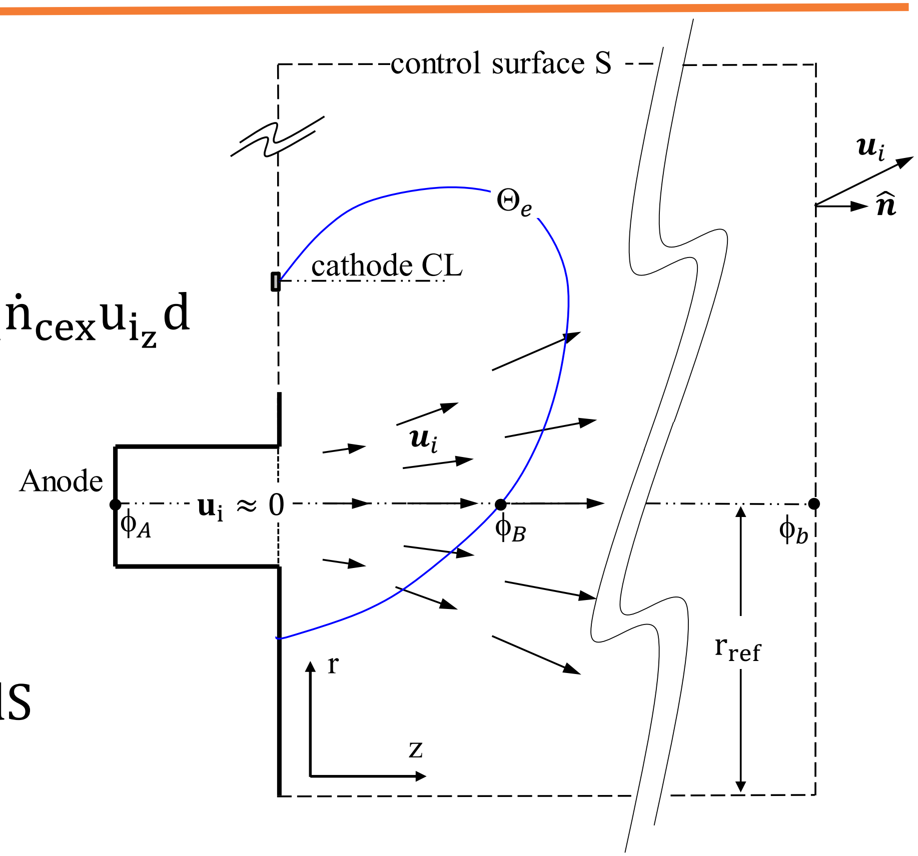
Analytical Model of the Thrust (T) Developed to Understand the Numerical Simulation Results and Beyond…

$$T = T_i + T_n$$

$$T_i = \oiint_S m_i n_i (\mathbf{u}_i \cdot \hat{\mathbf{n}}) u_{i_z} dS \qquad T_n = \iiint m_n \dot{n}_{cex} u_{i_z} d$$

$$T_i \approx m n_{ib}^T u_{ib}^2 \iint f_i \cos^2\theta dA$$

$$T_n \approx m \ell_{cex} \sigma \iint n_i(\bar{r}) n_n(\bar{r}) u_{ib}^2 \cos\theta(\bar{r}) dS$$



$$T \approx T_{ref}\left[1 - \bar{\phi}(\phi_B/\phi_A)\right]\left[c_i + n_{nb}^T \sigma \ell_{cex}\left(c_{n_1} + c_{n_2} \beta \bar{n}_{n_{ref}}^F\right)\right]$$

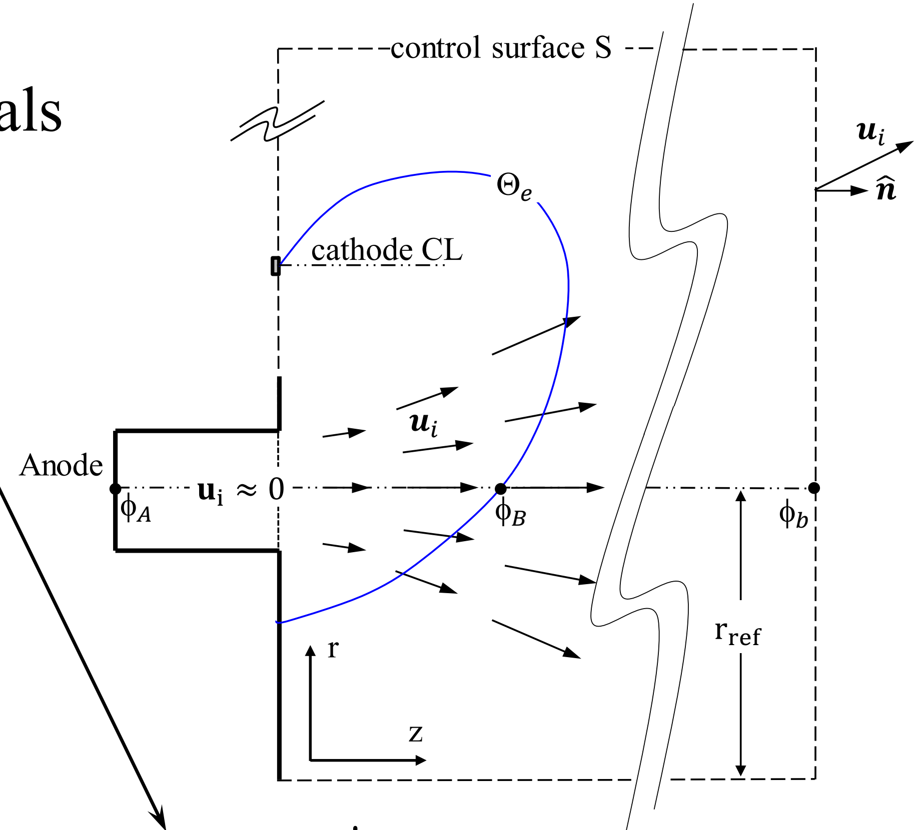
$$c_i \equiv \int f_i \cos^2\theta \bar{r} d\bar{r} \qquad c_{n_1} \equiv \int f_i f_n \cos\theta \bar{r} d\bar{r} \qquad c_{n_2} \equiv \int f_i \cos\theta \bar{r} d\bar{r}$$

Analytical Model of the Thrust (T) Developed to Understand the Numerical Simulation Results and Beyond…

Contribution to thrust by fast neutrals

Contribution to thrust by ions

Ion energy ~ u_i^2

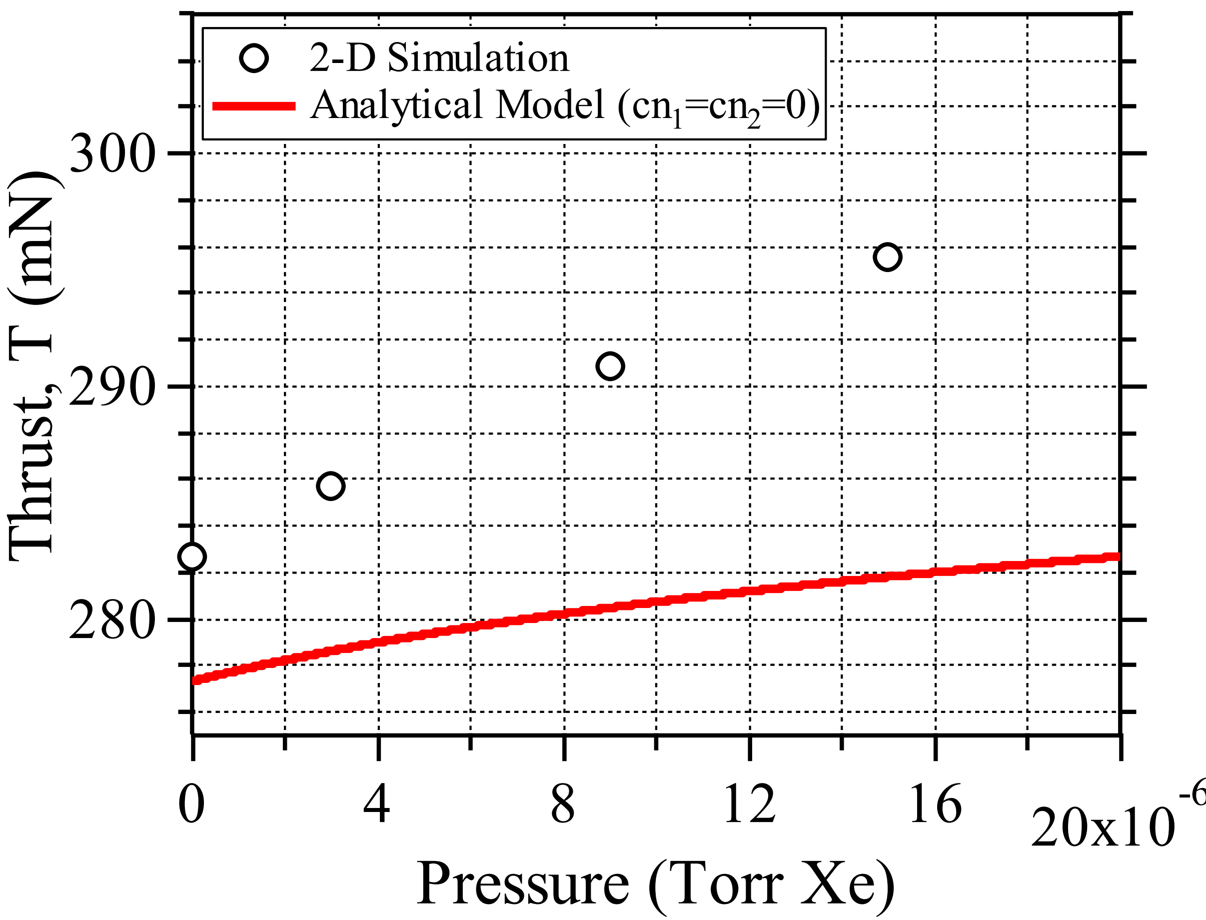


$$T \approx T_{ref}\left[1 - \bar{\phi}(\phi_B/\phi_A)\right]\left[c_i + n_{nb}^{T}\sigma\ell_{cex}\left(c_{n_1} + c_{n_2}\beta\bar{n}_{n_{ref}}^{F}\right)\right]$$

Thruster neutrals

Facility neutrals

Analytical Model of the Thrust (T) Developed to Understand the Numerical Simulation Results and Beyond…



- No displacement of the acceleration zone for p_F<16 μTorr
- No contribution to thrust by fast neutrals
- Calculated thrust under-estimated and increasing with backpressure

$$T \approx T_{ref}\left[1 - \bar{\phi}(\phi_B/\phi_A)\right]\left[c_i + n_{nb}^{T}\sigma\ell_{cex}\left(c_{n_1} + c_{n_2}\beta\bar{n}_{n_{ref}}^{F}\right)\right]$$

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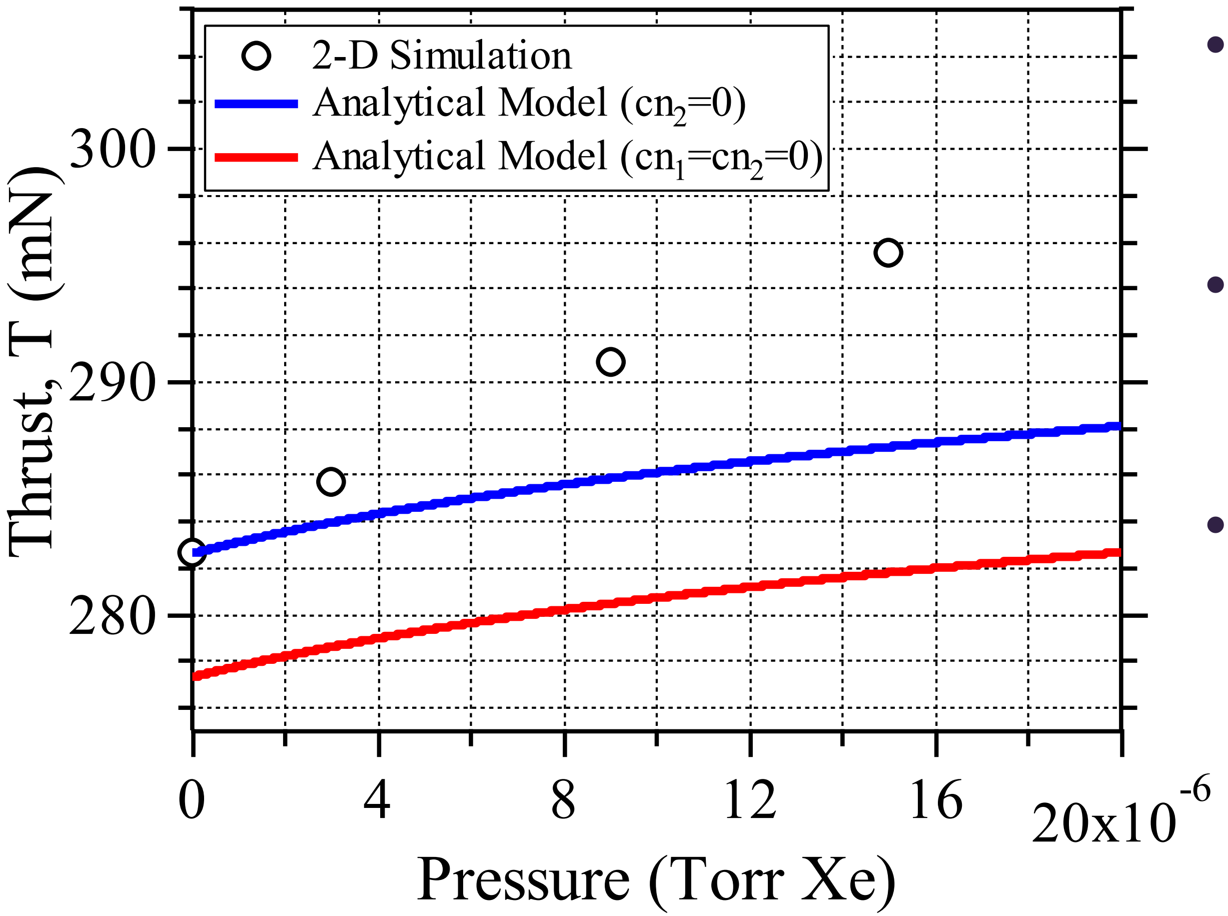

- No displacement of the acceleration zone for $p_F < 16\ \mu$Torr
- Contribution to thrust only from thruster neutrals
- Calculated thrust higher but underestimates rate of increase

$$T \approx T_{ref}\left[1 - \bar{\phi}(\phi_B/\phi_A)\right]\left[c_i + n_{nb}^{T}\sigma\ell_{cex}\left(c_{n_1} + c_{n_2}\beta\bar{n}_{n_{ref}}^{F}\right)\right]$$

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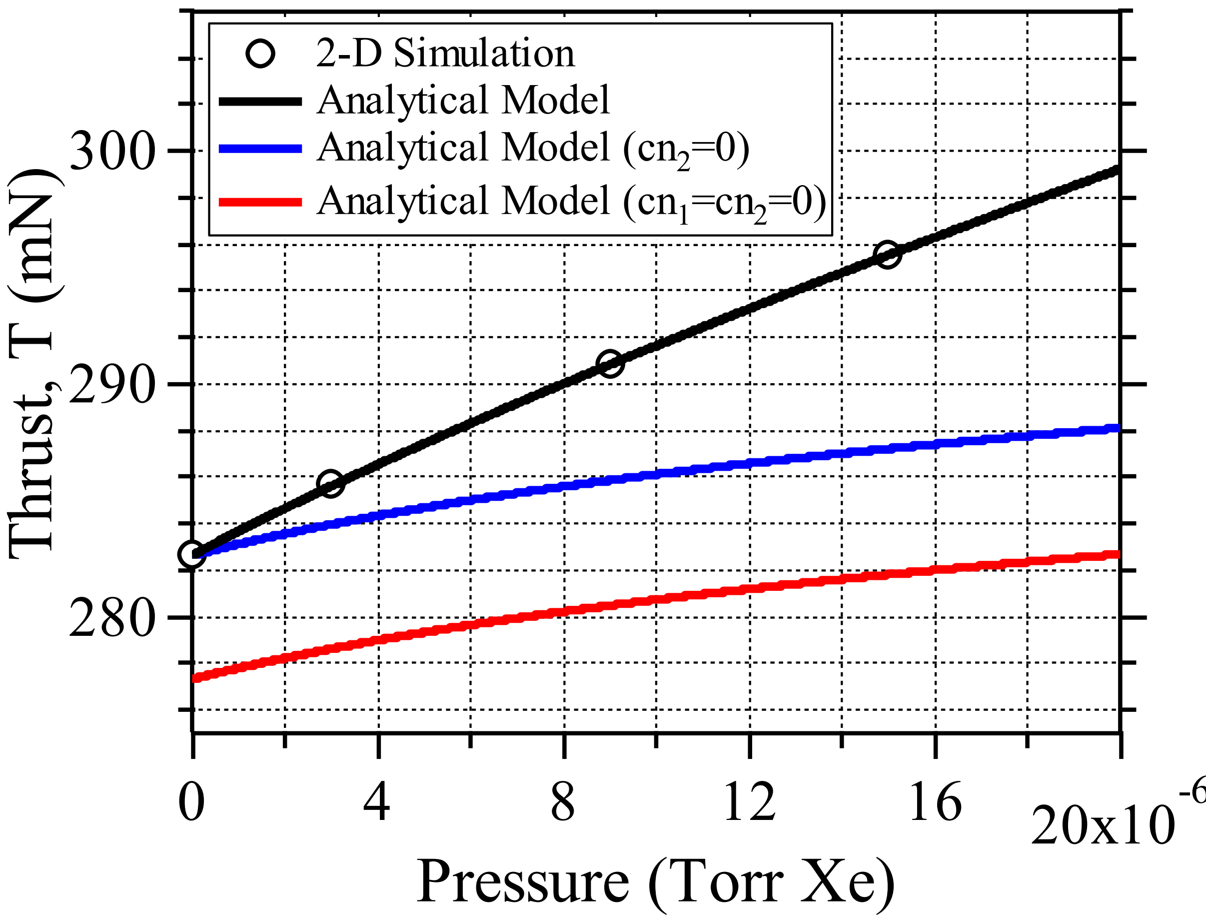


- No displacement of the acceleration zone for p_F<16 μTorr
- Contribution to thrust from facility neutrals added
- Calculated thrust matches simulation results

$$T \approx T_{ref}\left[1-\bar{\phi}(\phi_B/\phi_A)\right]\left[c_i + n_{nb}^{T}\sigma\ell_{cex}\left(c_{n_1} + c_{n_2}\beta\bar{n}_{n_{ref}}^{F}\right)\right]$$

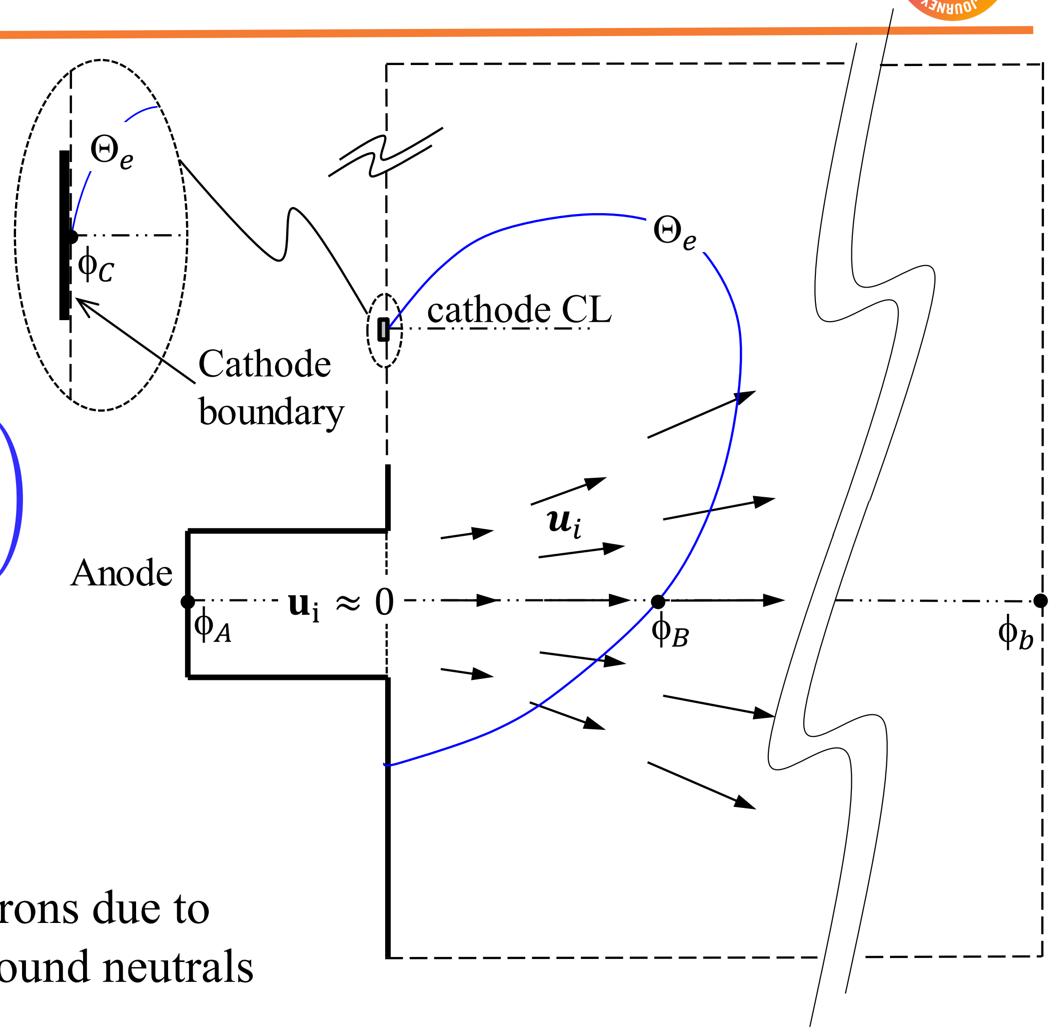
Analytical Model of the Thrust (T) Developed to Understand the Numerical Simulation Results and Beyond…

$$\phi_B = \phi_C + \Theta_e \ln\left(\frac{n_{eB}}{n_{eC}}\right)$$

$$\approx \phi_C + \Theta_e \ln\left(\frac{n^{T}_{eB}}{\tilde{n}^{C}_{eC} + \beta n^{F}_{eC_{ref}}}\right)$$

Cathode (or primary) electrons: azimuthally-averaged value

(Secondary) Electrons due to ionization of background neutrals



$$T \approx T_{ref}\left[1 - \bar{\phi}(\phi_B/\phi_A)\right]\left[c_i + n^{T}_{nb}\sigma\ell_{cex}\left(c_{n_1} + c_{n_2}\beta\bar{n}^{F}_{n_{ref}}\right)\right]$$

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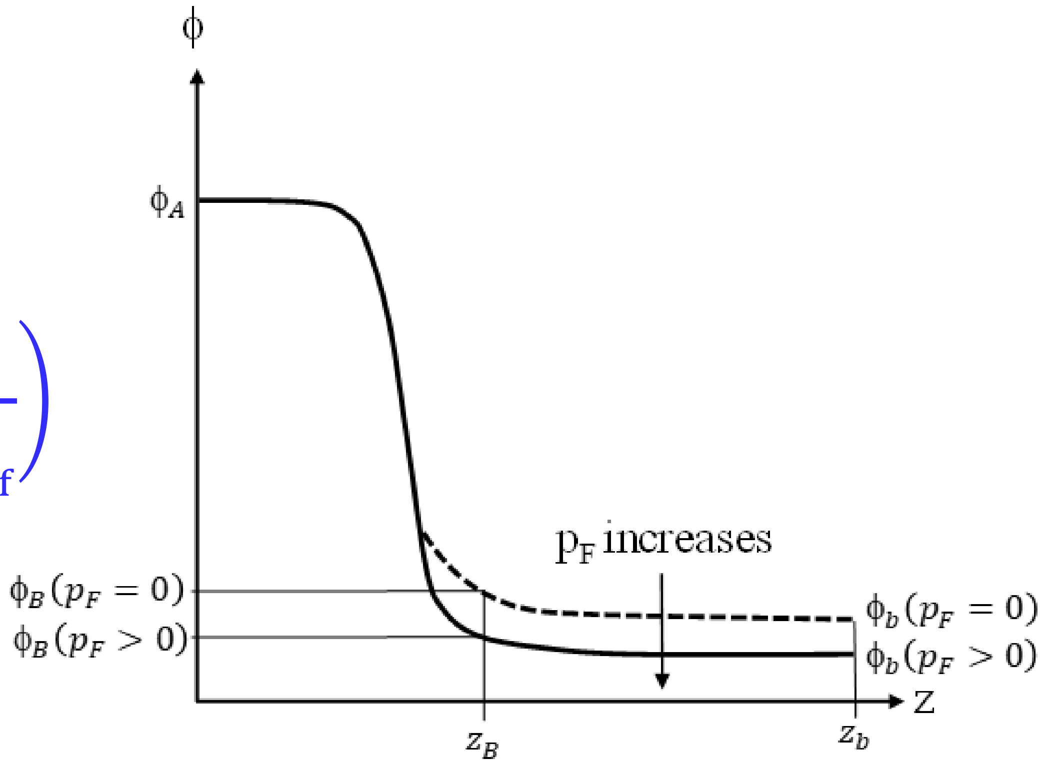
$$\approx \phi_C + \Theta_e \ln\left(\frac{n_{eB}^{T}}{\tilde{n}_{eC}^{C} + \beta n_{eC_{ref}}^{F}}\right)$$

Controls near-plume potential



$$T \approx T_{ref}\left[1 - \bar{\phi}(\phi_B/\phi_A)\right]\left[c_i + n_{nb}^{T}\sigma\ell_{cex}\left(c_{n_1} + c_{n_2}\beta\bar{n}_{n_{ref}}^{F}\right)\right]$$

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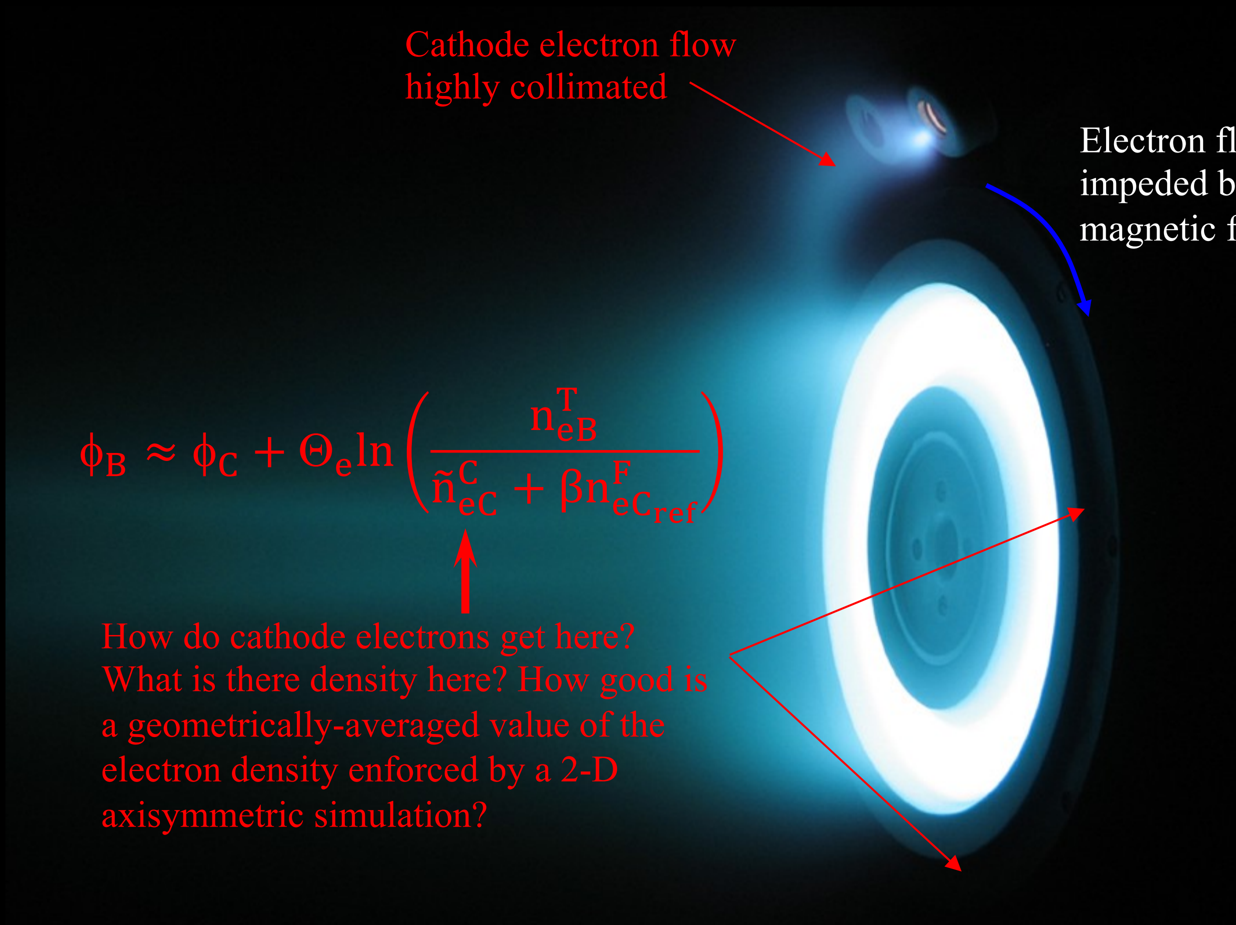

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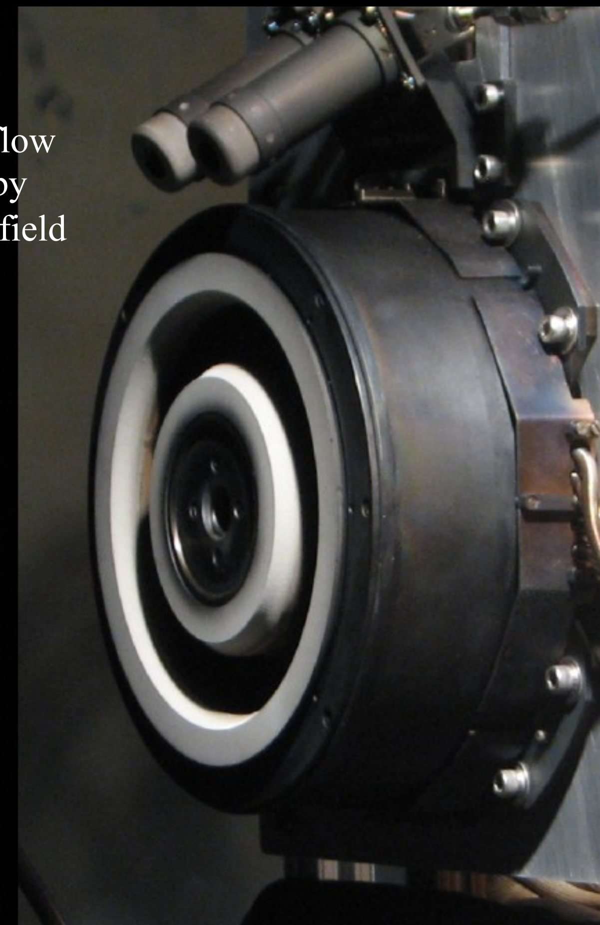

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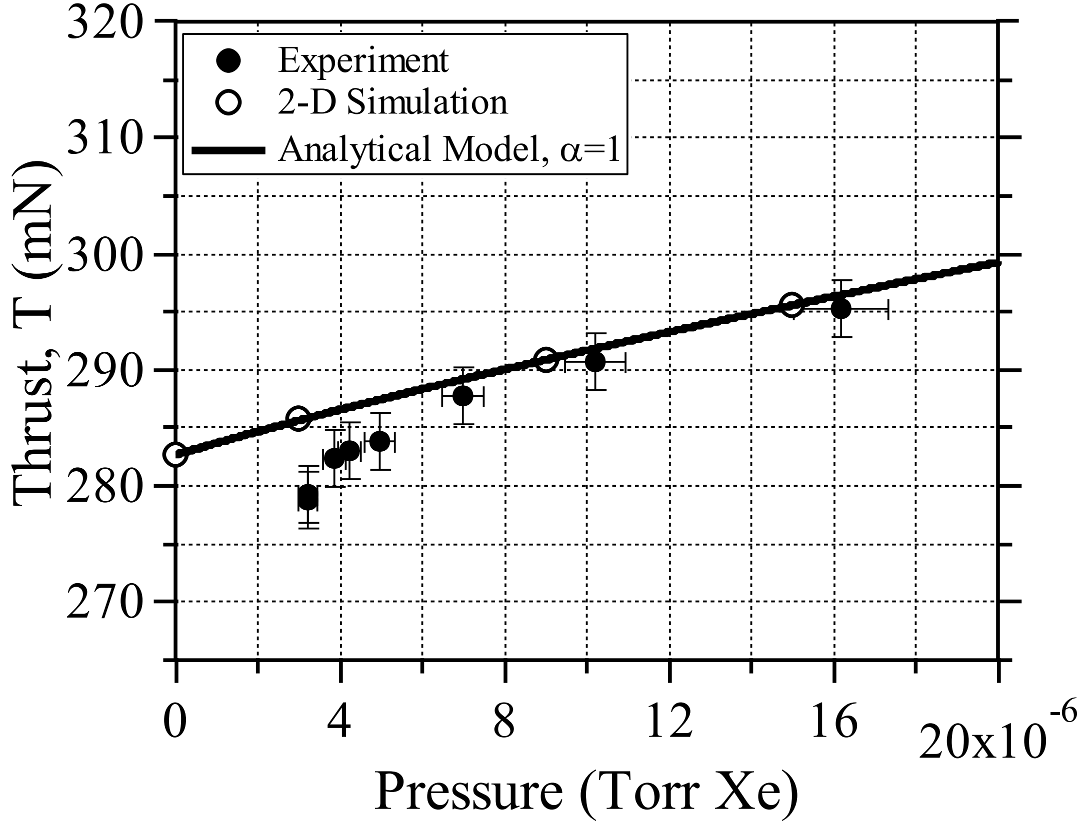

$$\phi_B \approx \phi_C + \Theta_e \ln\left(\frac{n_{eB}^{T}}{\boldsymbol{\alpha\tilde{n}_{eC}^{C}} + \beta n_{eC_{ref}}^{F}}\right)$$

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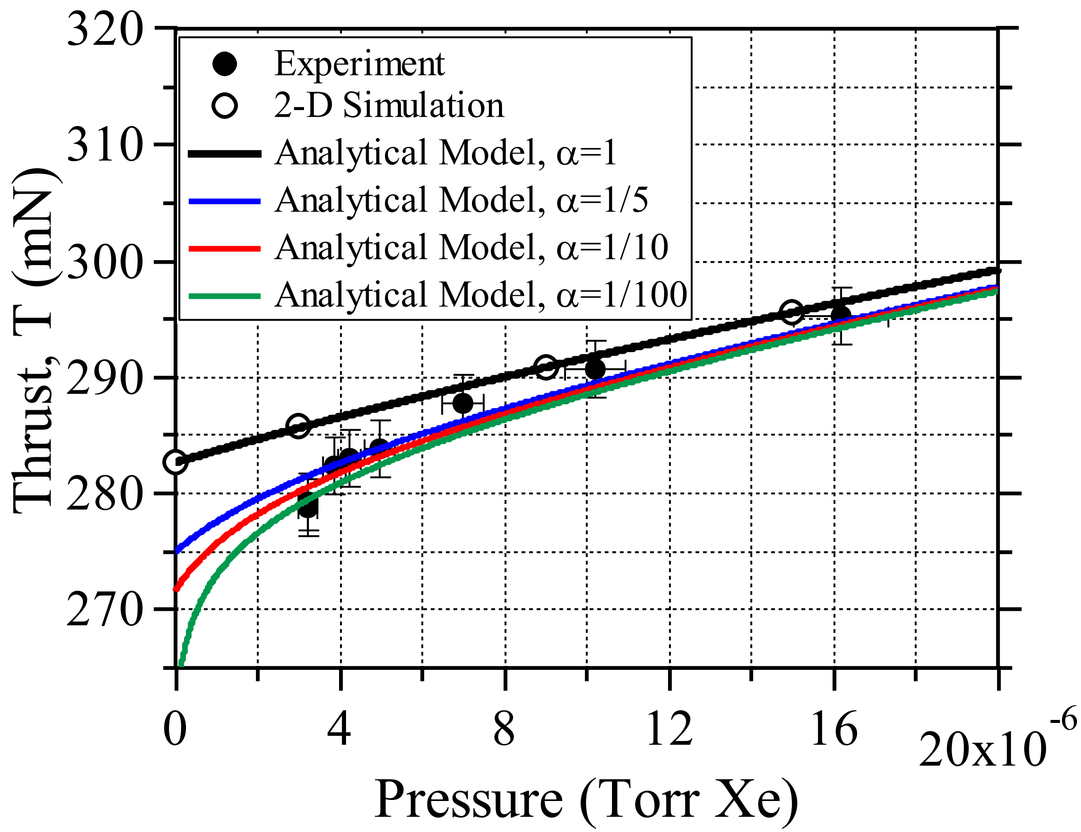

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Summary Remarks

- Ground tests of the SPT-140 for NASA's Psyche mission showed thrust increased by as much as 7.2% when the facility pressure increased by ~10x
- Simulations with the 2-D axisymmetric code Hall2De reveal
  - Excellent agreement with test data at intermediate pressures (9-15 μTorr), where no displacement of the acceleration zone was measured
  - Without movement of the acceleration zone the comparison degraded at lower pressures, where no measurements were possible
- New thrust model suggests azimuthal asymmetries in the cathode electron flow could be the source of the steep rise of the thrust with backpressure at the lowest pressures (<9 μTorr)
  - Explains past measurements with the H6 in which thrust sensitivity decreased as external cathode was moved closer to the channel
  - Explains insensitivity of thrust to backpressure in Hall thrusters with centrally-mounted cathodes

Numerical Investigations of Background Pressure Effects and Channel Erosion in the SPT-140 Hall Thruster for the Psyche Mission

- Alejandro Lopez Ortega
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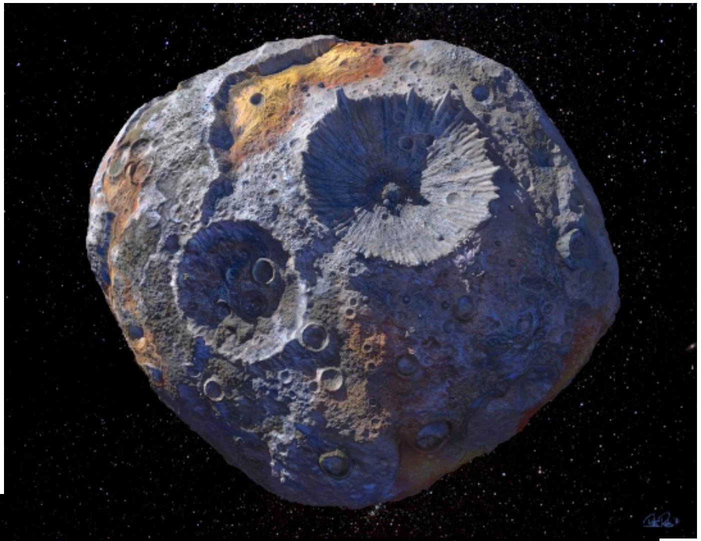
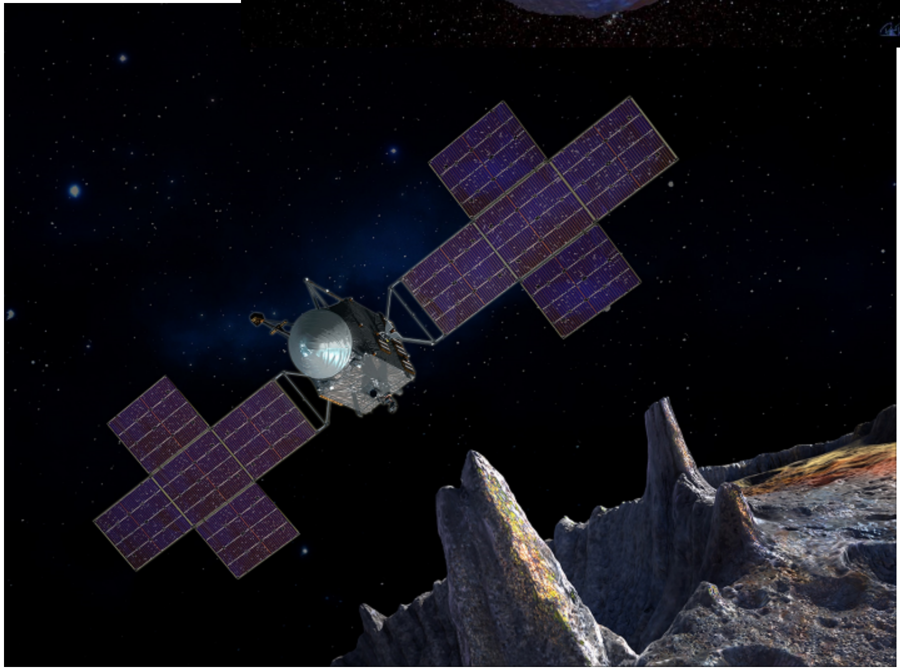
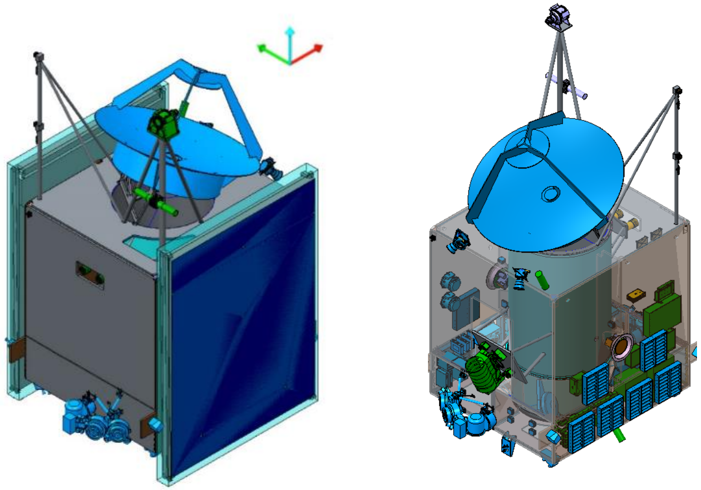
Psyche Mission

- Target: Metallic Asteroid Psyche
  - Is it the core of a planet interrupted by impacts during formation?
- JPL-Maxar hybrid spacecraft
  - Maxar provides the Solar Electric Propulsion Chassis
  - JPL provides command and data handling, fault protection, flight software, autonomous operations
- SPT-140 Electric Propulsion System

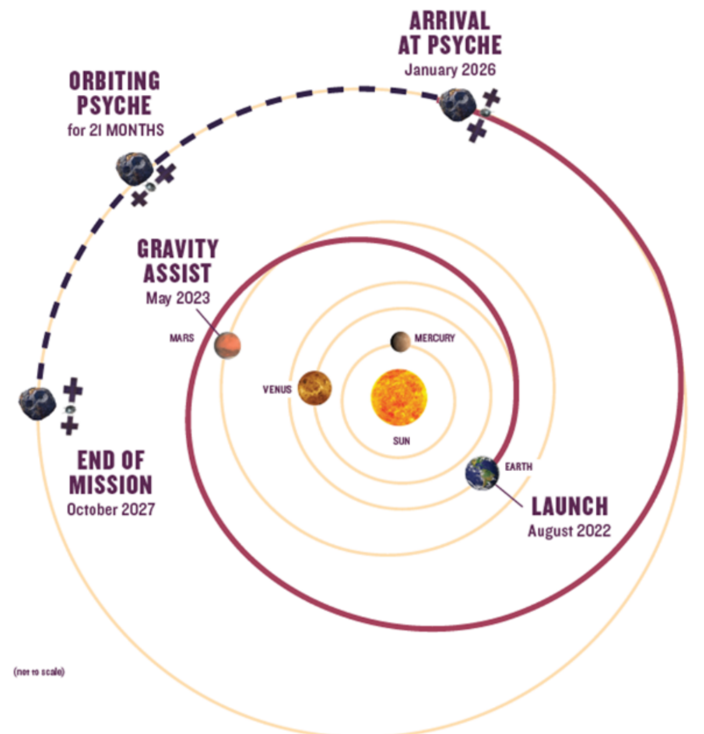


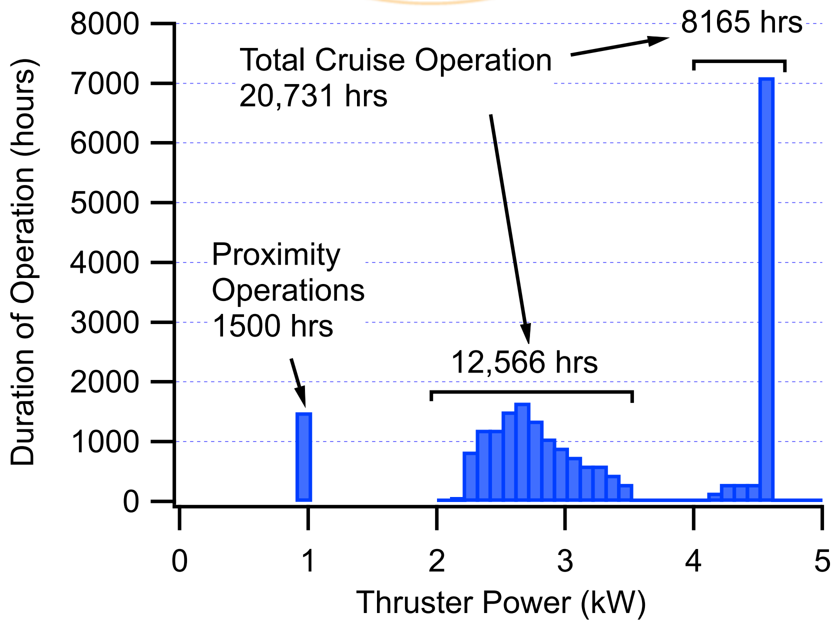




Trajectory

- Launch August 2022
- 3.5 year cruise
- 21 months orbital science operations
- EP system used for cruise and asteroid proximity operations
- SPT-140 system qualified for GEO missions at 3.0 and 4.5 kW
  - Psyche mission requires significant operation at lower powers





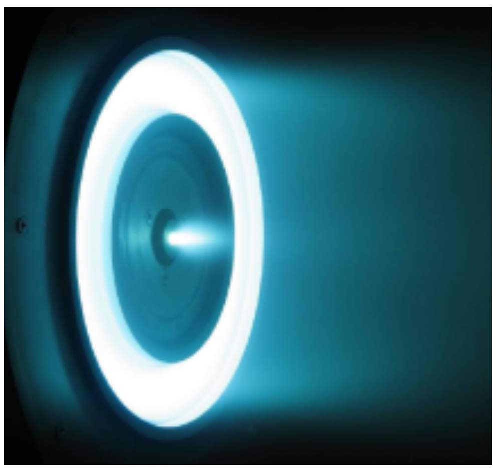
Motivation

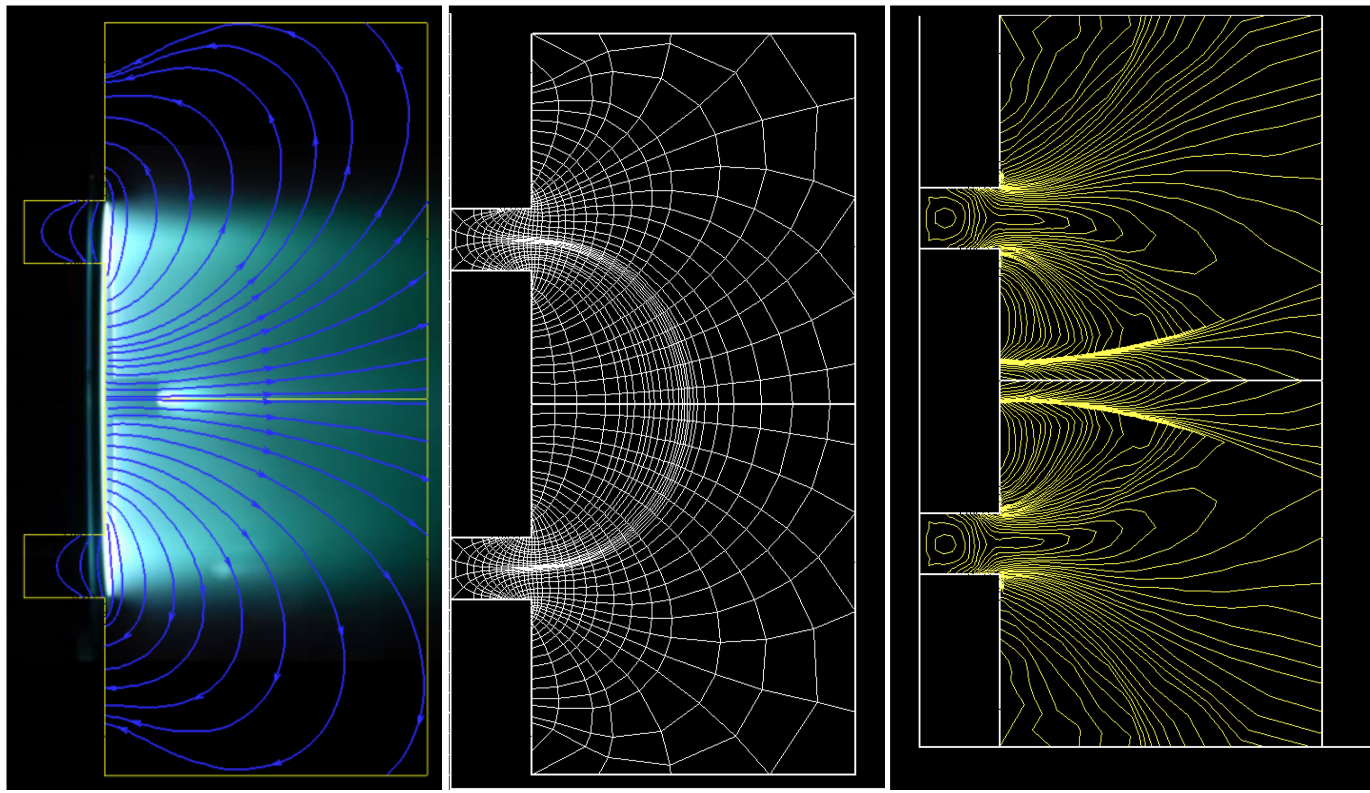
- SPT-140 shows a performance dependence on test facility background pressure (Snyder et al., JPC 2018)
  - Can modeling and simulation replicate experimental trends for varying background pressure?
  - Can modeling and simulation be used to predict performance in space for the power range used in the mission?

- Can we predict lifetime in space?
  - Can modeling and simulation predict erosion rates at the conditions of the long-duration wear test?
  - What are the expected erosion rates in space?
  - How does erosion change with time and operating condition?
  - What is the effect of erosion of the channel walls on thruster performance?

The Hall2De code

- The 2-D axisymmetric code Hall2De is a physics-based plasma and erosion solver that began development at JPL in 2008 [1] to support the design and life qualification of Hall thrusters for NASA science missions.
  - Discretization of all conservation laws on a magnetic field-aligned mesh (MFAM)
  - Two components of the electron current density field accounted for in Ohm's law
  - Sheath physics modeled in appropriate boundary conditions
  - No statistical noise in the numerical solution of the heavy-species conservation laws

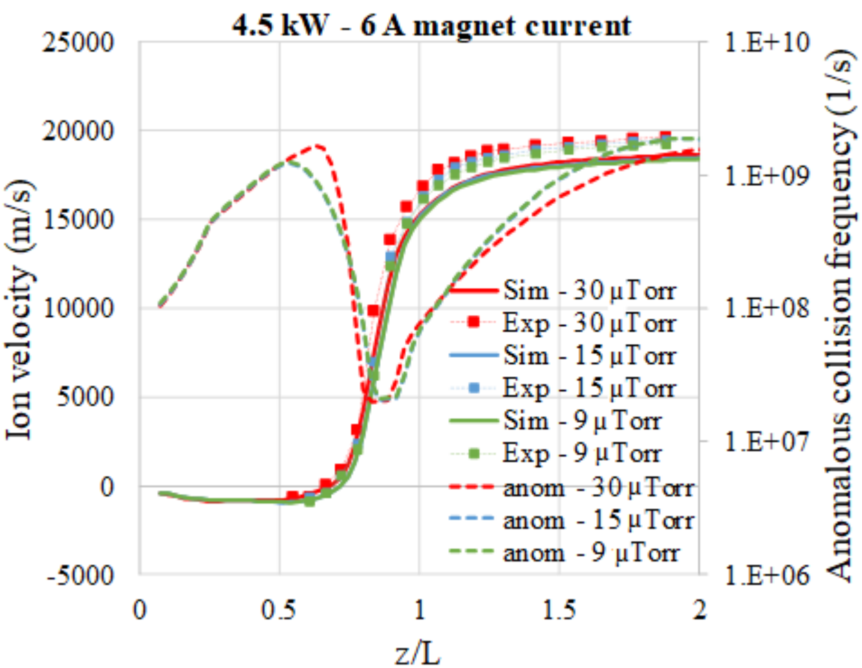


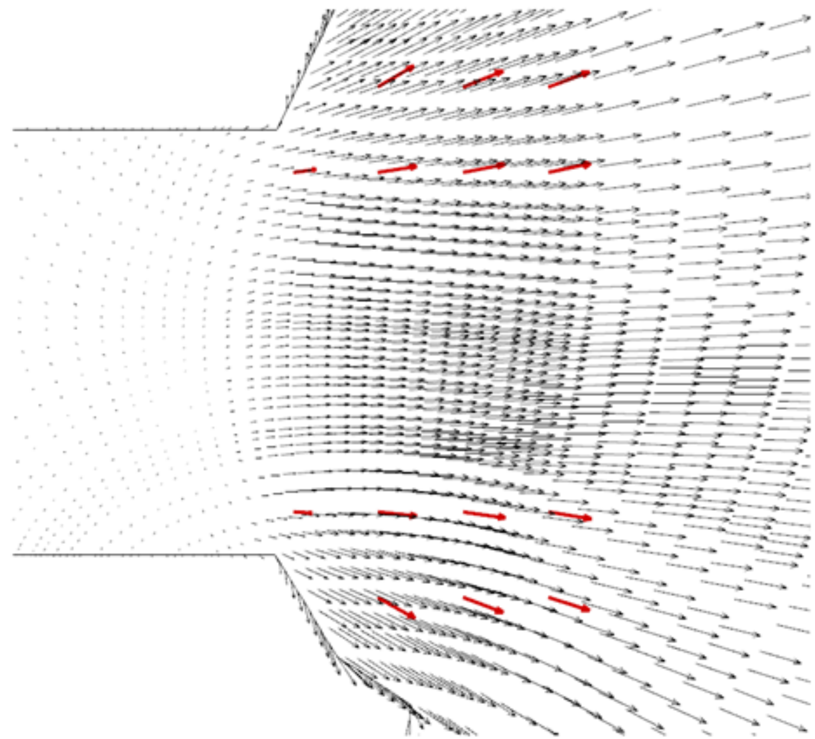


[1] First journal article on Hall2De: Mikellides, I. G., and Katz, I., "Simulation of Hall-effect Plasma Accelerators on a Magnetic-field-aligned Mesh," Physical Review E, Vol. 86, No. 4, 2012, pp. 046703 (1-17).

Comparisons between numerical simulations and experiments: plasma parameters

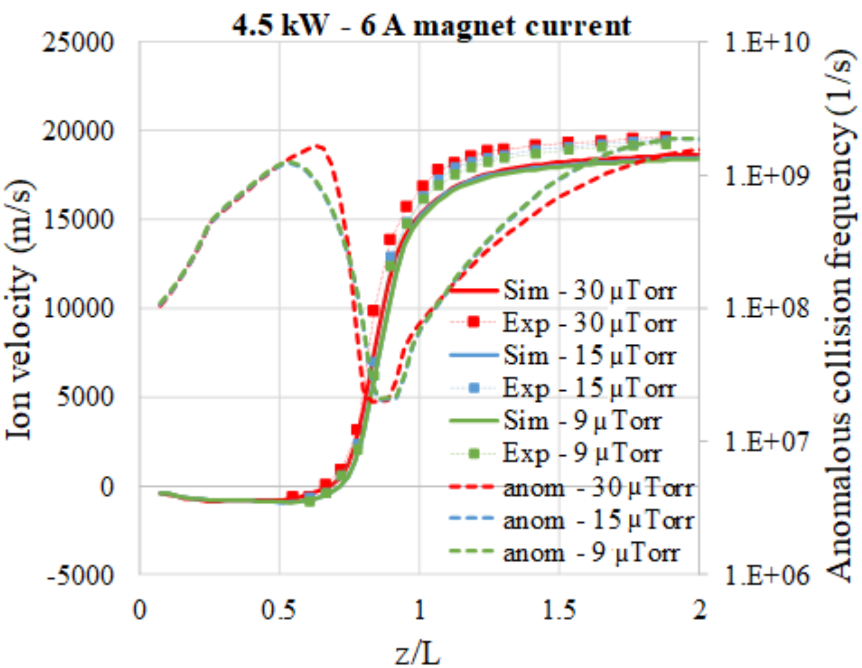
- Numerical simulations are compared with non-intrusive measurements of the ion velocity (2-D and along the channel centerline) obtained with laser-induced fluorescence (LIF)





*Comparisons for other operating conditions are summarized in the paper

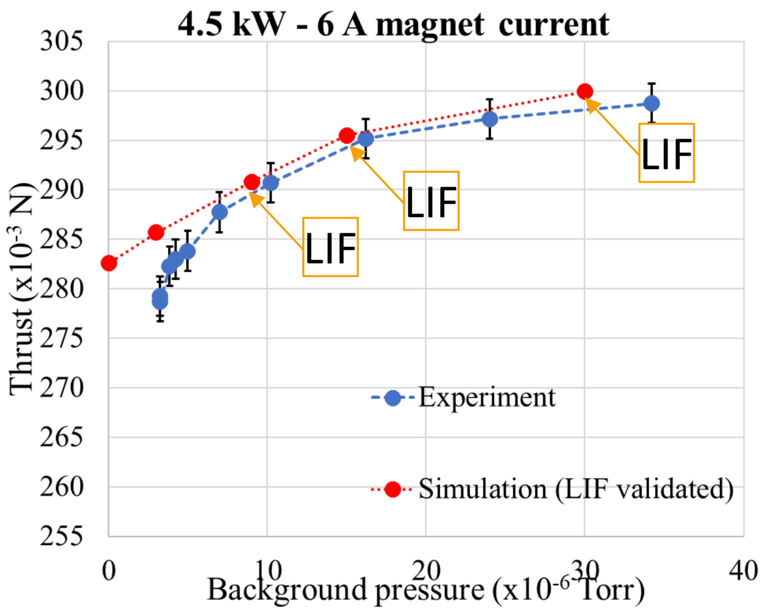
Comparisons between numerical simulations and experiments: plasma parameters

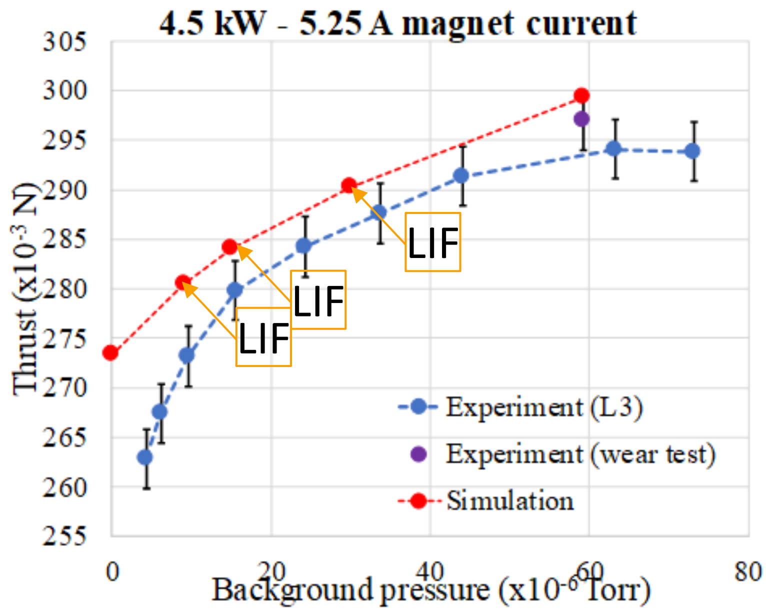


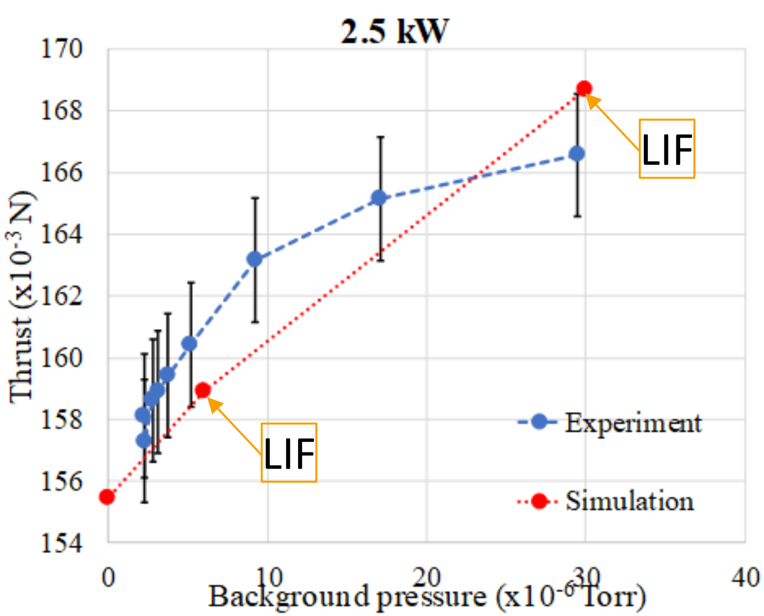
MAIN TAKEAWAYS

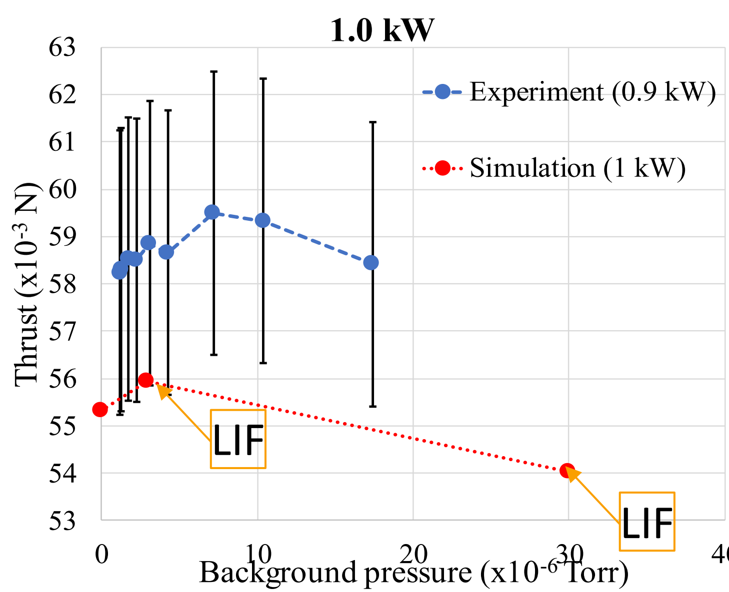
- Good agreement between simulations and experiments
- We do not observe a large shift downstream of the acceleration region at lower background pressures (up to the lowest pressure that could be achieved in the vacuum facility)
- At 4.5 kW, there is a 1-2 mm shift downstream between 30 µTorr and 15 µTorr but no shift observed between 15 µTorr and 9 µTorr

Comparisons between numerical simulations and experiments: performance









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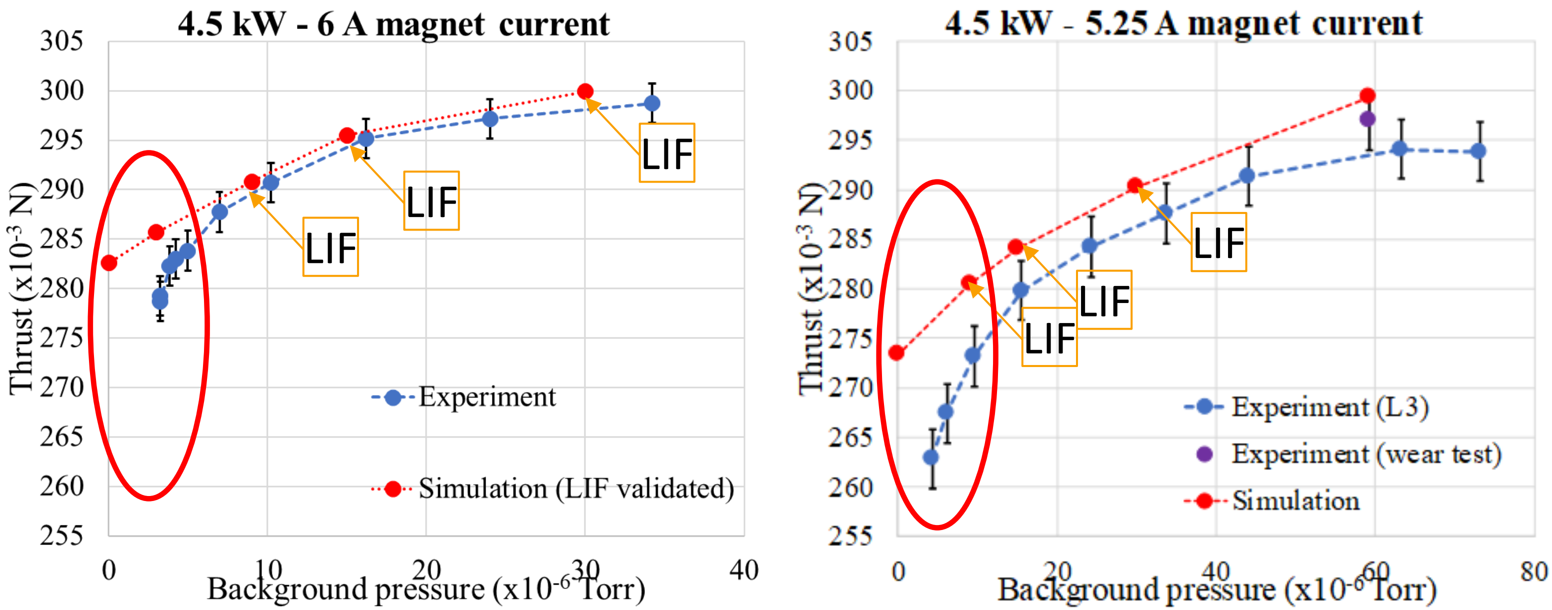


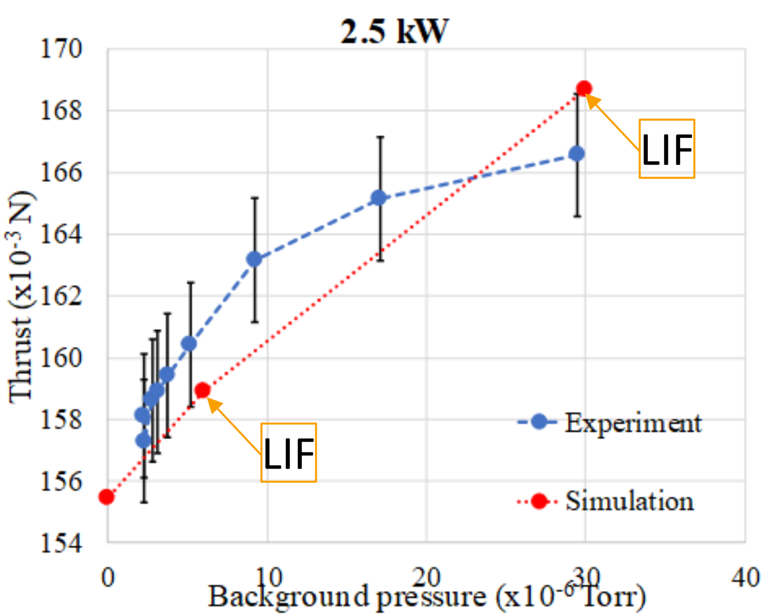
MAIN TAKEAWAYS

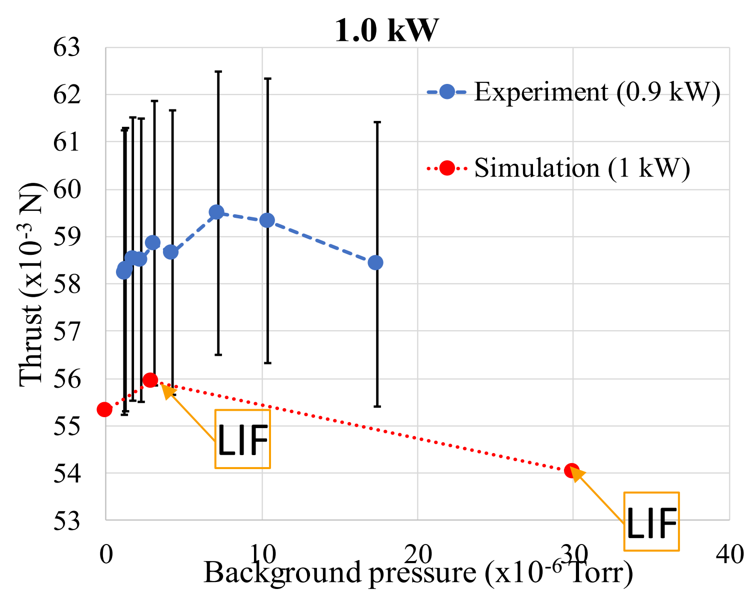
- Computed thrust agrees with measurements at locations for which the simulations could be validated by LIF
- Simulations show less steep decrease in thrust at low background pressure than measurements

Comparisons between numerical simulations and experiments: performance

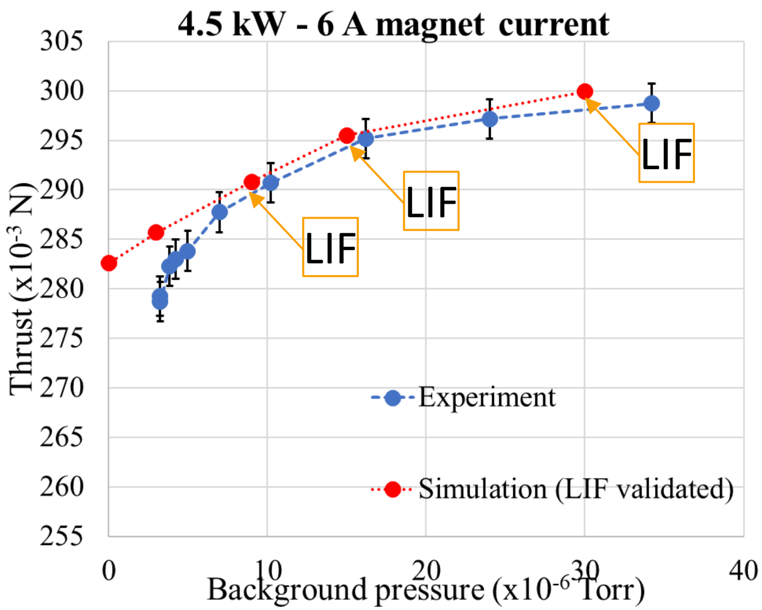
MAIN TAKEAWAYS

- Computed thrust agrees with measurements at locations for which the simulations could be validated by LIF
- Thrust does not decay with background pressure at 1.0 kW because mass flow rate increases by 10 % between 30 μTorr and 3 μTorr. In other operating conditions, mass flow rate stays approximately constant





Predicting performance in vacuum

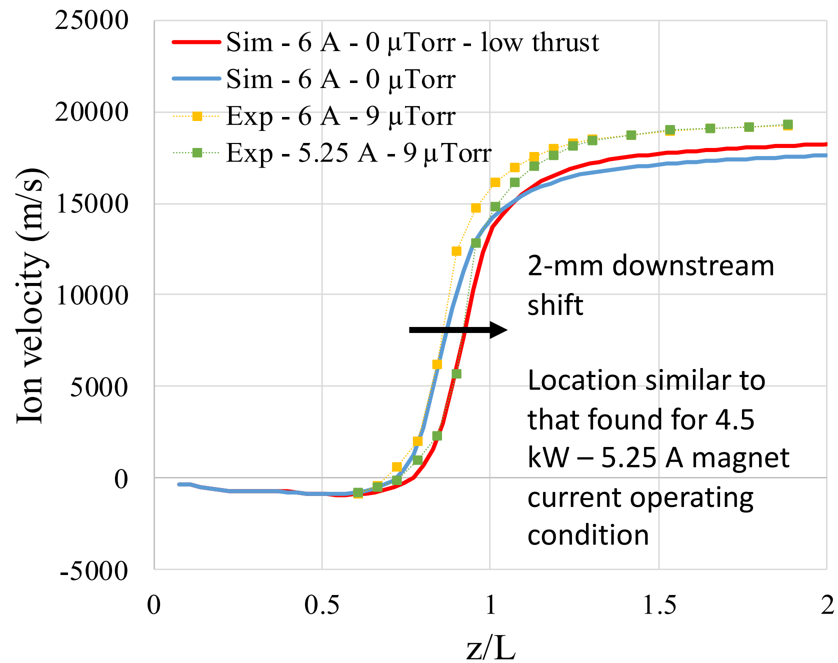


Is it possible that acceleration region moves further downstream at very low background pressure?

How far the acceleration region needs to move in order to achieve a thrust value for vacuum that is consistent with the experimental trend?

Another possible explanation for behavior in vacuum based on location of the externally mounted cathode and non-axisymmetric effects:

Mikellides, I. G., et al., IEPC 2019-410



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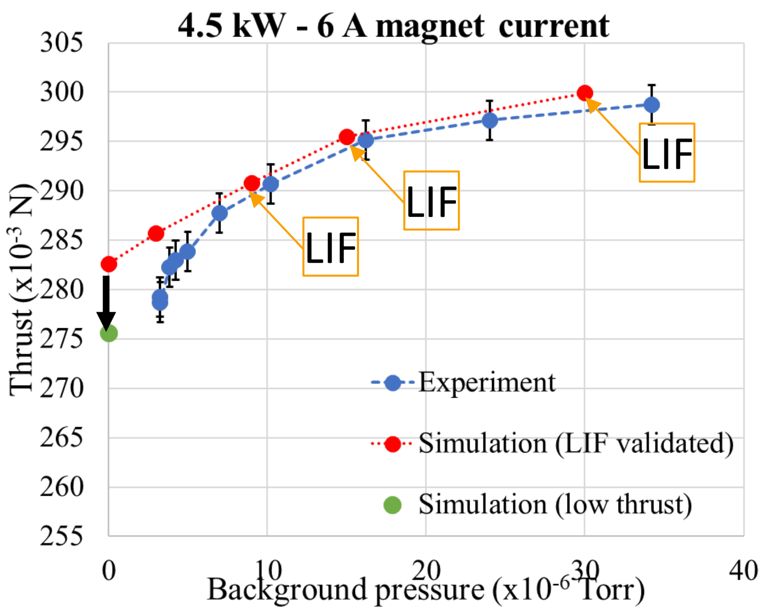

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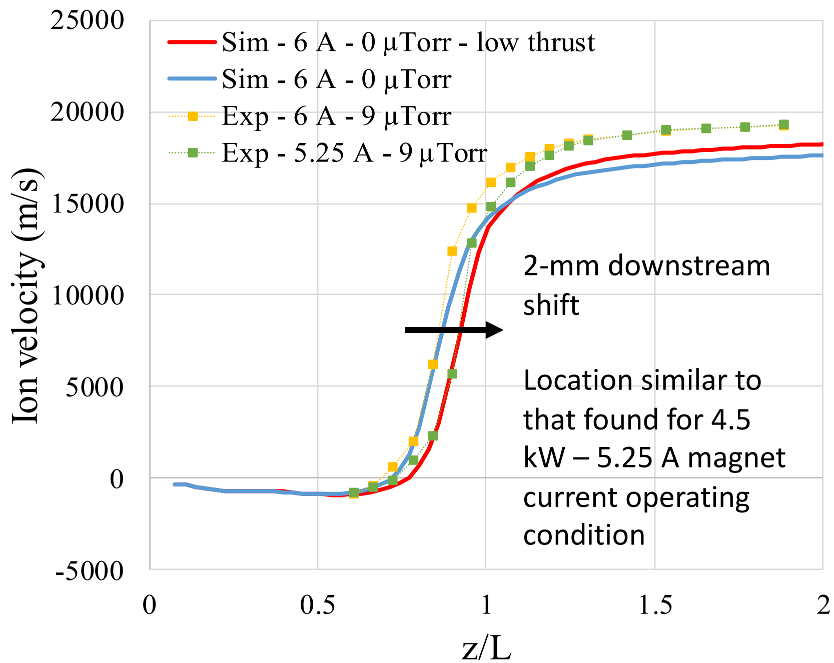

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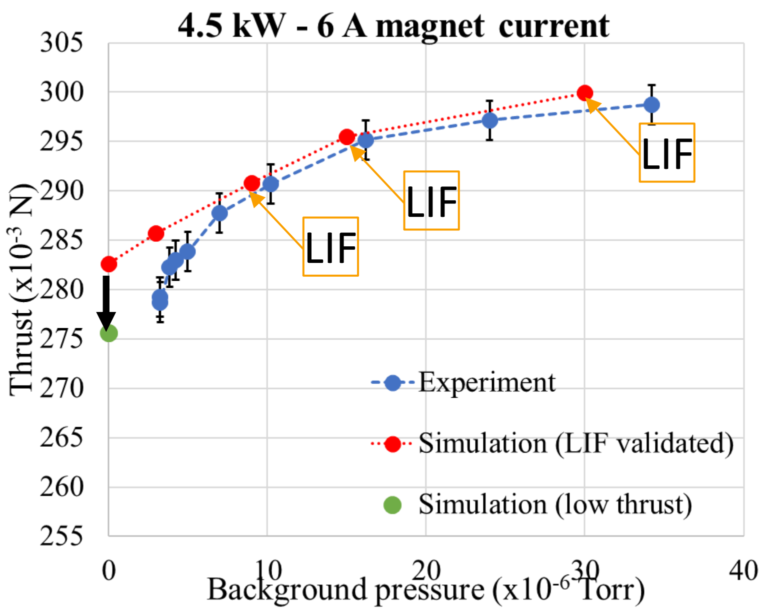
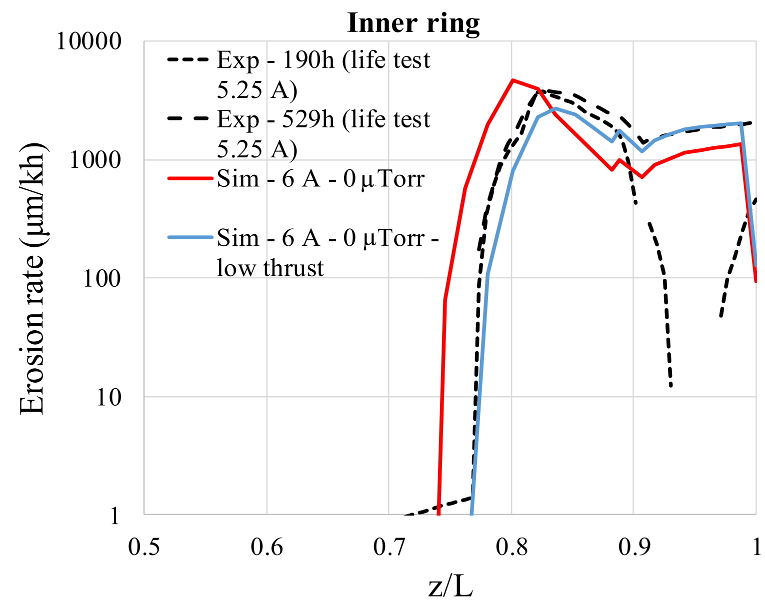
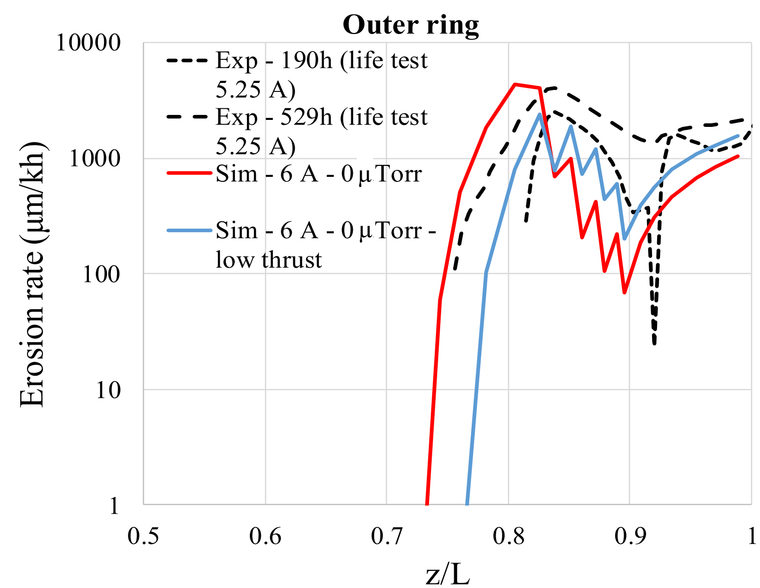
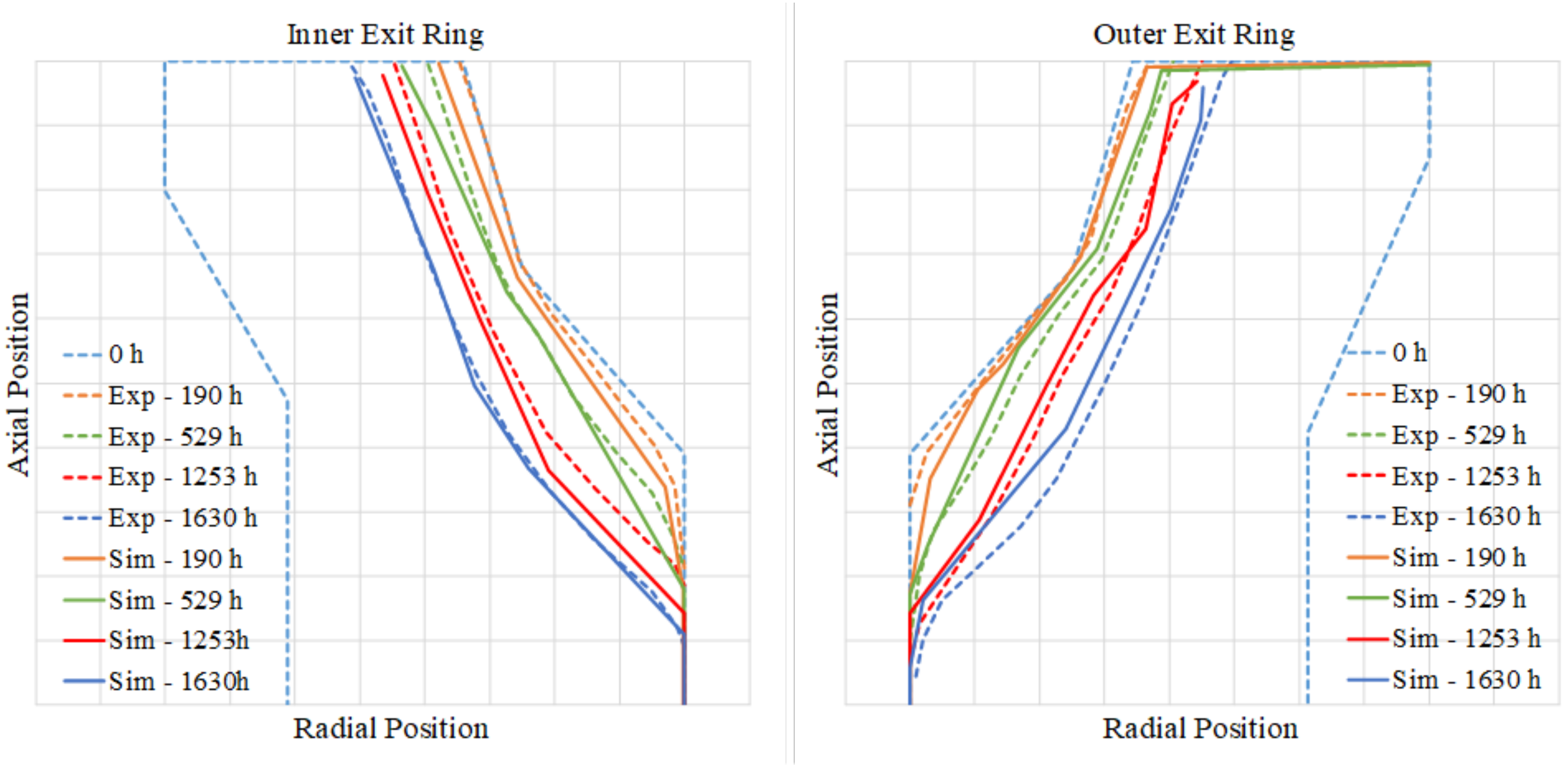




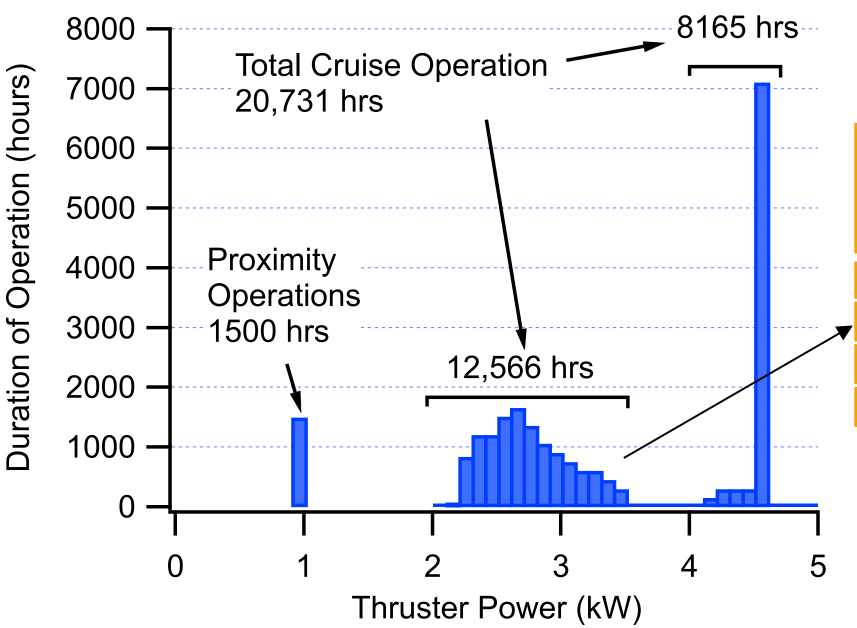


No significant change in erosion rates at the channel walls between the two solutions at vacuum

Hall2De predictions of erosion rates at wear test conditions match measurements



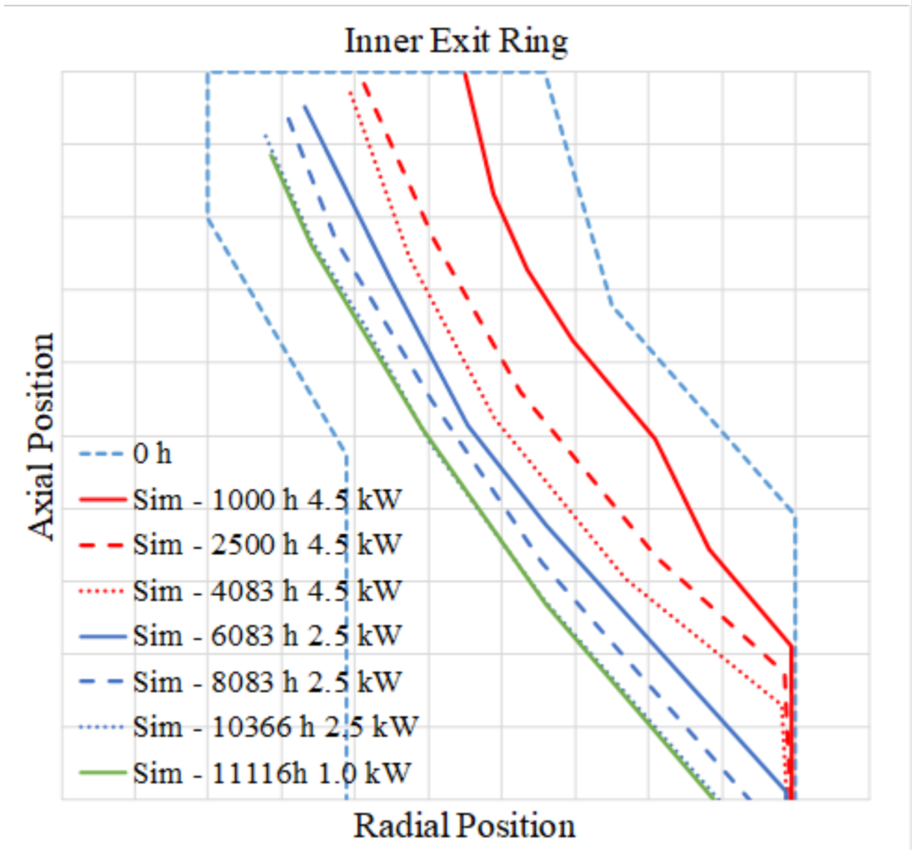
Prediction of channel erosion for a simplified mission profile for a single thruster (+ 50% margin)

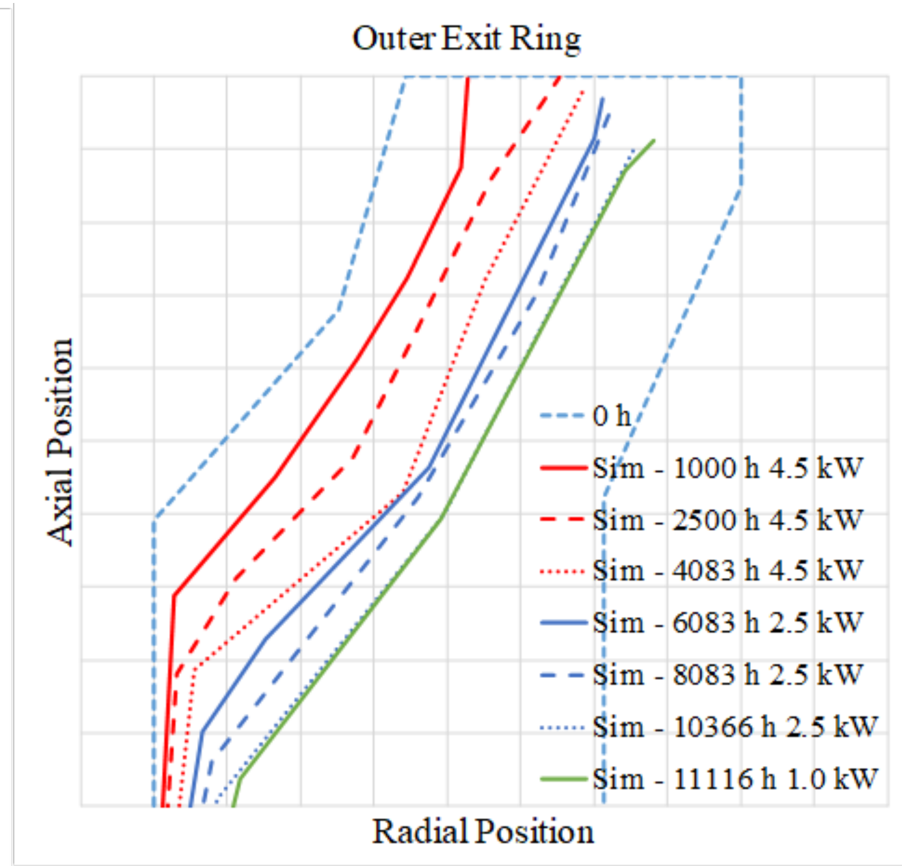


Order of Analysis	Thruster Discharge Power (kW)	Magnet current (A)	Operating Duration (with 50% margin) (h)
1	4.5	6.0	4,083
2	2.5	4.0	6,283
3	1.0	2.75	750
Total			11,116

Mid-power operation (2-3.5 kW) simplified to continuous operation at 2.5 kW in numerical analysis

Prediction of channel erosion for a simplified mission profile for a single thruster (+ 50% margin)





Prediction of time-dependent performance in space

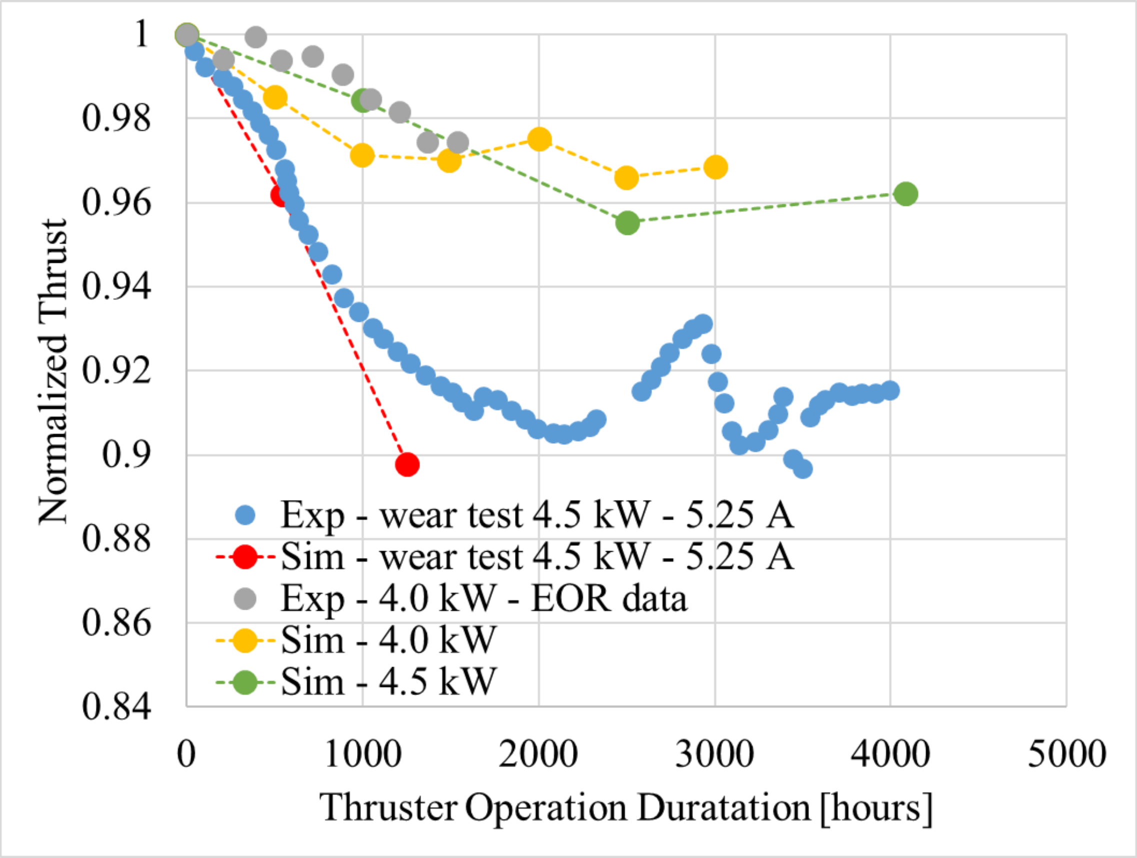
MAIN TAKEAWAYS

Thrust decay rate was very different in life test compared to the flight data

- Acceleration zone moves upstream with increased pressure
- This causes faster erosion of the thruster walls
- Thrust decreases due to greater wall erosion because of increased divergence losses
- **As erosion rates decrease and especially after location of acceleration stops eroding, thrust becomes approximately constant**

Simulations do a very good job of capturing the laboratory and flight data

Higher expected thrust with time beneficial for mission planning (i.e., less propellant necessary)



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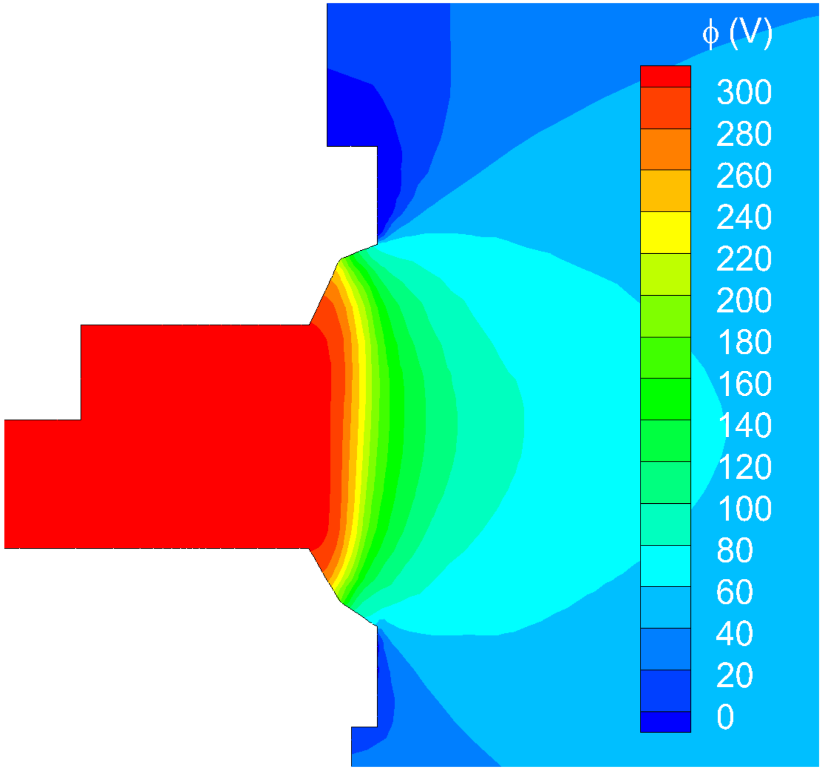

0 h

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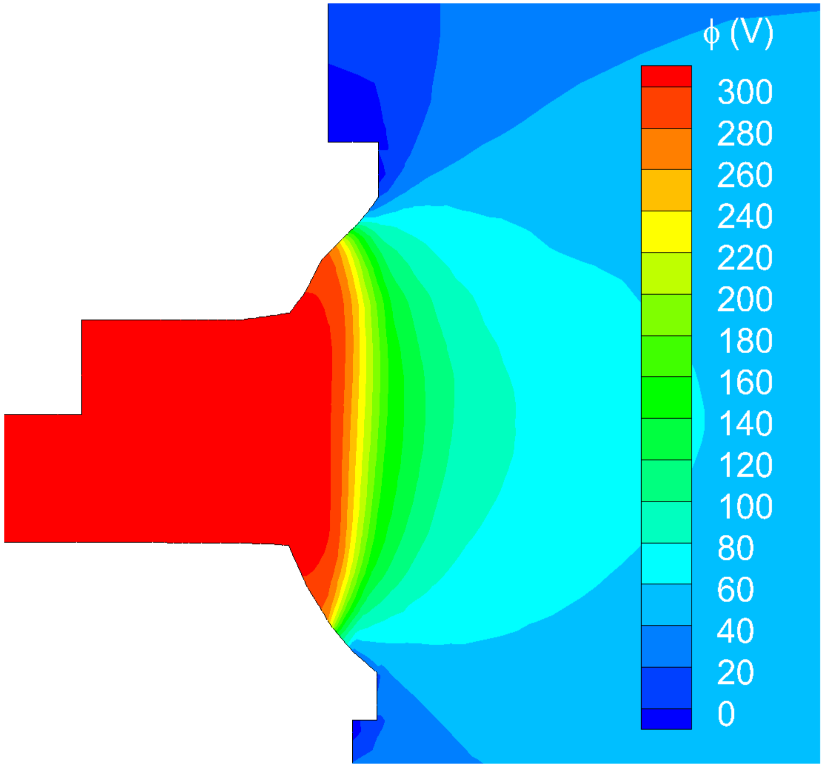

2500 h

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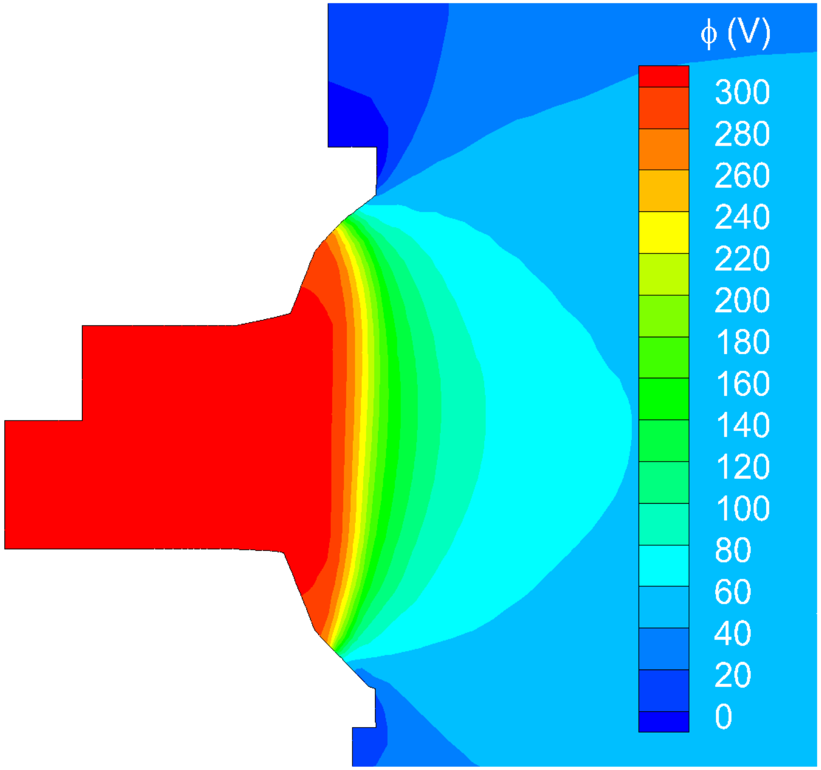

4000 h

Concluding remarks

- SPT-140 shows a performance dependence on test facility background pressure (Snyder et al., JPC 2018)
  - Can modeling and simulation replicate experimental trends for varying background pressure? **Yes, at background pressures for which simulations have been validated by LIF measurements**
  - Can modeling and simulation be used to predict performance in space for the power range used in the mission? **Yes. However some assumptions may be necessary (i.e., assume a downstream shift in acceleration region or non-axisymmetric effects)**

- Can we predict lifetime in space?
  - Can modeling and simulation predict erosion rates at the conditions of the long-duration wear test? **Yes. Excellent agreement between simulation and wear test channel profiles**
  - What are the expected erosion rates in space? **Predicted erosion rates in space for Psyche mission profile + 50% margin. Channel not completely eroded at end of mission**
  - How does erosion change with time and operating condition? **Erosion rates become lower with time and at low power operating conditions**
  - What is the effect of erosion of the channel walls on thruster performance? **Identified that decay of thrust in vacuum conditions as a function of time is less than that measured during wear test**