Correlation between empirical and self-consistent models of Hall thruster anomalous transport

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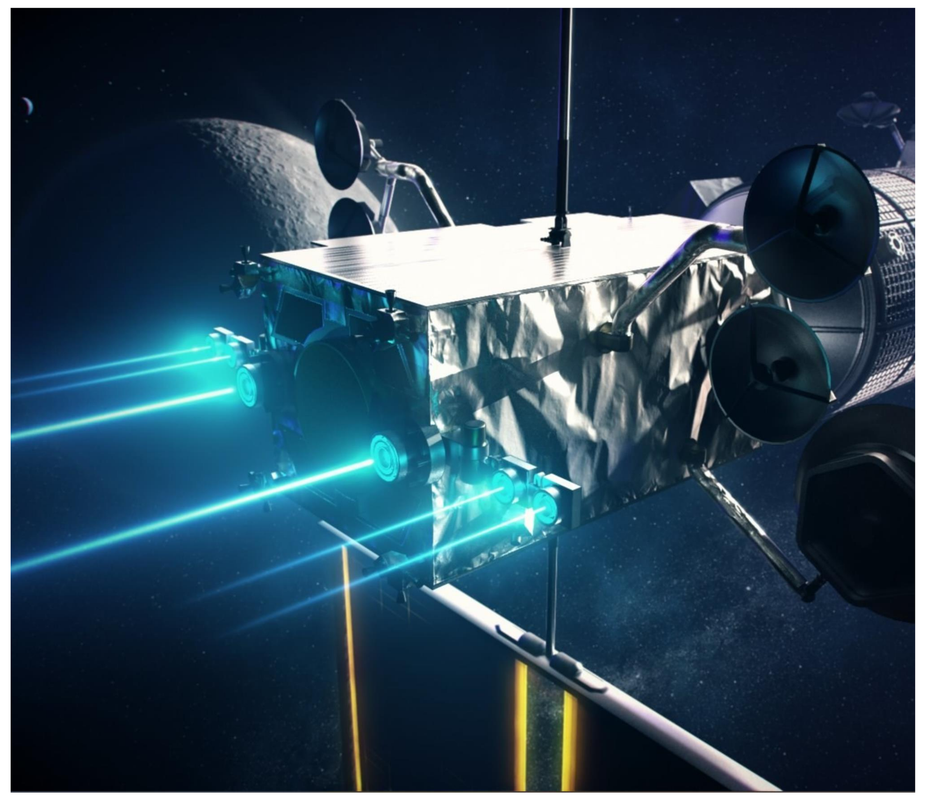
Problem: Hall thruster simulations are not predictive due to incomplete understanding of electron transport physics.

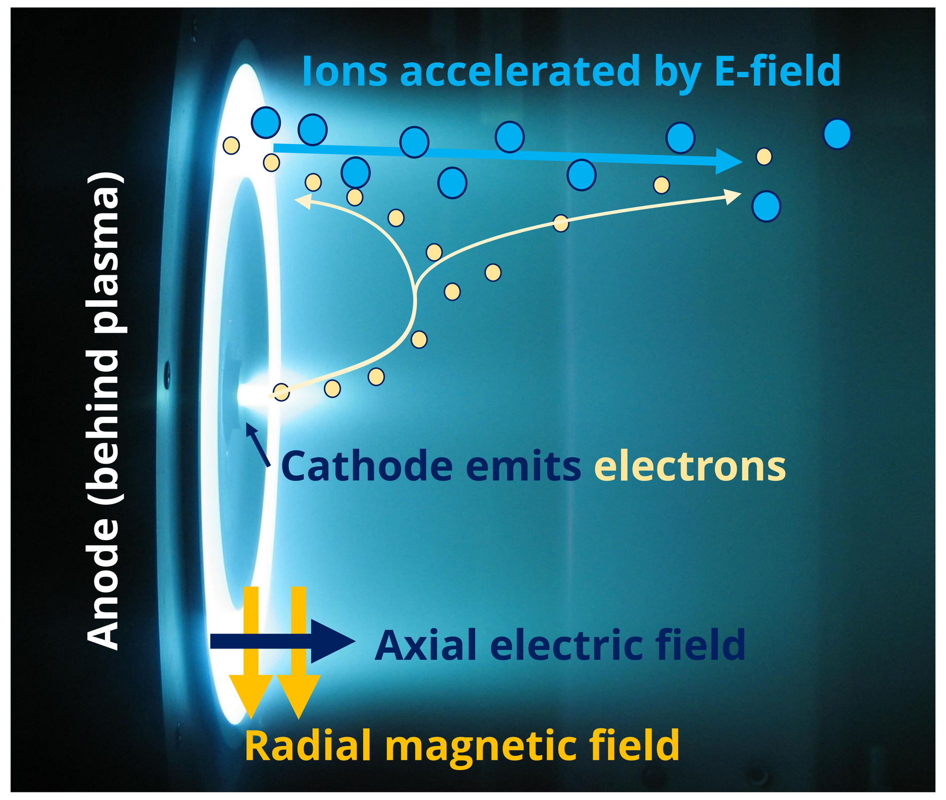


NASA Lunar Gateway concept art

Hall thrusters are electric spacecraft propulsion devices which use crossed electric and magnetic fields to generate and accelerate a plasma to produce thrust.

They are widely used for satellite station-keeping but there is **increasing interest in deep space and crewed missions**

We would like to use simulation to aid the design of new thrusters. **However, current simulations are not predictive!**

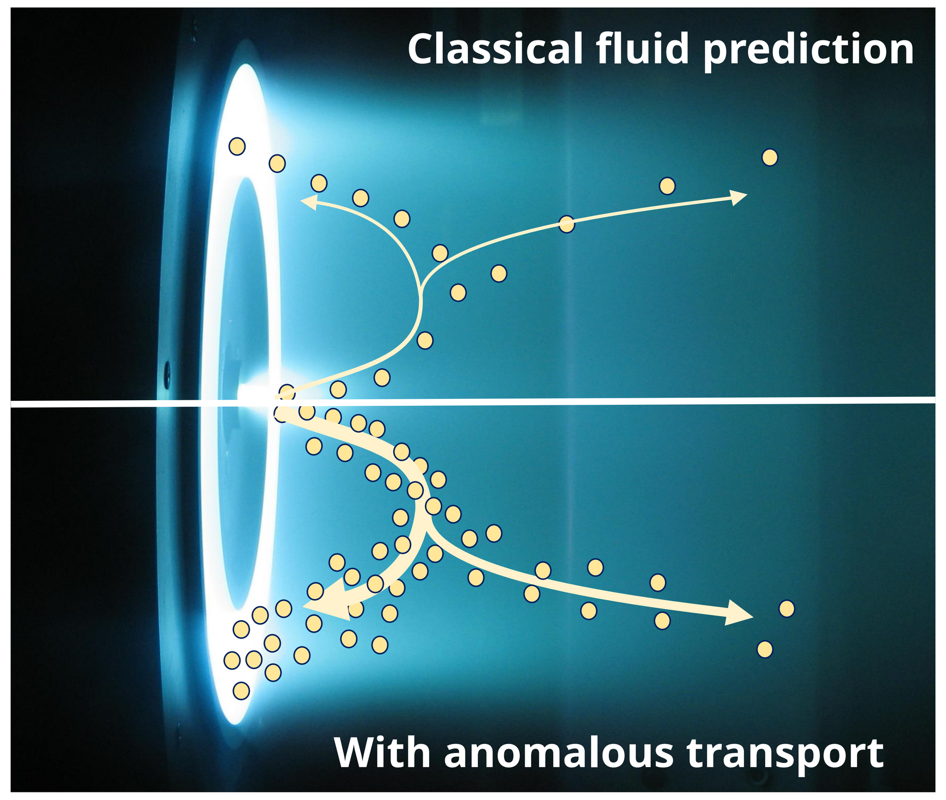


H9 Hall thruster operating on Xenon

Electrons are inhibited in their drift from cathode to anode by magnetic field, electron mobility should be very low.

However, the electron current we observe in Hall thrusters is 10-100x what we would predict from classical theory. **We need an enhanced "anomalous" mobility to make simulations match experiment**

Many models (empirical and first-principles) have been proposed, but there is little experimental data to compare to.

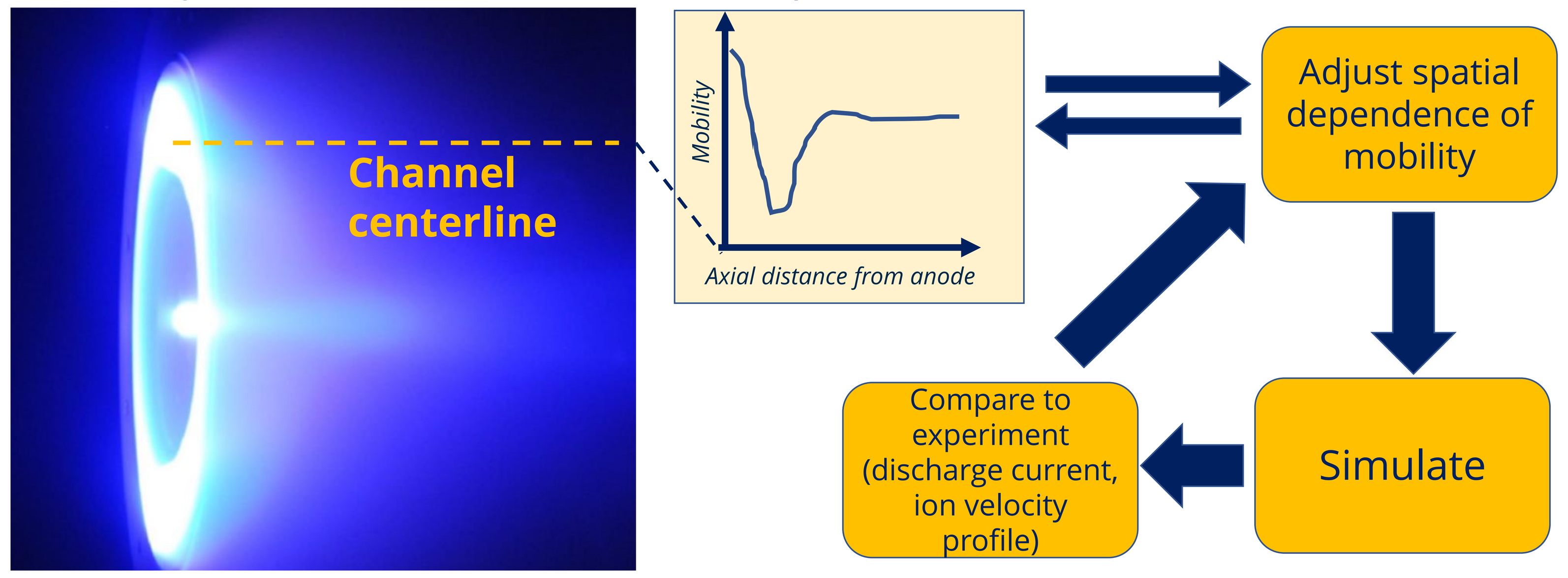


Enhanced electron transport

Question: How can we calibrate and validate proposed models of anomalous electron transport in Hall thrusters?

Empirically inferring electron mobility

In the absence of a suitable model for the anomalous mobility, researchers typically make simulations match experiment by prescribing it along the channel centerline of the Hall thruster and varying the spatial dependence of the transport iteratively until the simulations match experiment[1].



H9 operating on Krypton

The mobilities inferred from this empirical calibration procedure are often treated as surrogate measurements of the true anomalous mobility in the thruster.

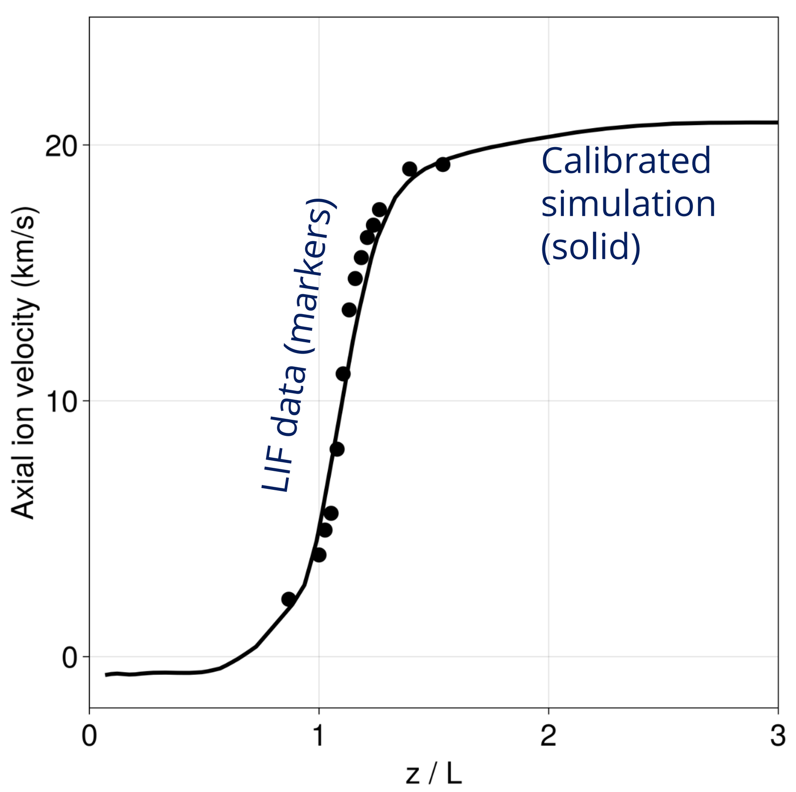
Idea: calibrate self-consistent models by comparing to empirical mobilities

Generating an empirical reference simulation

- Calibrated a Hall2De (2D axisymmetric fluid code from JPL)[1] simulation to match **time-averaged** experimental discharge current and ion velocity profile for H9 Hall thruster at 300V and 15 A.
- Required 29 iterations, each simulation took ~ 1 day.
- We can match experiment well but thrust is somewhat low.

Performance metrics

Case	T	I_d	η_a
Experiment	292.9 ± 3.5 mN	15.0 A	64.4 ± 1.5 %
Ref. sim.	258.3 mN	15.2 A	49.4%



Comparing empirical and self-consistent models

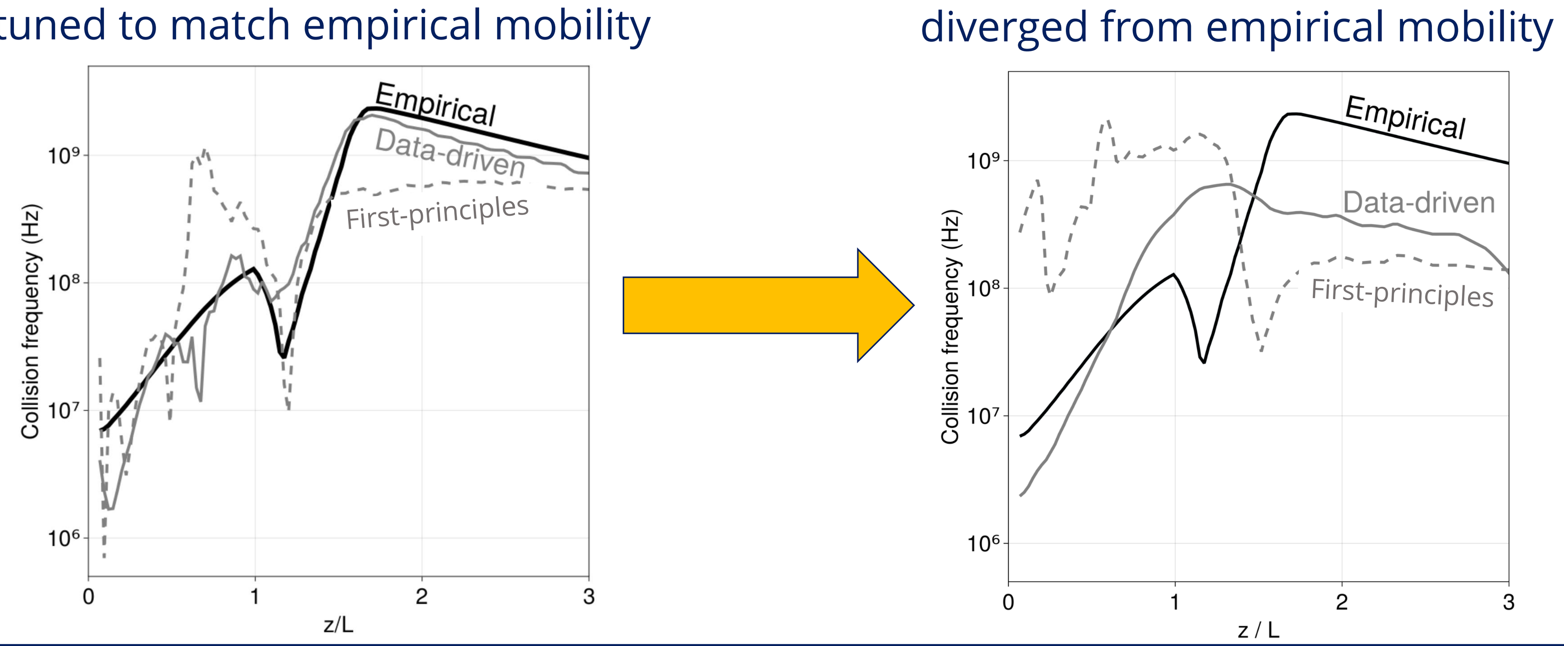
Can we use empirically-inferred mobility to calibrate better models?

Models
Two algebraic models investigated. Both integrated into Hall2De and allowed to update at each solver timestep along.

1. *First-Principles* model derived from assumptions about the scaling of Hall thruster turbulence[2].
2. *Data-Driven* model obtained by regressing a dataset of empirical mobilities (not including H9)[3]

Before simulation, models tuned to match empirical mobility

After simulation, models have diverged from empirical mobility



Performance is poor, despite initial agreement

- First-principles model agrees better with reference simulation despite worse initial agreement
- Data-driven model matches efficiency better but predicts discharge current 2x experiment
- Velocity profile of first-principles model shifted downstream from empirical profile
- Velocity profile of data-driven profile much more shallow than empirical profile due to high mobility in the acceleration region.
- **Takeaway: agreement with empirical mobility does not guarantee model quality.**

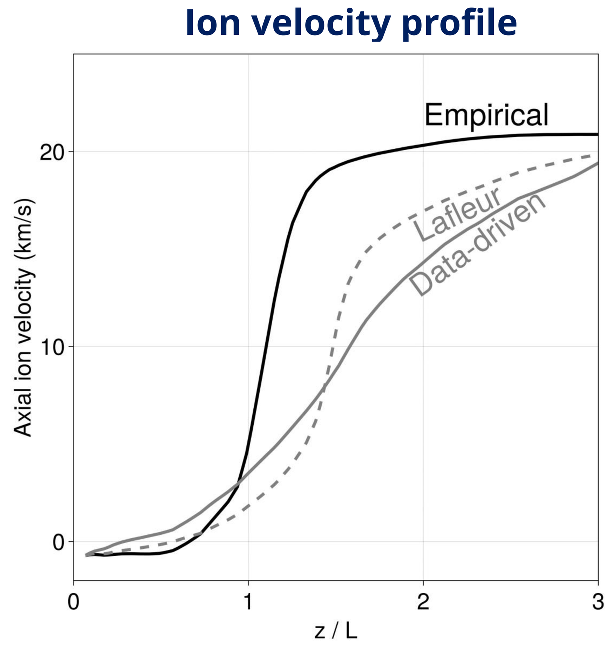
Why does this occur?

What does it mean?

Performance metrics

Case	T	I_d	η_a
Ref. sim.	258.3 mN	15.2 A	49.4%
First-principles (FP)	257.6 mN	19.7 A	37.9%
Data-driven (DD)	333.6 mN	31.1 A	40.3%

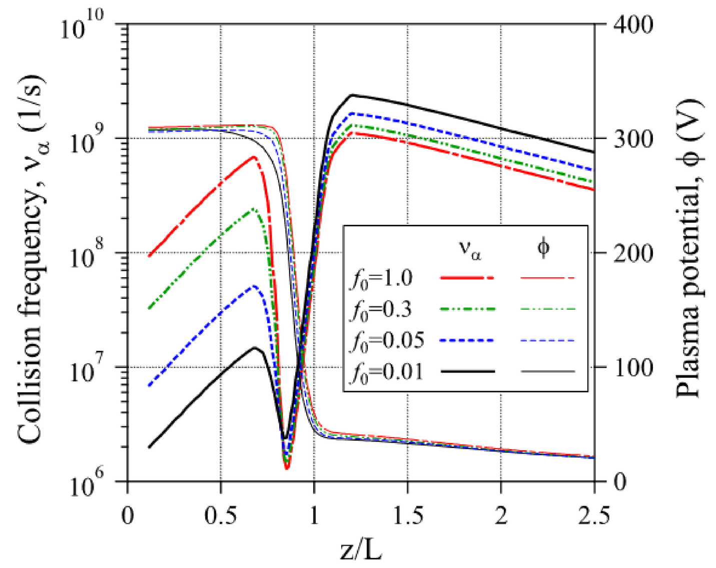
Ion velocity profile



Discussion

Reasons for divergence from empirically-inferred mobility

1. **Non-linearity in governing equations** means small deviations from empirical mobility can be amplified
2. **Hall thrusters are oscillatory, so evaluating models on time-averaged data is subject to artifacts** (product of averages is not equal to the average of products)
3. **Empirically-inferred mobilities are non-unique**[4] and large changes in mobility in certain parts of the device may not change observables much (right)



Implications for modeling anomalous transport

Instead of inferring static anomalous mobility using simulations, should try to measure it experimentally as a function of time.
This would give much more information about the dynamic behavior of the transport and would provide more data for model calibration and validation

Conclusion

Empirically-inferred mobility profiles are useful for making simulations match experiment. However, they should not be treated as surrogate measurements of the anomalous transport. Models should instead be compared to direct time-resolved measurements of the anomalous mobility (if available) or implemented directly into simulations to gauge their performance.

References and Acknowledgements

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[3]*B. Jorns, Plasma Sources Sci. Technol. 27 104007 (2018)*
[4]*I. G. Mikellides and A. L. Ortega. Plasma Sources Sci. Technol. 28 014003 (2019)*

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