National Aeronautics and Space Administration

Hall Thruster Stability at Low Power and High Specific Impulse

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Objectives

- The objectives of this collaboration are to investigate, explain, predict, and mitigate the severe plasma instabilities that occur in magnetically-shielded (MS) Hall thrusters at high specific impulse and low power.

Background

- Magnetic shielding is a design configuration for Hall thrusters developed by the Electric Propulsion Group that radically increases thruster life to the 10-50 kh necessary for deep space exploration.
- However, for a given magnetically-shielded thruster, it has been found that if the device is throttled below <60% nominal power at high specific impulse (> 2500 s), it will exhibit large amplitude current oscillations.
- This unstable operation when throttling limits the mission performance where high-specific impulse is needed as solar power decreases.
- We believe that there may be a way to overcome this challenge through a detailed physics-based investigation.

Approach and Results

Task I: Generate experimental map of the mode transition as a function of operating condition (current, voltage, magnetic field).

Fig. 1 shows the results of the measured stability maps on the H9 Hall thruster. Fig 1a shows the ratio of the amplitude of the peak-to-peak oscillations compared to the mean current expressed as a percentage. Fig. 1b shows the frequency of the dominant oscillation at each operating condition. There is a strong correlation between low frequency (< 20 kHz) and the onset of the unstable mode. Fig. 1c shows the frequency of the oscillation associated with the unstable mode as a function of operating condition.

Task II: At an unstable operating condition, experimentally identify where oscillations originate in the thruster and their fluctuation levels.

Fig. 3 shows spatially-averaged plasma parameters in the acceleration zone as functions of discharge current phase. These were inferred from 1D measurements in Year 2 [A]. We leveraged the amplitude and phase relationships of these quantities to inform the 0D mode transition theory [B].

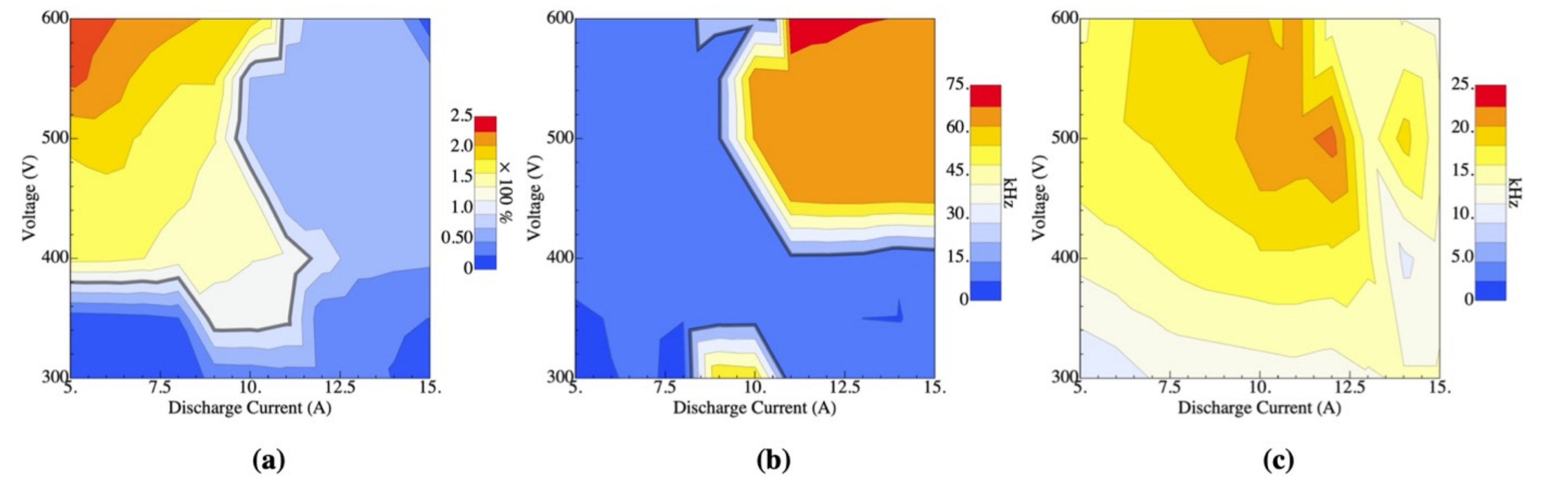

Figure 1: Measurements of a) relative peak-to-peak discharge current oscillations, b) dominant frequency of oscillation, and c) frequency of the oscillation as a function of discharge current and voltage. The bolded contour on (a) is the 100% fluctuation level while in (b) it is the mode transition.

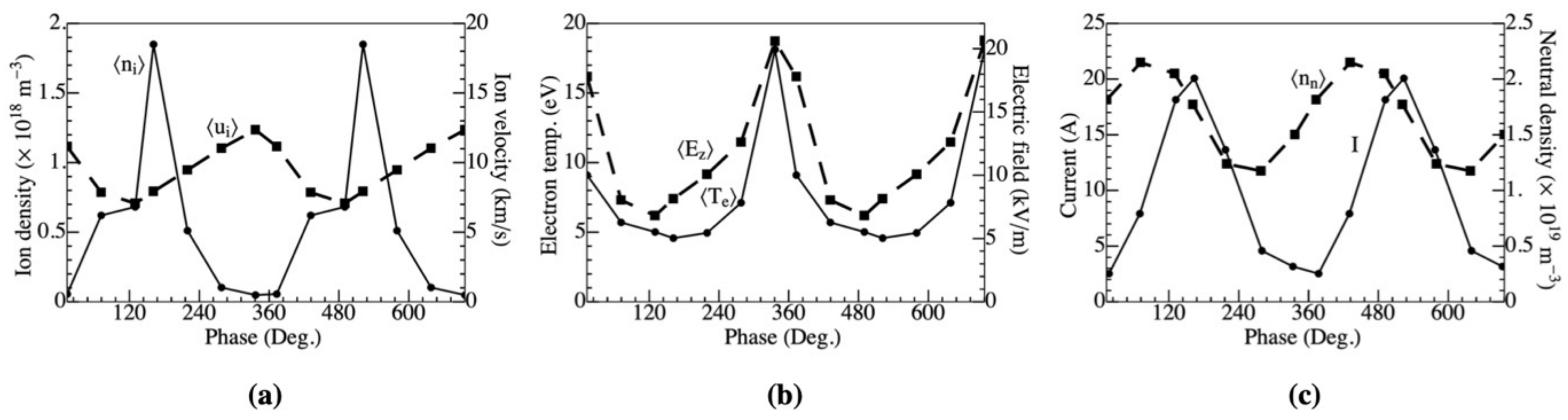

Figure 2: Spatially-averaged measurements of a) plasma density and ion velocity, b) electric field and electron temperature, and c) current and neutral density in the acceleration zone as a function of phase of the discharge current oscillation.

Task III: Combine results from I and II to guide first-principles perturbation analysis. Apply model to identify analytical stability criteria for transition.

Based on the measurements, we developed a quasi-0D model for the mode transition and frequency of oscillations. Fig. 3 compares the model and measurements of current oscillations and power spectra. The strong agreement illustrates the ability of the model to capture the mode transition. Fig. 4 demonstrates the model validity over the full parameter space.

Task IV: Leverage tools and criteria developed in Phase III to predict the mode transition and to explore methods to mitigate it.

Our major insight from modeling was that the mode transition can be related to the transit time of the neutrals in the thruster. We in turn demonstrated experimentally in Year 3 that by heating the anode, we can reduce this transit time and shift the current transition occurs to a lower value (Fig. 5). This was a successful demonstration of how to partially mitigate the transition.

Significance/Benefits to JPL and NASA

This effort has culminated in a new theory for the mode transition in low current, high voltage, magnetically shielded Hall thrusters. We in turn have leveraged this result to investigate a mitigation strategy for expanding the stability margin and have identified others that could be explored in the future. The abilities to predict the transition and to identify mitigations are the major benefits. These new capabilities can be leveraged to inform new thruster designs that can access a larger trade space of interest to 4X missions.

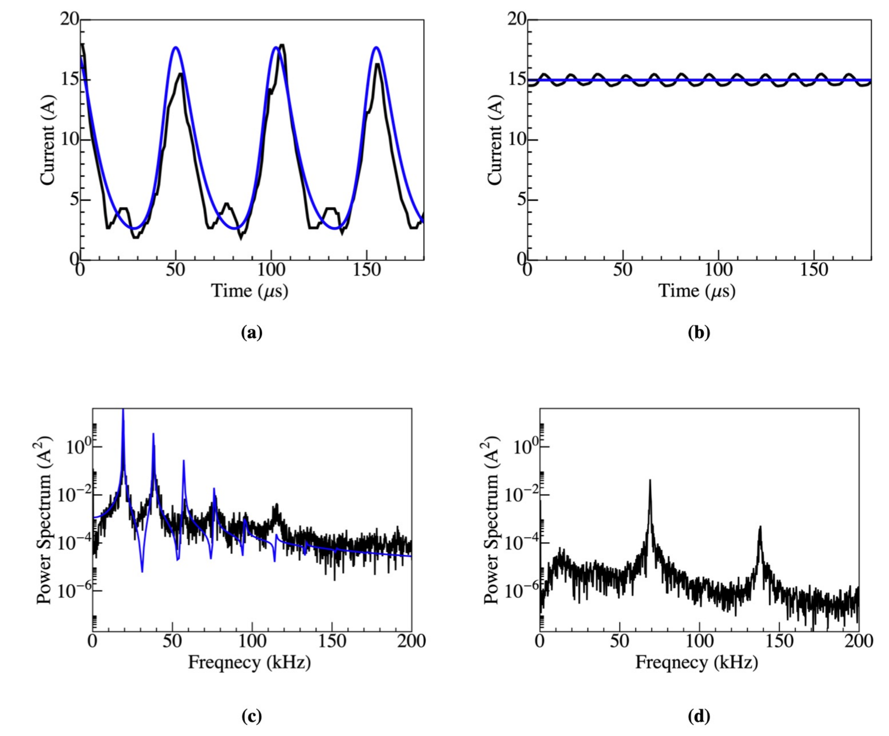

Figure 3: a) Comparison of the measured (black) and modeled (blue) discharge current oscillations in time at a) 600 V and 7.5A and b) 600 V and 15 A. Discharge current power spectra at c) 600 V and 7.5 A and d) 600V and 15A. The model result for the power spectrum is not shown for (d) as the oscillation level is negligible at this level.

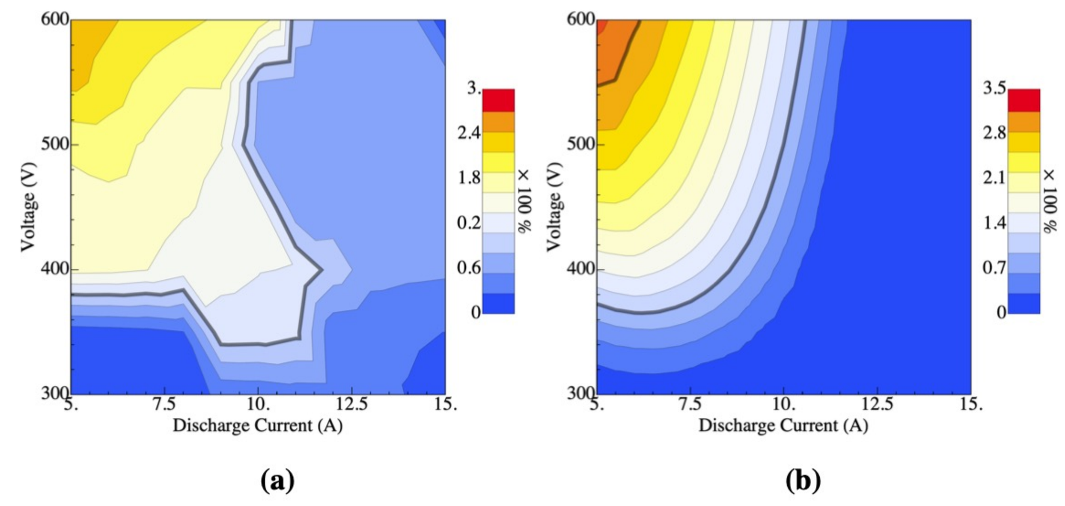

Figure 4: Relative peak-to-peak in discharge current oscillation level from a) experiment and b) quasi-0D model.

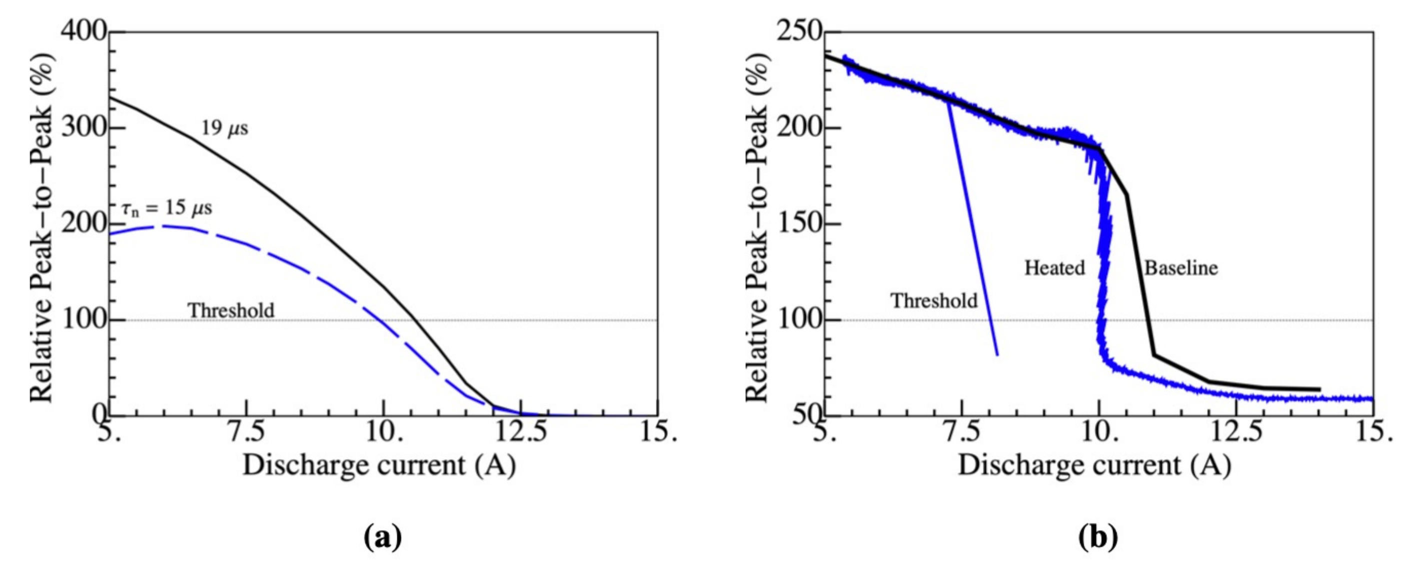

Figure 5: Comparison of the oscillation amplitude at 600 V for a) model predictions for different neutral transit times and b) measurements for different anode temperatures as a function of discharge current.

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Publications:

[A] Ethan Dale and Benjamin Jorns, “Experimental characterization of Hall thruster breathing mode dynamics,” Journal of Applied Physics. **130**, 133302 (2021)

[B] B. Jorns, M. Byrne, L. Su, P. Roberts, and R. Hofer, “Prediction and Mitigation of the Mode Transition in a Magnetically Shielded Hall Thruster at High-Specific Impulse and Low Current,” 37th IEPC, IEPC-2022-372.

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