National Aeronautics and Space Administration

# Hall Thruster Stability at Low Power and High Specific Impulse

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**Program: FY21 SURP** **Strategic Focus Area: Electric propulsion**

## Objectives

The objectives of this collaboration with the University of Michigan are to investigate, explain, predict, and mitigate the severe plasma instabilities that occur in magnetically-shielded (MS) Hall thrusters at high specific impulse (discharge voltage) and low power. Magnetic shielding is a design configuration for Hall thrusters developed by 353B in 2011-2012 that drastically increases thruster life to the 10-50 kh necessary for deep space exploration. Through extensive efforts conducted at JPL over the past decade, it has been shown that MS thrusters can be optimized for a wide range of power levels (500 W to 20 kW) and specific impulse (1500-3000 s) to accommodate an expansive range of mission profiles. However, once a MS thruster is built for a given power level, it has been found that if the device is throttled below 50% the nominal design point at high specific impulse (> 2000 s), it will exhibit large amplitude and high frequency (~10-30 kHz) current oscillations. These oscillations can cause life-limiting damage to the thruster. This unstable operation when throttling limits the common mission profile where there is a need to maintain high-specific as solar power decreases with distance from the sun.

## Background

Hall thrusters are already considered a core technology by JPL. A 12.5 kW system is actively being developed for NASA's Advanced Electric Propulsion System (AEPS) program, a 4.5 kW commercial system will fly on the Psyche mission in 2022, and JPL has developed a sub-kW Hall thruster for a range of mission opportunities. With that said, the AEPS program would not have been possible without a fundamental research program that emerged from JPL's electric propulsion group. Indeed, it was through a combination of experiment, analysis, and numerical simulation that enabled the identification of the physics of magnetic shielding by JPL, which effectively prolonged thruster life by an order of magnitude.

Before MS, although Hall thrusters were attractive for a wide range of missions, their lifetime was a limiting factor. We are at a similar technological impasse right now for MS thrusters operating at low power and high specific impulse. Although there is a significant pull for this technology for 4X missions spanning across the solar system, their performance at high solar range suffers unless they can maintain high specific impulse at low power. We believe that there may be a way to overcome this challenge through a detailed physics-based investigation.

## Approach and Results

*Summary of Approach*

Task I: Generate experimental map between operating conditions (flow rate, magnetic field, voltage, etc.) and transition to instability for the University of Michigan's laboratory-model MS Hall thruster.

Task II: At an unstable operating condition, experimentally identify where oscillations originate in thruster and the phase relationship between fluctuating quantities.

Task III: Combine results from I and II to guide model-based discovery, first-principles perturbation analysis, and reduced fidelity numerical modeling. Apply models to hypothesize physical mechanism driving the stability.

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

*Progress to date*

In Year 2 of this effort, we performed additional experiments to expand the range of the stability map of the test-article, a 9-kW laboratory thruster, at the University of Michigan (Task I). We employed a laser-based method to measure the time-resolved plasma properties inside the thruster discharge (Task II). We used results from this study to inform a new quasi-0D model for the stability (Task III). And, we have applied the results from Task III to identify a possible mitigation strategy for operating the thruster at low power and high specific impulse (Task IV).

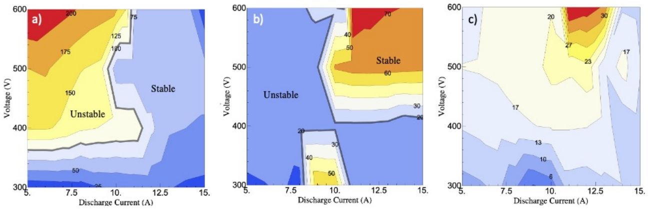

**Figure 1.** Parametric plots as a function of discharge current and discharge voltage. a) Ratio of the amplitude of the peak-to-peak oscillations in discharge current compared to the mean value expressed as a percentage. Gray line denotes a transition to oscillations greater than 100%. b) The frequency in kilohertz of the dominant oscillation in the discharge current. Dark line corresponds to the 20 kHz mark and is correlated with transition to instability. c) Frequency of the oscillation associated with the unstable mode. This oscillation persists at all operating conditions but is only dominant when the thruster is "unstable."

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## Results and milestones

Task I: Fig. 1 shows the results of the expanded parametric map performed in Year 2. This spans operating conditions from 300-600 V at 100 V intervals and discharge currents from 5-15 A at 1 A intervals. The magnetic field magnitude remained the same. Fig 1a shows the ratio of the amplitude of the peak-to-peak oscillations compared to the mean current expressed as a percentage. Higher values correspond to larger relative instability. 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 only the frequency of the oscillation associated with the unstable mode as a function of operating condition.

Task II: Fig. 2 shows contour maps of the relative fluctuations in plasma density, neutral density, and electron temperature over one period of the low frequency oscillation associated with the unstable mode. The oscillation is correlated with both neutral and ion drift waves that propagate from a location upstream of the exit plane. The electron temperature is dispersionless.

Task III: Based on the measurements from I and II, we have developed a quasi-0D model for the instability that has yielded both stability and frequency predictions (Fig. 3). The trends illustrated in this plot are qualitatively consistent with Fig. 1, though they require further refinement.

Task IV: A major insight that has emerged from the analytical modeling is that the stability may be governed by the transit times of the neutrals in the thruster. By decreasing this transit time, it may be possible to increase the stability margin (Fig. 4). This is a strategy that will be explored in Year 3 by actively controlling the anode temperature.

## Significance/Benefits to JPL and NASA

Years 1 and 2 of this effort have resulted in new insight into the nature of the onset of the unstable transition at low power and high specific impulse. We have used experimental measurements to inform a simple quasi-0D model for the transition and in turn calibrated this model against a detailed parametric map of a thruster's stability. This work has led to the hypothesis that it is the disparity between transit times of ions and neutrals in the thruster discharge chamber which is a critical factor in leading to the onset of instability. This result suggests a potential mitigation strategy for expanding the stability margin of the thruster—actively controlling the temperature of the thruster anode. This will lead to changes in the characteristic velocity (and therefore residence time) of the neutrals, thereby pushing the stability threshold to lower powers. We will explore this strategy experimentally in the final year of this effort. If successful, this will provide an actionable design technique that could enable Hall thrusters to access a larger mission space, which is of key interest to a number of 4X missions.

## Publications

Ethan Dale and Benjamin Jorns, "Experimental characterization of Hall thruster breathing mode dynamics," Journal of Applied Physics. Accepted Sept. 2021.

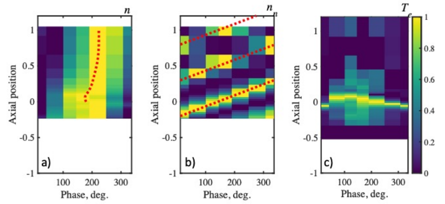

**Figure 2.** Spatial variations in a) plasma density, b) neutral density, and c) electron temperature over one period of a 10 kHz low frequency current oscillation associated with the unstable mode. Properties have been normalized to the peak value in the domain to highlight trends. Axial positions are normalized to channel length where 0 is coincident with the exit plane.

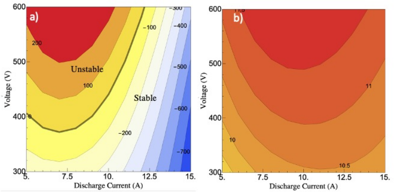

**Figure 3.** Quasi-0D model with time delay predictions for a) instability growth rate in Hz and b) frequency of oscillation in kHz. The gray line denotes the transition from stability (negative growth rate) to instability (positive growth). Model has been tuned to match the experimental stability maps shown in Fig. 1.

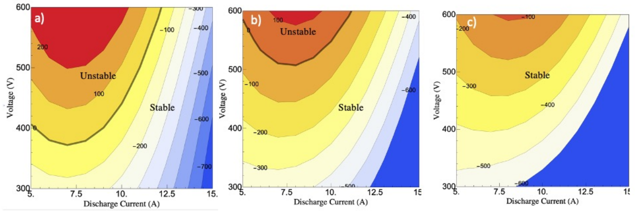

**Figure 4.** Predictions for growth rate from quasi-0D model as a function of assumed neutral speed with a) 300 m/s, b) 350 m/s, and c) 400 m/s. Neutral speed is dictated by anode temperature.

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