RPC 2020

Virtual Research Presentation Conference

Control of Hall Thruster Oscillations by External Voltage Modulations

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Program: SURP

Assigned Presentation # RPC-240

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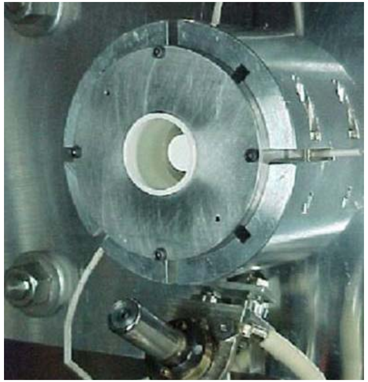
Tutorial Introduction

Abstract

Typically Hall thrusters are operated using a DC power supply in voltage regulated mode, and naturally arising 5-50 kHz ionization oscillations known as the “breathing mode” [1] modulate the current carried by the discharge plasma. This SURP project explores the potential benefits of altering the breathing mode by driving modulations of the discharge voltage [2] using an AC amplifier in series with the main discharge supply. Following up on promising results in Ref. [3], we use numerical simulations and plasma measurements to understand how nonlinear effects of voltage modulation can increase time-averaged thrust. Improvements in total thruster efficiency are sought through optimization of the modulation frequency, amplitude, and waveform. Initial studies were carried out on Princeton’s Cylindrical Hall Thruster (CHT); the remainder of the Year 1 effort focuses on applying the technology to JPL’s Magnetically Shielded Miniature (MaSMi) Hall thruster [4], an annular thruster that is likely to fly on future NASA planetary science missions. We have completed simulations of discharge voltage modulation in MaSMi, and the accompanying testing has been deferred to early FY21 due to COVID-19 lab shutdowns and related delays in hardware availability.



Princeton’s CHT.

JPL’s MaSMi thruster.

Problem Description

Context / Relevance to NASA and JPL: Along with gridded ion thrusters, Hall thrusters are one of the two leading technologies for high-Isp electric propulsion. Psyche will be the first NASA mission to fly Hall thrusters, and also the world's first application of Hall thrusters beyond lunar orbit. The Advanced Electric Propulsion System (AEPS), a collaboration between JPL, NASA GRC, and Aerojet Rocketdyne, is built around a 12.5 kW Hall thruster that is scheduled to fly on the Power and Propulsion Element of the Lunar Gateway. Low-power (≤1 kW) Hall thrusters, most notably the Magnetically Shielded Miniature (MaSMi) Hall thruster [4] under development at JPL, are an attractive option for SmallSat interplanetary missions. Achievement of the goals of this SURP project, namely a successful demonstration that discharge voltage modulation can be used to improve the total efficiency in an annular Hall thruster, would immediately open up opportunities to improve thruster performance in future NASA missions. This would be particularly valuable for smaller satellites, which often face tight constraints on electrical power availability and propellant storage volume.

SOA: Our discharge voltage modulation technology involves coupling of an external driving signal to the "breathing mode", a ubiquitous natural oscillation mode of Hall thruster discharges that has been studied extensively [1] but remains incompletely understood. Previous work on externally modifying the breathing mode has usually focused on attempting to control or damp it; in contrast, we are exploring possible benefits of resonant driving of the oscillation to larger amplitudes, taking advantage of nonlinear effects to improve performance.

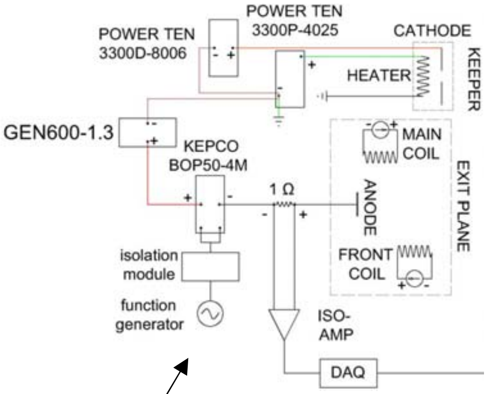
Methodology

Key project steps

1. Use numerical simulations to understand the physics of discharge voltage modulation, and explore the parameter space to optimize the modulation frequency, amplitude, and waveform for improving thruster efficiency.
2. Validate the simulations against existing and new data from Princeton's Cylindrical Hall Thruster (CHT).
3. Demonstrate the technology on JPL's annular MaSMi Hall thruster.

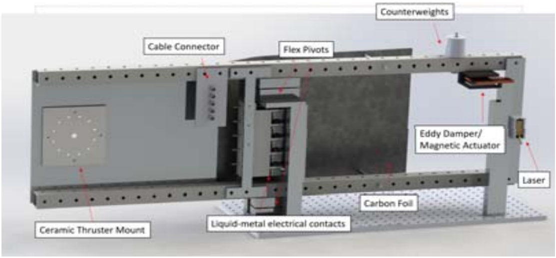
Approach

- Simulations of the CHT and MaSMi were carried out using a 1D hybrid code developed at CNRS- LAPLACE [5] (uses a particle model for ions/neutrals and a fluid model for electrons).
- Time-resolved measurements included beam ion energy and current, discharge voltage and current.
- New torsion balance thrust stand (liquid metal electrical contacts, low thermal drift) was fabricated to test MaSMi, which is larger than the CHT.



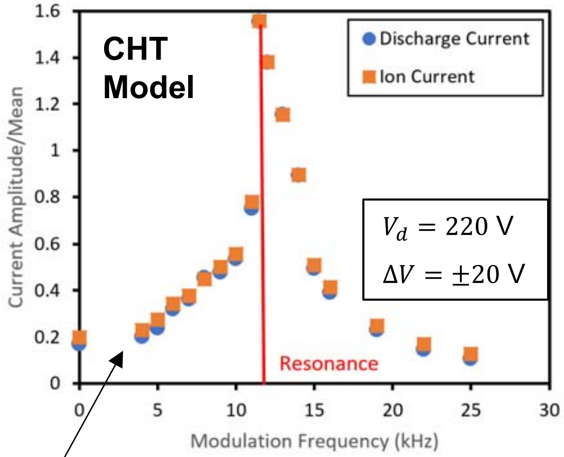
Discharge voltage modulation circuit

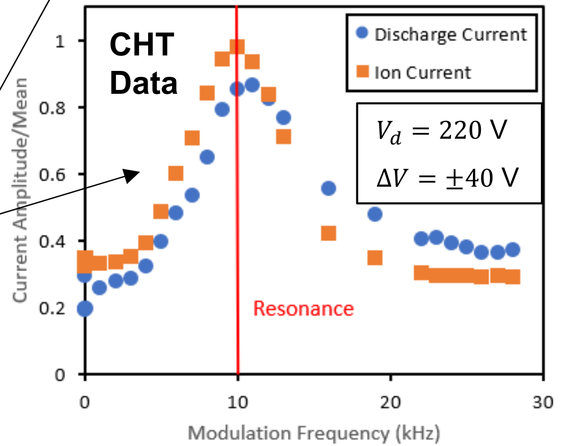
Thrust stand design



Results – CHT

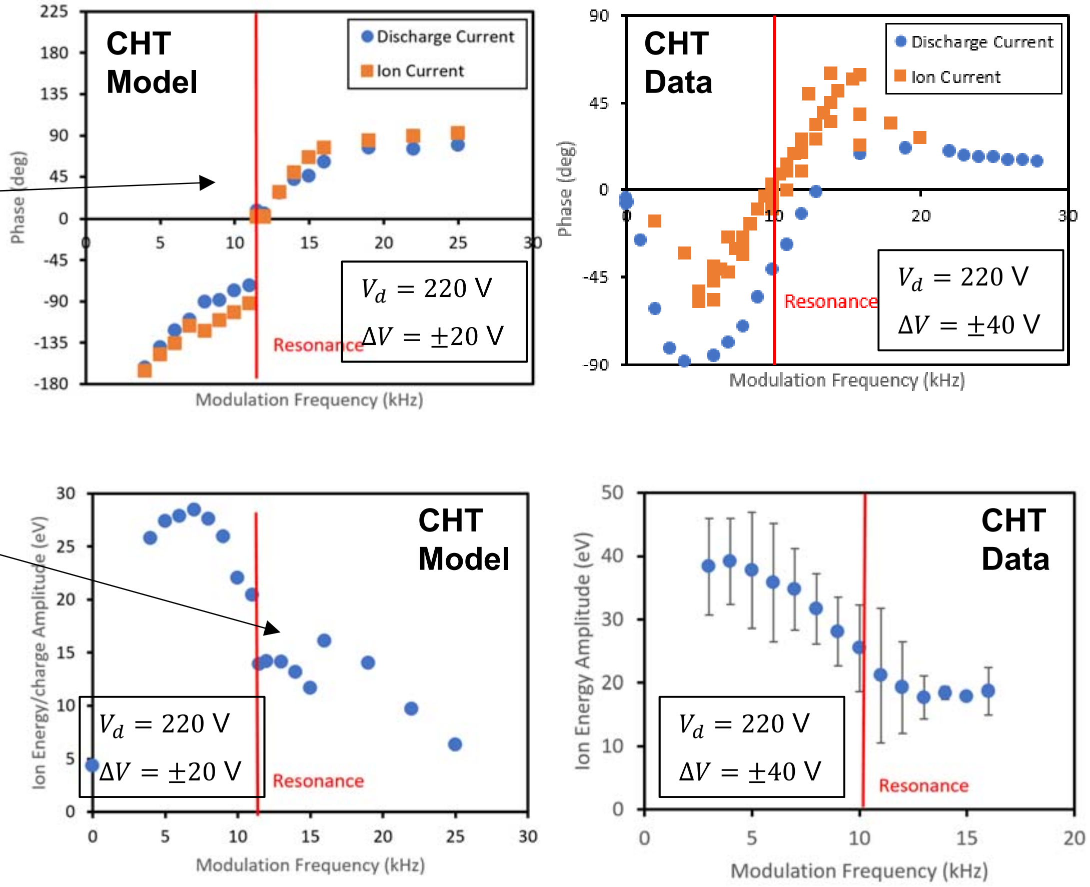
- In initial proof-of-principle experiments at Princeton, thrust increased due to a reduction in the phase shift between the ion energy and ion velocity oscillations [3], but the overall electrical efficiency did not improve because the phase shift between discharge current and voltage oscillations also decreased, increasing the time-averaged power draw.
  - A key goal of the new hybrid simulations was to learn how to independently control these phase shifts and thereby increase total efficiency.
- Our simulations focused first on reproducing time-averaged thruster operating parameters and natural breathing mode oscillations; then sinusoidal discharge voltage modulation was attempted at a range of frequencies.
- In both experiments and simulations, external voltage modulation produced a resonant increase in the discharge current and ion current oscillation amplitudes when the driving frequency approximately matched the natural breathing mode frequency.





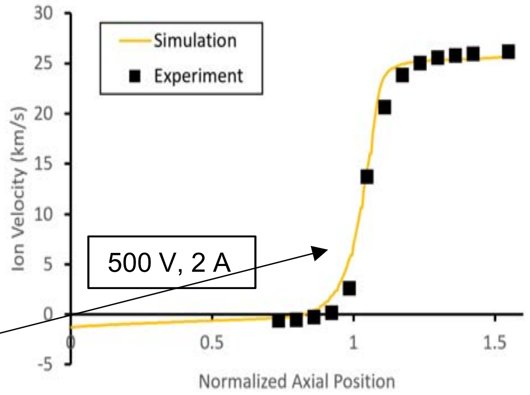
Results – CHT

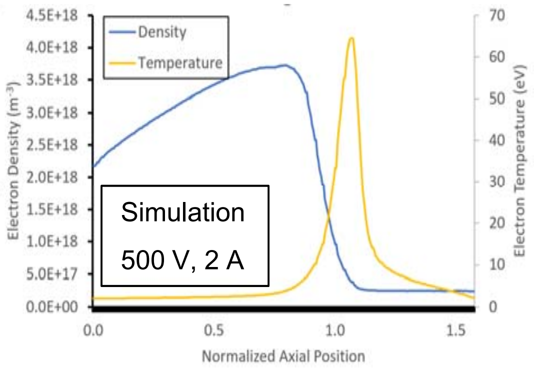
- Simulations qualitatively reproduced measured phasing trends.
  - In CHT testing, the largest thrust increases were seen in a highly nonlinear regime with large modulation amplitude (± 40 V), but stable simulations have not yet been achieved under these conditions.
- Coupling of voltage modulations to ion energy oscillations was weak above the natural breathing mode frequency.
  - The transit time for neutrals to fill the ionization region limits the plasma's frequency response.
  - Implies that using complex driving waveforms with high frequency content will have minimal benefit, unless the gas replenishment time can be decreased (for example, by injecting gas closer to the ionization region).

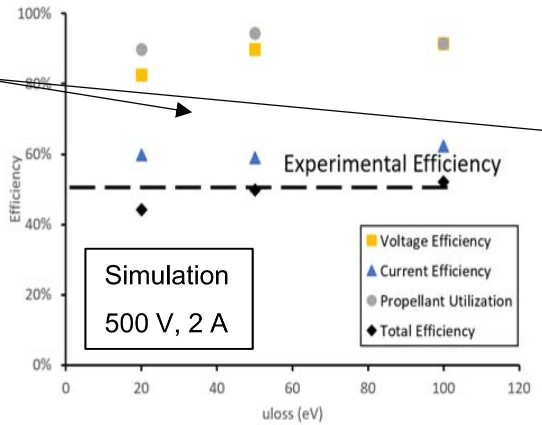


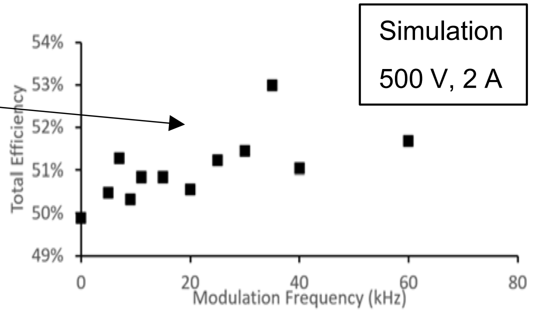
Results – MaSMi

- Ion velocity data [6] from JPL laser-induced fluorescence (LIF) measurements were used to infer the spatial dependence of non-classical cross-field electron transport (needed as an input for simulations) [7].
    - Achieved excellent agreement between measured/simulated time-averaged velocity.
- Simulations were able to roughly reproduce the measured thruster efficiency at full power (500 V, 2 A) and predicted a small efficiency increase during modulation near resonance.
    - Greater benefits may be possible at 200 V, 1 A, an operating condition with lower baseline efficiency and larger natural breathing mode oscillations (will be tested).
- Testing of voltage modulation in MaSMi during high and low power operation will be carried out at Princeton in early FY21.









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[7] I. G. Mikellides and A. Lopez Ortega, "Challenges in the development and verification of first-principles models in Hall-effect thruster simulations that are based on anomalous resistivity and generalized Ohm's law", *Plasma Sources Sci. Technol.*, **28**, 014003, 2019.

Publications

Abstracts have been submitted (with Jacob Simmonds as the lead author) for presentations on this work at the upcoming Gaseous Electronics Conference (Oct.) and the American Physical Society Division of Plasma Physics meeting (Nov.).