National Aeronautics and Space Administration

Control of Hall Thruster Oscillations by External Voltage Modulations

Principal Investigator: Vernon Chaplin (353); Co-Investigators: Jacob Simmonds (Princeton University), Yevgeny Raitses (Princeton University)

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

Objective: Use external modulation of the discharge voltage (V_d) to improve Hall thruster performance (thrust, specific impulse, efficiency)

- The use of driven voltage modulation to modify a Hall thruster's global "breathing mode" dynamics was previously demonstrated on a Cylindrical Hall thruster (CHT) at Princeton [1, 2]
- A key priority for the SURP task was to demonstrate application of this technology to an annular Hall thruster similar to those likely to fly on future NASA planetary science missions

Approach and Results

- 1D hybrid fluid/PIC simulations [5] were used to investigate modulation physics and explore the parameter space
- Discharge voltage modulations at a range of frequencies were simulated for the CHT (Fig. 1)
- Learning to independently control the phase shifts (Fig. 2) between the discharge current/voltage and the ion energy/density was believed to be the key to improving thruster efficiency
- Modulation of JPL's MaSMi thruster [4] was simulated (Fig. 3), with a modest performance improvement predicted when the driving frequency was resonant with the natural breathing mode frequency
- Experiments were carried out on Princeton's low-power annular Hall thruster [6], modulating V_d (Fig. 4), cathode keeper current (Fig. 5), and magnetic field strength. Unlike the CHT, this thruster did not demonstrate significant propellant or current utilization efficiency improvement, and total efficiency was unaffected or in some cases reduced by modulation

Background

- Global "breathing mode" oscillations at 5 – 50 kHz are a nearly universal phenomenon in Hall thrusters, known to affect performance and operational life [3]
- Ref. [1] demonstrated that external modulation of the discharge voltage could increase time-averaged ion beam current and thrust in the CHT, but discharge power increased so efficiency did not improve
- This SURP project aimed to use plasma measurements and numerical simulations to understand physical mechanisms behind modulation impacts and to optimize the modulation frequency, amplitude, and waveform

Significance/Benefits to JPL and NASA

- Demonstration that external breathing mode modulation can improve total efficiency in an annular Hall thruster would provide a path to improve thruster performance in future NASA missions (particularly valuable for small satellites, which have tightly constrained electrical power availability and propellant storage volume)
- This SURP project was not able to identify a regime with substantial performance benefits, however

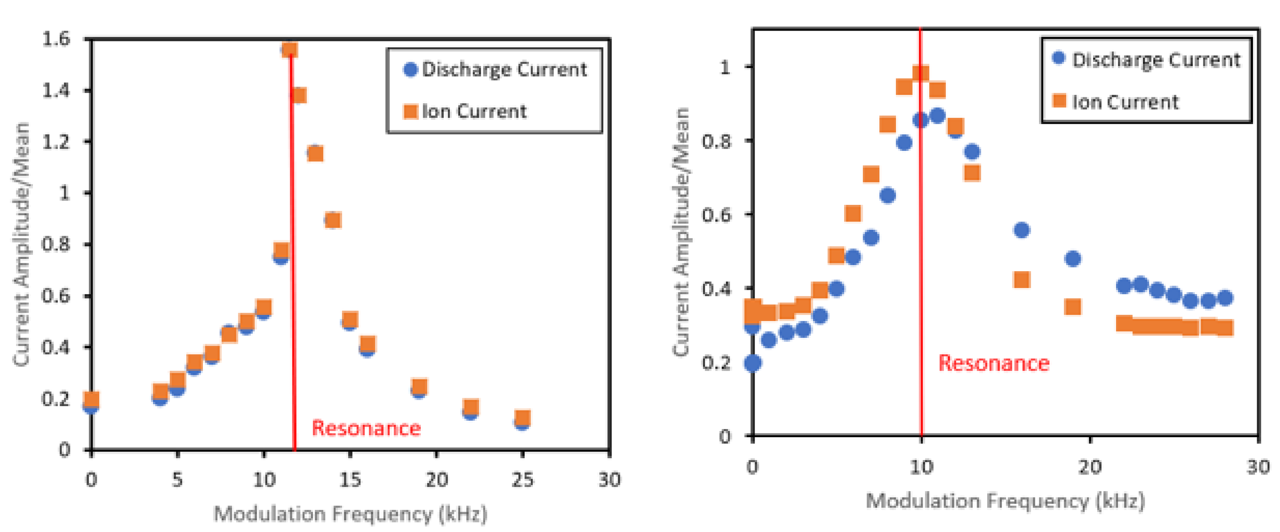

Figure 1. Simulated (left) and measured (right) discharge current oscillation amplitude as a function of discharge voltage modulation frequency in the CHT ($V_d = 220$ V, modulated at ± 20 V in the simulations and ± 40 V in the experiments).

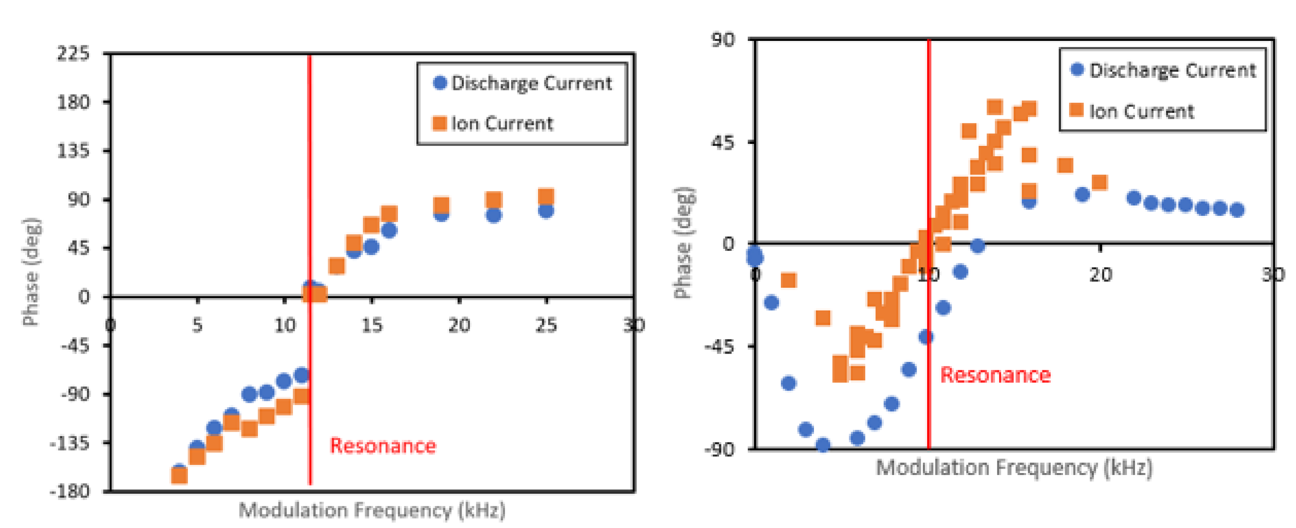

Figure 2. Simulated (left) and measured (right) phasing between discharge current and discharge voltage, and between ion current and ion energy, for the CHT ($V_d = 220$ V, modulated at ± 20 V in the simulations and ± 40 V in the experiments).

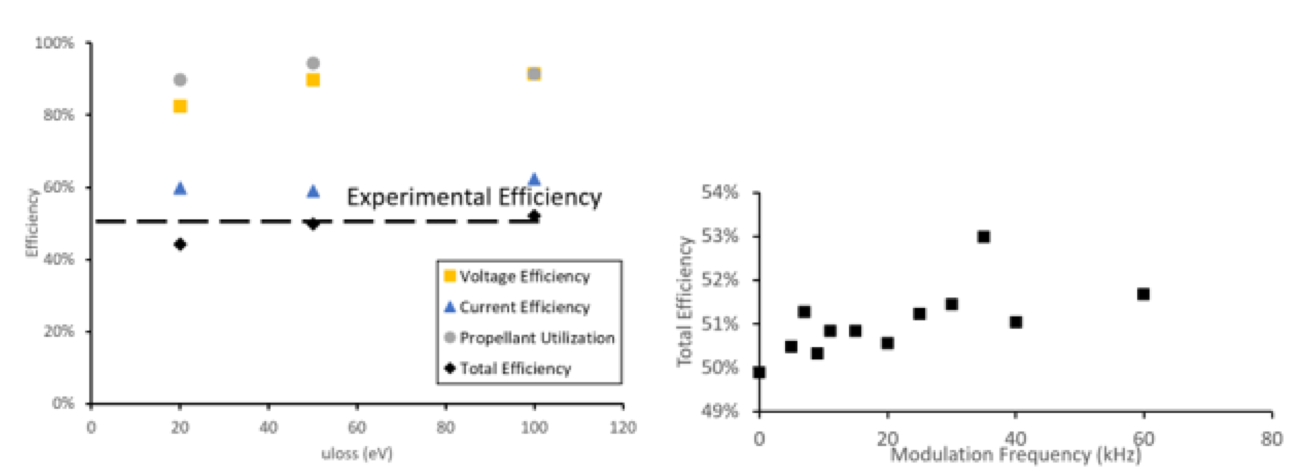

Figure 3. Left: Simulated contributions to MaSMi-DM anode efficiency during undriven operation at 500 V, 2 A. Right: Simulated anode efficiency as a function of discharge voltage modulation frequency, with 30 V modulation amplitude.

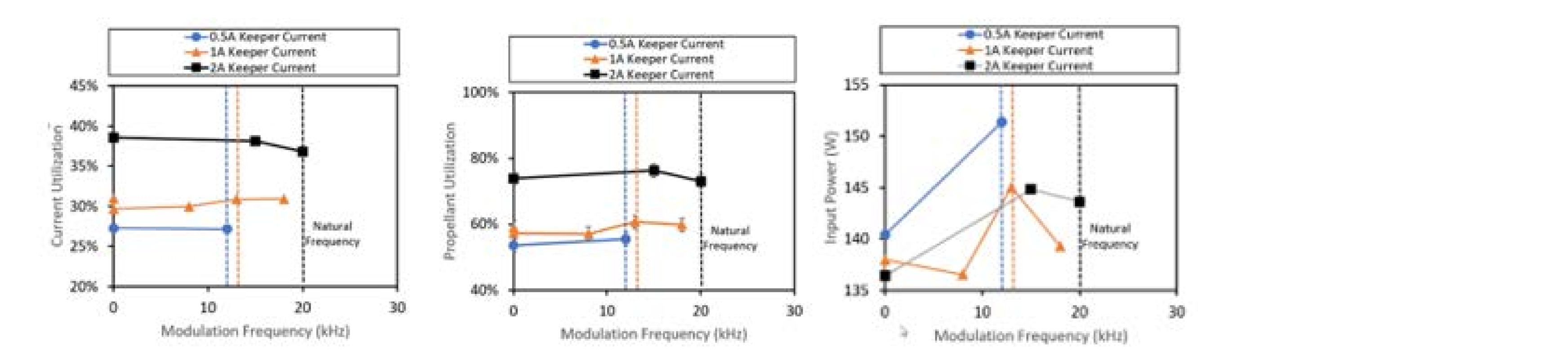

Figure 4. Experimental results from discharge voltage modulations in Princeton's low-power annular Hall thruster. Left: Current utilization efficiency. Center: Propellant utilization efficiency. Right: Discharge power.

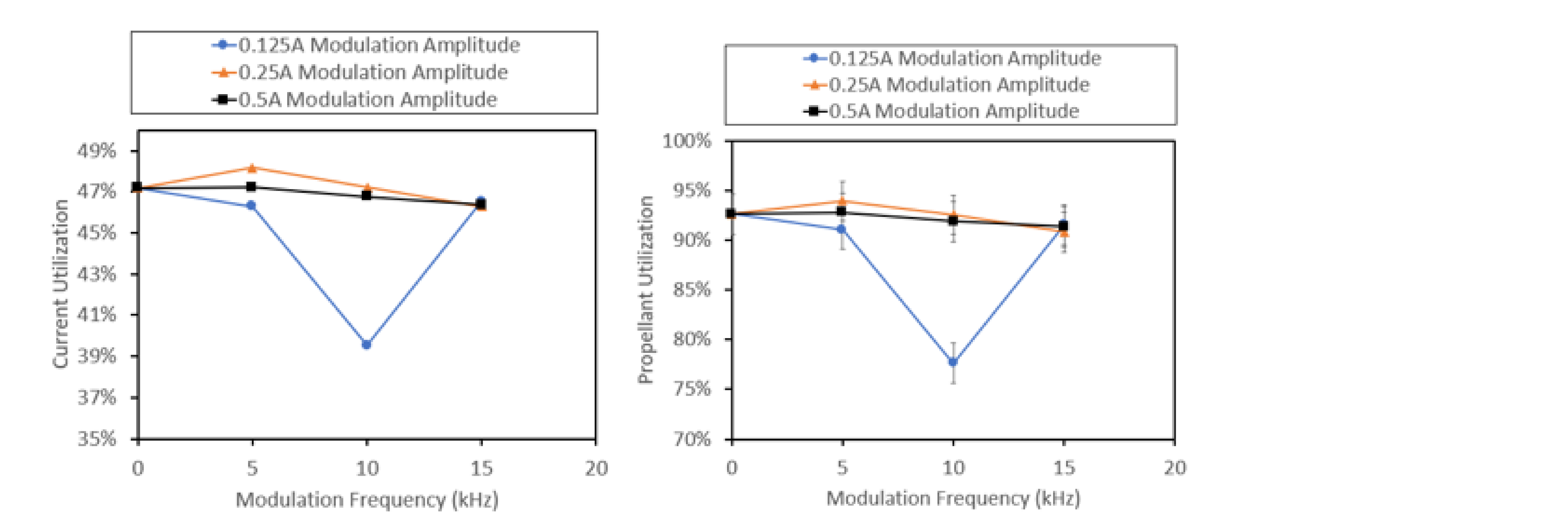

Figure 5. Experimental results from keeper current modulations in Princeton's low-power annular Hall thruster. Left: Current utilization efficiency. Right: Propellant utilization efficiency.

Publications

[A] Jacob Simmonds, Yevgeny Raitses, Andrei Smolyakov, and Oleksandr Chapurin, "Studies of a modulated Hall thruster," *Plasma Sources Science and Technology*, 30, 055011, 2021.

[B] Jacob Simmonds, Yevgeny Raitses, Vernon Chaplin, Andrei Smolyakov, and Oleksandr Chapurin, "Studies of voltage-modulated Hall thrusters," *62nd Annual Meeting of the APS Division of Plasma Physics*, virtual meeting, Nov. 9-13, 2020, PO05.00002.

[C] Jacob Simmonds, Yevgeny Raitses, and Vernon Chaplin, "The Effect of Modulation on the Magnetically Shielded Miniature (MaSMi) Hall Thurster's Performance and Plasma Properties," *73rd Gaseous Electronic Conference*, virtual meeting, Oct. 5-9, 2020, FT4.00004.

References

[1] I. Romadanov, Y. Raitses, and A. Smolyakov, "Hall thruster operation with externally driven breathing mode oscillations", *Plasma Sources Sci. Technol.*, **27**, 094006, 2018.

[2] K. Hara, S. Keller, and Y. Raitses, "Measurements and theory of driven breathing oscillations in a Hall effect thruster", *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, Salt Lake City, Utah, July 25-27, 2016, AIAA-2016-4532.

[3] S. Barral and Z. Peradzynski, "Ionization oscillations in Hall thrusters", *Phys. Plasmas*, **17**, 014505, 2010.

[4] R. W. Conversano, R. B. Lobbia, T. V. Kerber, K. C. Tilley, D. M. Goebel, and S. W. Reilly, "Performance characterization of a low-power magnetically shielded Hall thruster with an internally-mounted hollow cathode", *Plasma Sources Sci. Technol.*, **28**, 105011, 2019.

[5] G. J. M. Hagelaar, J. Bareilles, L. Garrigues, and J. P. Boeuf, "Modeling of stationary plasma thrusters", *Contributions to Plasma Physics*, **44**, 529-535, 2004.

[6] A. Smirnov, Y. Raitses, and N. J. Fisch, "Parametric investigation of miniaturized cylindrical and annular Hall thrusters", *J. Appl. Phys.*, **92**, 5673, 2002..

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
www.nasa.gov

PI/Task Mgr Contact
Email: Vernon.H.Chaplin@jpl.nasa.gov

Clearance Number:
RPC/JPL Task Number: SP20013