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Laboratory Demonstration of a Staging System for Electrospray Thrusters

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Oliver Jia-Richards* and Paulo C. Lozano†
Massachusetts Institute of Technology, Cambridge, Massachusetts, 02144, U.S.A.

Development of high-ΔV propulsion systems compatible with the CubeSat form factor is one of the last remaining technology gaps required to open up deep-space missions to CubeSats. Electrospray thrusters are a promising technology due to their inherently small form factor. However, the ΔV output of current electrospray thrusters is insufficient for a deep-space mission due to lifetime limitations. The use of a staging system, analogous to launch vehicle staging, allows the lifetime limitations to be bypassed in order to increase the overall lifetime of the propulsion system. The core concept of staging as well as the required mechanisms have been developed in previous work. This work contributes towards the development of staging systems by performing the first demonstration of a staging system with electrospray thrusters. Two separate stages of thrusters are fired in a vacuum environment with an intermediate staging event thereby verifying the mechanical and electrical feasibility of the staging configuration.

I. Introduction

Electrospray thrusters are a promising technology for main propulsion of a deep-space CubeSat due to their mechanical simplicity and small form factor. Several devices using microfabrication techniques have been proposed.[1–4] The ion Electrospray Propulsion System (iEPS)[4] is an example of one of these devices and leverages zero-vapor pressure ionic liquids[5,6] that are fed to the thrusters through passive, capillary forces in order to eliminate the need for pressurized tanks and complex propellant management systems. The resulting thruster is one that is compatible with the CubeSat form factor in size, weight, and power.

Due to the scalability of electrospray thrusters, propulsion modules with arrays of iEPS thrusters can provide enough thrust for main propulsion of a CubeSat[7] with propulsive accelerations greater than that of the Dawn spacecraft. However, the throughput, and therefore ΔV, of microfabricated electrospray thrusters is limited by their operational lifetime. Models as well as experimental techniques to analyze the general lifetime limitations of electrospray thrusters have been developed.[8,9] For iEPS thrusters, the two main life-limiting mechanisms are propellant accumulation on the extractor grid as well as arcing between isolated tips on the emitter array and the extractor grid. Difficulties with repeatable manufacturing on the micron scale as well as inherent material non-uniformity[10] can lead to relatively wide emission cones with observed half angles of up to 60 degrees[4] increasing propellant accumulation on the extractor grid. In addition, some emitter tips might have unstable menisci[11] which can lead to erratic liquid emission and occasional electrical discharges between the emitter tip and extractor grid[12] degrading the thruster over time.

Overcoming these lifetime limitations and increasing the throughput of microfabricated electrospray thrusters will greatly increase the capabilities of CubeSats. The Mars Cube One (MarCO)[13] mission demonstrated many of the subsystems required for deep-space exploration with CubeSats. However, neither MarCO

*Sc.D. Candidate, Department of Aeronautics and Astronautics, oliverjr@mit.edu
†Professor, Department of Aeronautics and Astronautics, plozano@mit.edu

spacecraft carried a high-ΔV propulsion system and required a ride-share with the InSight lander. Development of high-ΔV propulsion systems compatible with the CubeSat form factor is one of the last remaining technology gaps required to open up deep-space missions to CubeSats. This increased capability could then be used to provide substantial benefits for exploration of small asteroids and other planetary bodies in terms of affordability, visit rates, and overall science return.

The use of a staging system, analogous to launch vehicle staging, would allow for the lifetime limitations of an individual thruster to be bypassed in order to increase the overall lifetime of the propulsion system. While improvements to the lifetime of individual thrusters through a better understanding and mitigation of the life-limiting mechanisms is continuously being explored and will likely bring lifetime improvements in the future, the use of staging to bypass lifetime limitations is a strategy that could enable high-ΔV capabilities with existing electrospray technology. Furthermore, the use of a staging system in deep-space missions would provide additional redundancy and reliability, even for thrusters with improved lifetime, as sets of fresh units could replace functioning, albeit degraded, ones. Figure 1 shows a concept image of a staging system with electrospray thrusters on a 3U CubeSat.

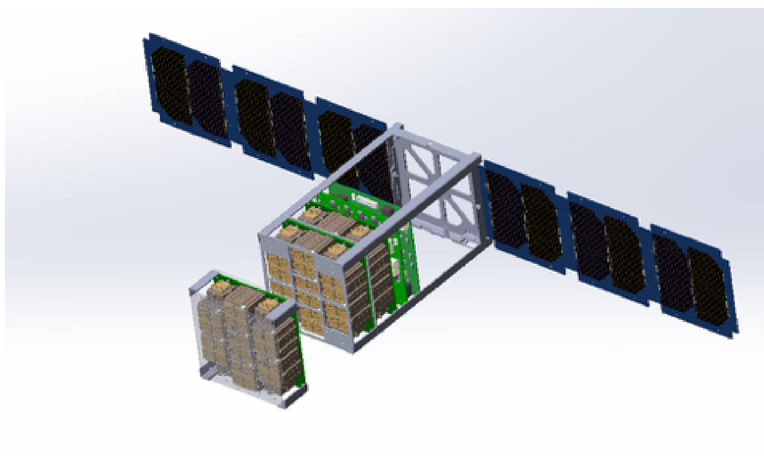

Figure 1. Concept image of a staging system for electrospray thrusters[14]

Figure 2 shows ΔV versus wet mass for a stage-based iEPS propulsion system with one to nine stages when used on a 3U CubeSat where each stage was assumed to have a lifetime of 500 hours. It also shows the ΔV versus wet mass for a theoretical single stage iEPS propulsion system as well as various commercial CubeSat propulsion systems based in cold-gas, monopropellant, and electric propulsion technology.[15] We can see that an iEPS system, either in a staged or unstaged configuration, outperforms the commercial CubeSat options. The staged configuration requires more mass and volume than the single-stage system with an expected 30% increase in mass and 70% increase in volume required for a 3 km/s ΔV system. However, while the single-stage system is not possible with current propulsion technology, the stage-based system is. In addition, neither the mass nor volume increase push the system to be incompatible with the 3U CubeSat form factor. Given the current performance metrics of the iEPS thrusters, a stage-based propulsion system that can produce 3 km/s ΔV on a 3U CubeSat and its power processing unit require 2.1 kg of mass and 1.5U of volume.

A staging system for electrospray thrusters was originally proposed to reduce propellant consumption and mission time for a lunar transfer[14] and was further analyzed for use in escape trajectories and missions to near-Earth asteroids.[16] Mechanisms required for a staging system were designed and tested in a vacuum environment[17] but a full demonstration of a staging system with operational thrusters has yet to be done. This paper aims to further the development of staging systems through the first demonstration of a staging system for electrospray thrusters. A two-stage system with iEPS thrusters is demonstrated in a vacuum environment with successful firing of both stages and an intermediate staging event. This test contributes towards previous work on staging systems by demonstrating the mechanical and electrical feasibility of the staging configuration.

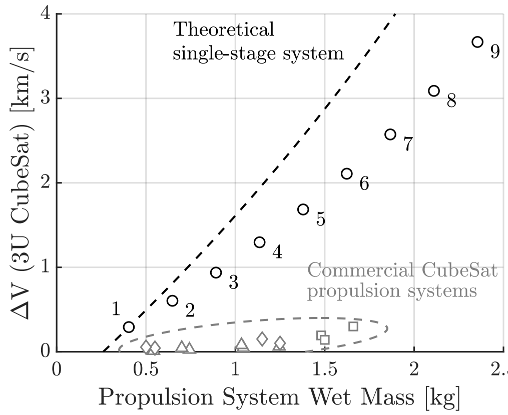

Figure 2. ΔV versus wet mass for a 3U CubeSat compatible, iEPS based (500 hour lifetime) staging system

II. Staging Configuration

Two mechanisms are required for the staging configuration: a staging mechanism to hold together successive stages and eject the outermost stage at the time of staging and a routing mechanism which passively routes control signals to the active stage. All stages will use the same power processing unit. Therefore, it is necessary to route the control signals to the correct stage. By performing the routing mechanically and passively, the power processing unit can remain "stage blind" and no electrical addressing of individual stages is required.

Both the staging and routing mechanism used here are based on previous design and analysis.[16,17] The staging mechanism uses a fuse wire approach: successive stages are held together with a thin stainless steel wire which is fused at the time of staging. A high-power-density ultracapacitor is used to fuse the fuse wire thereby reducing the instantaneous power load on the spacecraft bus. Figure 3 shows a prototype of the staging mechanism in operation. Initially, the mechanism is used to hold together successive stages. Next, the ultracapacitor is discharged through the fuse wire heating it up until it melts. After the fuse wire melts, the stages are released and a compression spring separates the ejected stage from the spacecraft.

The routing mechanism is a custom-made normally-closed, momentary push button switch. When a preceding stage is present, the preceding stage physically presses on the button and the mechanism is opened preventing control signals from entering the stage. When the preceding stage is ejected, the mechanism is closed and the stage becomes active. After the thrusters on the stage reach the end of their lifetime, the stage is ejected, automatically activating the next stage. With this mechanism the power processing unit remains "stage blind" and does not need to track which stage is active. This greatly simplifies the electronics design as existing iEPS electronics boards can continue to be used without needing to add extra electronics for addressing of individual stages. It also allows for greater flexibility when adding or removing stages as the number of stages does not impact the power processing unit. Figure 3 also shows a proof-of-concept design of the routing mechanism in operation.

Figure 4 shows the proposed flight stage configuration and testing configuration of a 10 cm x 10 cm array of thrusters. The proposed flight configuration has a total of 32 thrusters arranged in groups of four on eight fuel tanks. Four staging mechanisms are used to secure stages together and two routing mechanisms route all the necessary control signals. The testing configuration is a stripped down version of the proposed flight configuration where only the essential elements are kept. Two thrusters on individual tanks are used with only a single routing mechanism and two staging mechanisms on opposing corners of the test board. The testing configuration allows the major elements of the proposed flight configuration to be tested without the overhead and complexity involved in building the full configuration. Figure 5 shows two thrusters mounted on the test configuration board in preparation for testing.

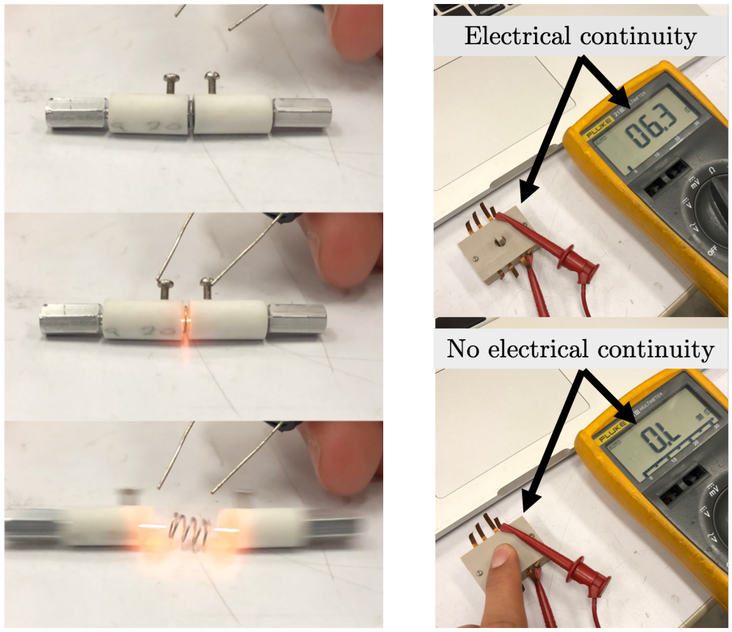

Figure 3. Prototypes of the staging (left) and routing (right) mechanisms

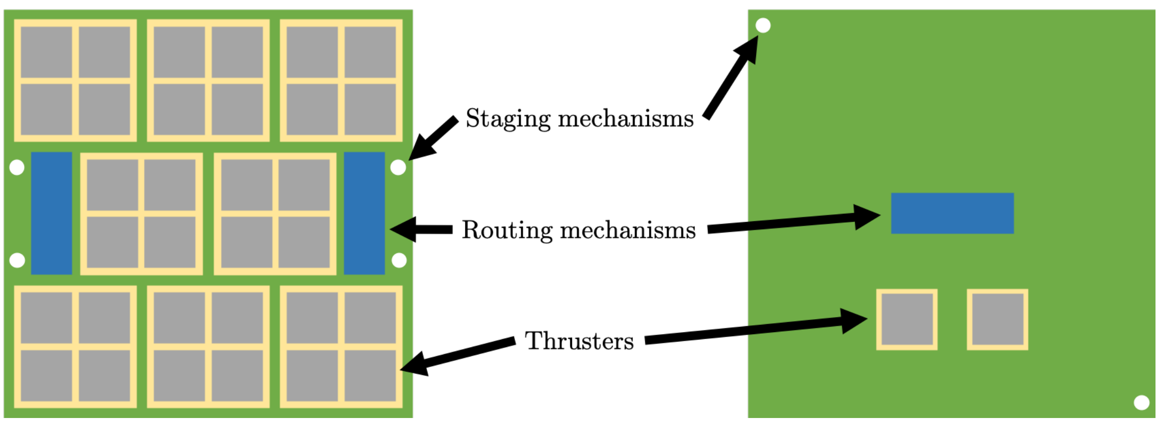

Figure 4. Proposed flight stage configuration (left) and testing configuration (right)

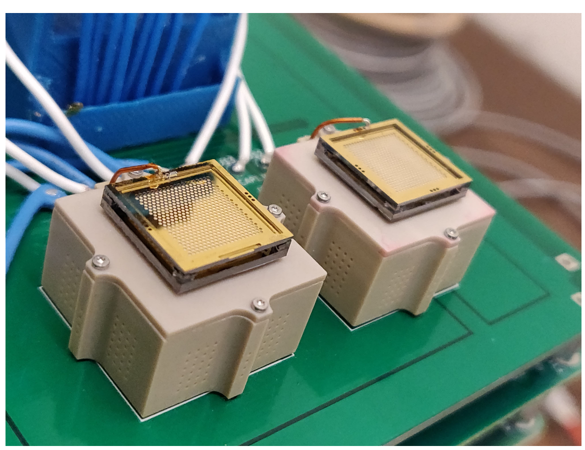

Figure 5. Thrusters mounted onto the test board

III. Vacuum Testing

Full system testing was conducted in a vacuum chamber at pressures on the order of 10 μTorr. Figure 6 shows the test setup in the vacuum chamber. The top image shows the test setup without thrusters and with the electronics boards exposed while the bottom image shows the setup just prior to testing with thrusters mounted on each stage and aluminum foil wrapped around the electronics boards to protect them from any reflected ions. All thrusters used for this test were lab test thrusters that were likely to fail given their construction. However, the focus of this work was to demonstrate the staging actuation regardless of thruster reliability. The two main elements for the electronics are a custom made board for the staging control electronics which holds a Tecate Group PBL-4.0/5.4 passively balanced ultracapacitor module used to fuse the staging mechanisms and the thruster power processing unit (PPU) which is the same PPU used in other tests of the iEPS thrusters in single-stage configurations. Throughout the test, the PPU does not track which stage is active. Instead, the control signals are routed to the active stage by the routing mechanism.

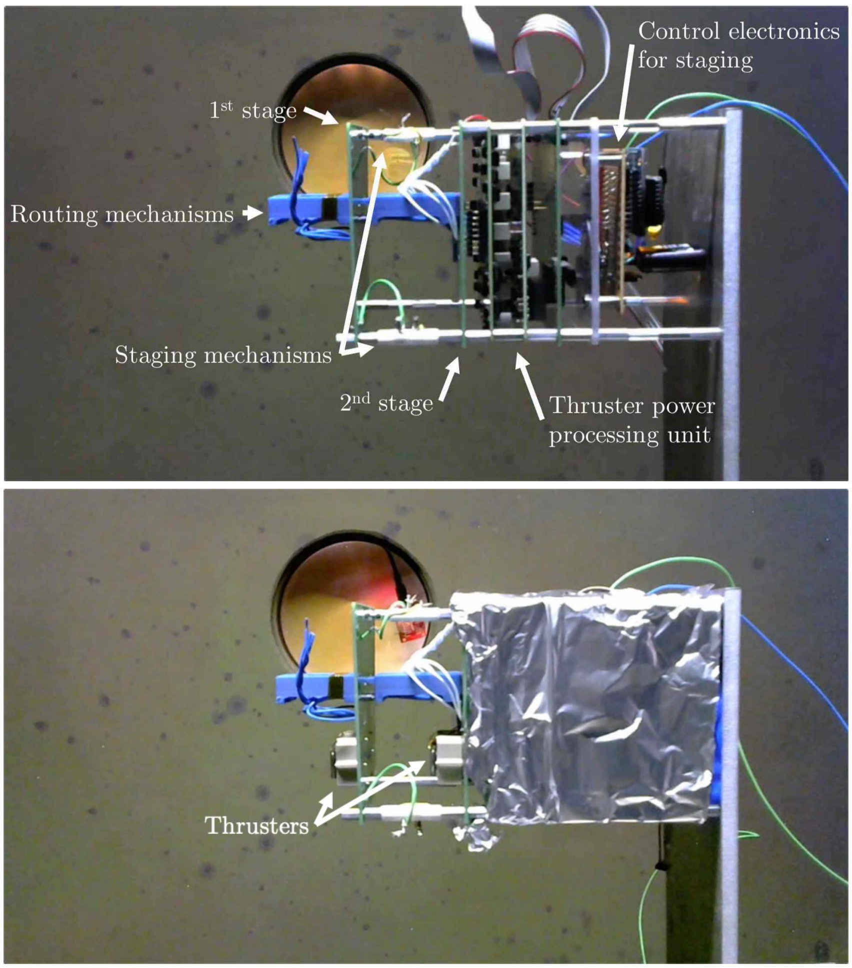

Figure 6. Test setup in vacuum chamber

Figure 7 shows the applied voltage and emitted current for first stage firing. Firing was short, with only 90 seconds of total firing time per thruster, and the thrusters were stressed up to 6x their nominal current output (150 μA) causing an asymmetry between the output current of the two thrusters. After firing, the thrusters were left idle overnight over which time an electrical short developed on both thrusters. It is believed that the electrical short was due to an ionic liquid connection between the emitter array and extractor grid that was caused by remnant ionic liquid on the emitter array being pulled by gravity into the tip-extractor gap. This is a failure mode that has previously been observed for these test thrusters and not caused by the staging configuration.

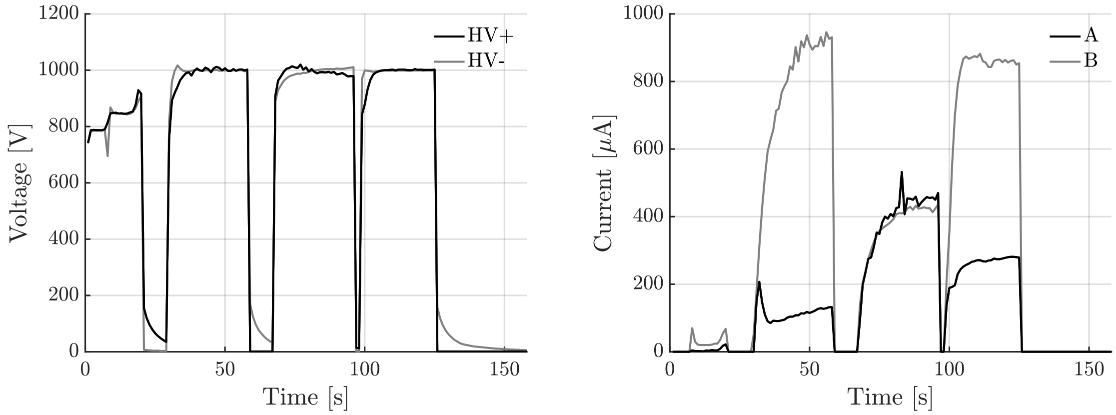

Figure 7. Applied voltage and emitted current for first stage firing

After the first stage was deemed inoperable, a staging event was initialed to eject the stage. Figure 8 shows the staging event. Initially, the system still has two stages with an inoperable first stage and inactive second stage. Staging is initiated through discharging the fusing capacitor through the staging mechanisms allowing the first stage to be ejected from the system. After staging, the first stage is fully ejected from the system and the second stage is now active and ready to be fired.

Figure 9 shows the applied voltage and emitted current for second stage firing. For the second stage, only one of the two thrusters successfully fired. The inoperable thruster initially showed no signs of firing and then developed an electrical short between the emitter array and extractor grid part way through the test. It is unknown what prevented thruster operation. However, as the thrusters were test models it was expected to see some unknown failures. The operable thruster was current regulated to 150 μA emitted current and successfully maintained steady firing for close to eight hours. Eight hours into the test, a voltage trip in the PPU stopped the applied voltage to the thruster. This resulted in the thruster being left idle overnight over which time an electrical short developed. It is believed that the reason for the electrical short on the second stage is the same reason for the electrical short on the first stage. Again, in this case, the thruster failure was due to the thrusters being test models and was not induced by the staging configuration.

IV. Conclusion

This test performed the first demonstration of a staging system for electrospray thrusters. Tests were conducted in a 10 μTorr vacuum environment with a two-stage system. Both stages achieved successful emission with an intermediate staging event. Both the staging mechanisms and routing mechanisms worked as intended. The routing mechanisms in particular allowed for easy integration of the staging configuration with the already existing iEPS PPU allowing for the same PPU to be used for a traditional single-array configuration and a staging configuration.

Although both stages suffered premature electrical shorts, it is not believed that the electrical shorts were due to the staging configuration and were instead caused by gravitational effects and from the thrusters being test models not intended for extended testing. Therefore, it does not appear that the staging configuration had any adverse effect on the operation of the iEPS thrusters.

Acknowledgments

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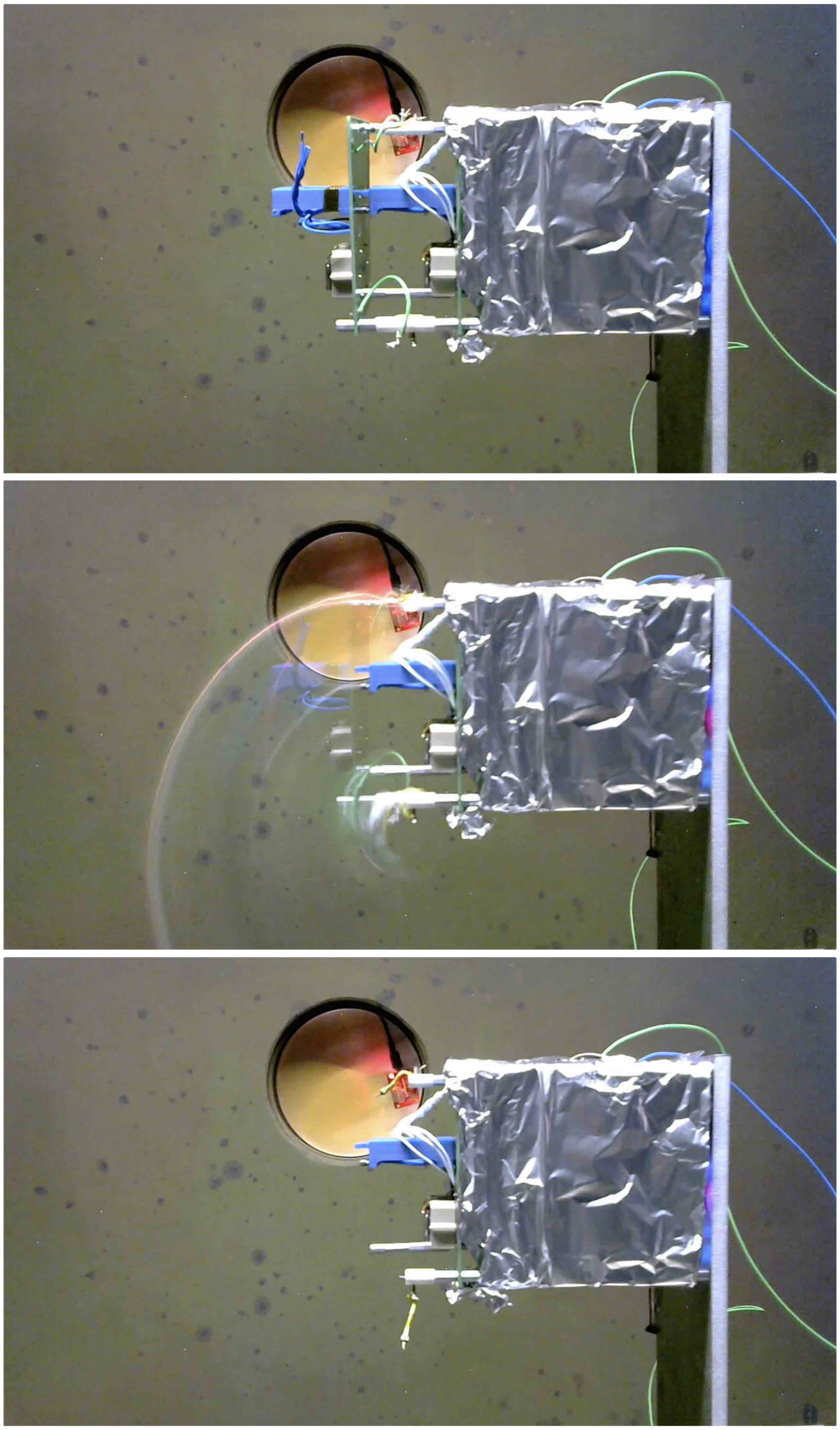

Figure 8. Demonstration of a staging system for electrospray thrusters

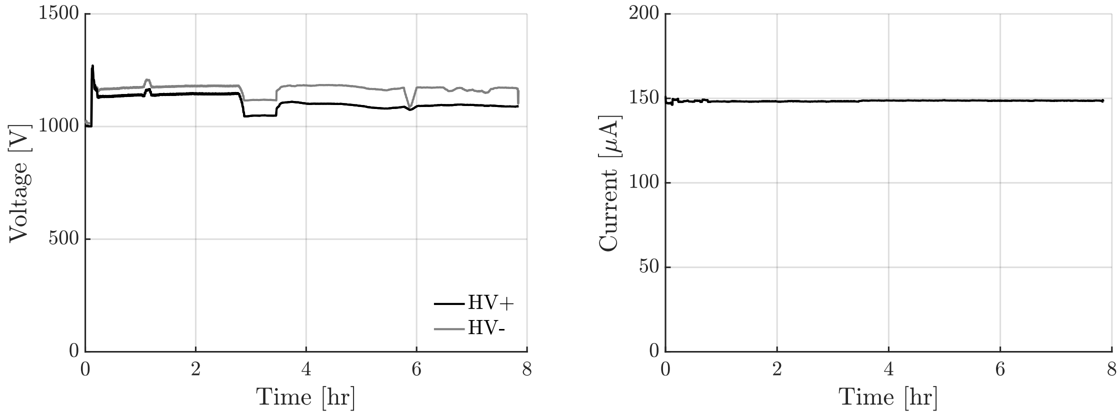

Figure 9. Applied voltage and emitted current for second stage firing

References

[1]Deng, W., Klemic, J. F., Lee, X., Reed, M. A., and Gomez, A., "Increase of Electrospray Throughput Using Multiplexed Microfabricated Sources for the Scalable Generation of Monodisperse Droplets," *Journal of Aerosol Science*, Vol. 37, No. 6, 2006, pp. 696–714.

[2]Alexander, M. S., Stark, J., Smith, K. L., Stevens, B., and Kent, B., "Electrospray Performance of Microfabricated Colloid Thruster Arrays," *Journal of Propulsion and Power*, Vol. 22, No. 3, 2006, pp. 620–627.

[3]Legge, R. S. and Lozano, P. C., "Electrospray Propulsion Based on Emitters Microfabricated in Porous Metals," *Journal of Propulsion and Power*, Vol. 27, No. 2, 2011, pp. 485–495.

[4]Krejci, D., Mier-Hicks, F., Thomas, R., Haag, T., and Lozano, P. C., "Emission Characteristics of Passively Fed Electrospray Microthrusters with Propellant Reservoirs," *Journal of Spacecraft and Rockets*, Vol. 54, No. 2, 2017, pp. 447–458.

[5]Rebelo, L. P. N., Canongia Lopes, J. N., Esperanca, J. M. S. S., and Filipe, E., "On the Critical Temperature, Normal Boiling Point, and Vapor Pressure of Ionic Liquids," *The Journal of Physical Chemistry B*, Vol. 109, No. 13, 2005, pp. 6040–6043.

[6]Earle, M. J., Esperanca, J. M. S. S., Gilea, M. A., Canongia Lopes, J. N., Rebelo, L. P. N., Magee, J. W., Seddon, K. R., and Widegren, J. A., "The Distillation and Volatility of Ionic Liquids," *Nature*, Vol. 439, No. 7078, 2006, pp. 831–834.

[7]Krejci, D., Mier-Hicks, F., Fucetola, C., and Lozano, P., "High efficiency ionic liquid electrospray propulsion for Nanosatellites," *Proceedings of the 67th International Astronautical Congress*, Guadalajara, Mexico, September 2016.

[8]Thuppul, A., Wright, P. L., and Wirz, R. E., "Lifetime Considerations and Estimation for Electrospray Thrusters," *Proceedings of 2018 Joint Propulsion Conference*, Cincinnati, OH, July 2018.

[9]Wright, P. L., Thuppul, A., and Wirz, R. E., "Life-Limiting Emission Modes for Electrospray Thrusters," *Proceedings of 2018 Joint Propulsion Conference*, Cincinnati, OH, July 2018.

[10]Rojas-Herrera, J., Fucetola, C., Krejci, D., Freeman, D., Jivanescu, I., and Lozano, P. C., "Porous Materials for Ion-Electrospray Spacecraft Micro-Engines," *Nanomechanics and Micromechanics*, Vol. 7, No. 3, 2017.

[11]Coffman, C., Martinez-Sanchez, M., Higuera, F. J., and Lozano, P. C., "Structure of the Menisci of Leaky Dielectric Liquids During Electrically-Assisted Evaporation of Ions," *Applied Physics Letters*, Vol. 109, No. 23, 2016.

[12]Brikner, N. and Lozano, P. C., "The Role of Upstream Distal Electrodes in Mitigating Electrochemical Degradation of Ionic Liquid Ion Sources," *Applied Physics Letters*, Vol. 101, No. 19, 2012.

[13]Klesh, A. and Krajewski, J., "MarCO: CubeSats to Mars in 2016," *Proceedings of the 29th Annual AIAA/USU Conference on Small Satellites*, Logan, UT, August 2015.

[14]Krejci, D., Jenkins, M. G., and Lozano, P. C., "Staging of electric propulsion systems: Enabling an interplanetary CubeSat," *Acta Astronautica*, Vol. 160, July 2019, pp. 175–182.

[15]Lemmer, K., "Propulsion for CubeSats," *Acta Astronautica*, Vol. 134, 2017, pp. 231–243.

[16]Jia-Richards, O., *Design and Analysis of a Stage-Based Electrospray Propulsion System for CubeSats*, Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, June 2019.

[17]Jia-Richards, O. and Lozano, P. C., "Stage-Based Electrospray Propulsion System for Deep-Space Exploration with CubeSats," *Proceedings of the 40th IEEE Aerospace Conference*, Big Sky, MT, March 2019.