

3-D Printed Electro Spray Thrusters for CubeSats



Hyeonseok Kim

kimhs@mit.edu

H. Kim¹, D. V. Melo Máximo², L. F. Velásquez-García²

1. Mechanical Engineering, Massachusetts Institute of Technology

2. Microsystems Technology Laboratories, Massachusetts Institute of Technology

MIT Portugal

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Introduction

An electro spray is an attractive method for propulsion of small satellites because it can produce high specific impulse and benefits from miniaturization of the thruster. The propellant can be supplied internally or externally to the emitters, and a high electric field on the liquid turns the meniscus into a conical shape called a Taylor cone (Figure 1). Small droplets and ions are ejected in a high speed from the apex of the cone produce thrust. We are exploring additive manufacturing to create CubeSat electro spray thrusters.

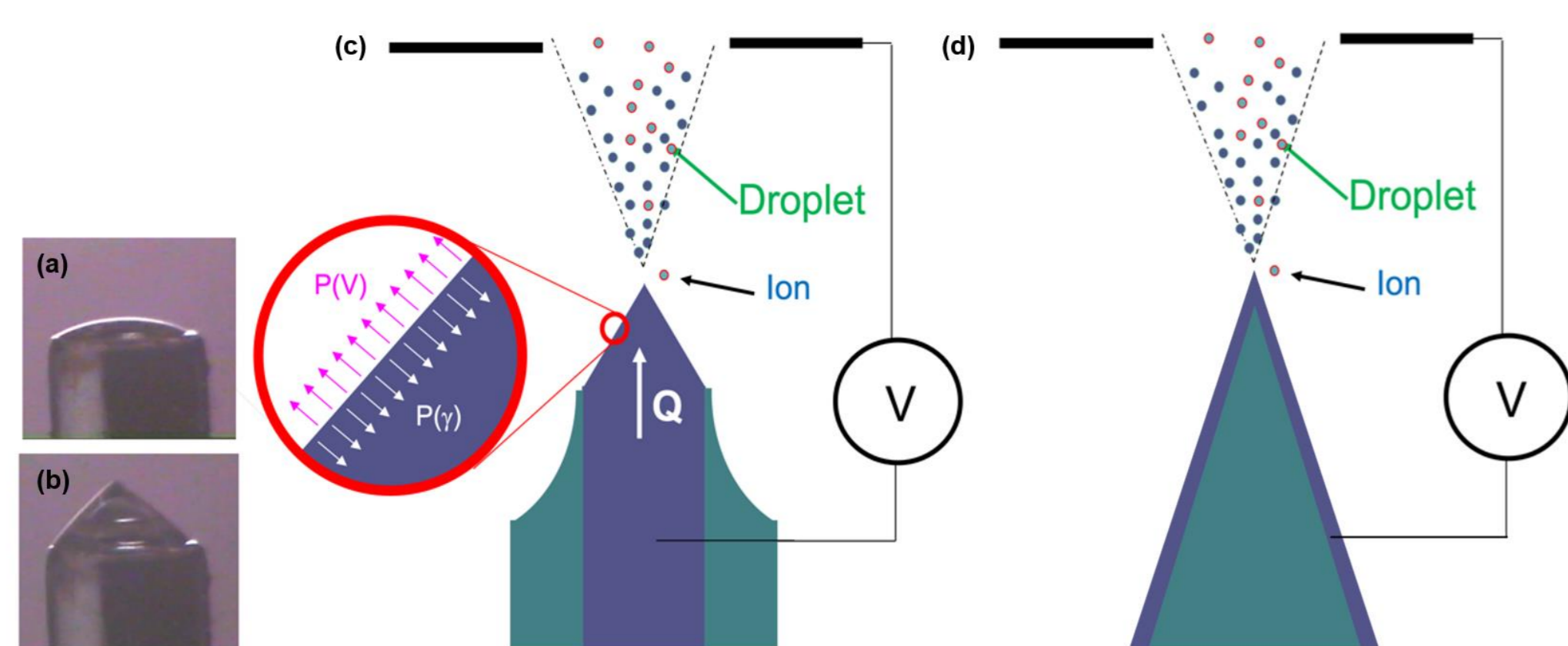


Figure 1. A schematic showing electro spray from a Taylor cone. (a) Liquid meniscus without electric field and (b) with sufficient electric field to form a Taylor cone. (c) Electro spray from an internally fed emitter. (d) Electro spray from an externally fed emitter

Design and Fabrication

We have made two designs of externally fed electro spray emitter arrays made of stainless steel 316L (SS 316L) via binder material jetting (Figure 2a) and FunToDo industrial blend resin (FTD-IB) via vat polymerization (Figure 2b). The same vat polymerization process was also used to make the internally fed electro spray emitter array design using a different resin (Figure 2c). The externally fed designs have a reservoir that supplies the propellant to emitters by wetting, which is enhanced by hydrothermally grown zinc oxide nanowires (ZnONWs). The emitters of the internally fed array design are fed by a network of bifurcating liquid channels that uniformly supply the propellant to each emitter. In all designs, the extractor electrode is a thin stainless steel plate with apertures concentric to the emitters.

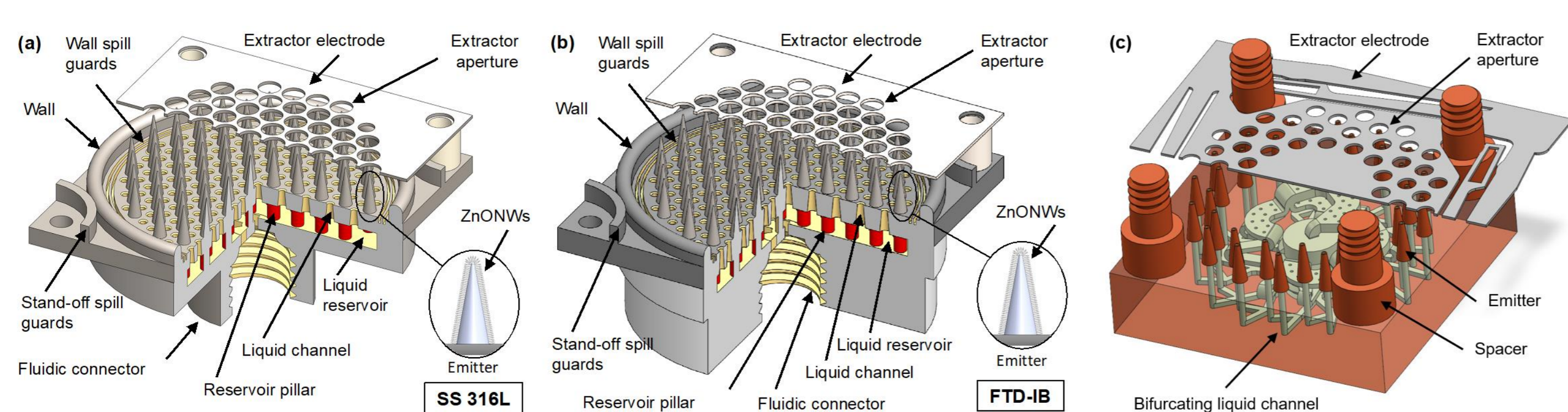


Figure 2. 3D schematics of 3D printed electro spray thrusters. (a) 3D schematic of the externally fed electro spray emitter array made of SS 316L. (b) 3D schematic of the externally fed electro spray emitter array made of FTD-IB. (c) 3D schematic of the internally fed electro spray emitter array.

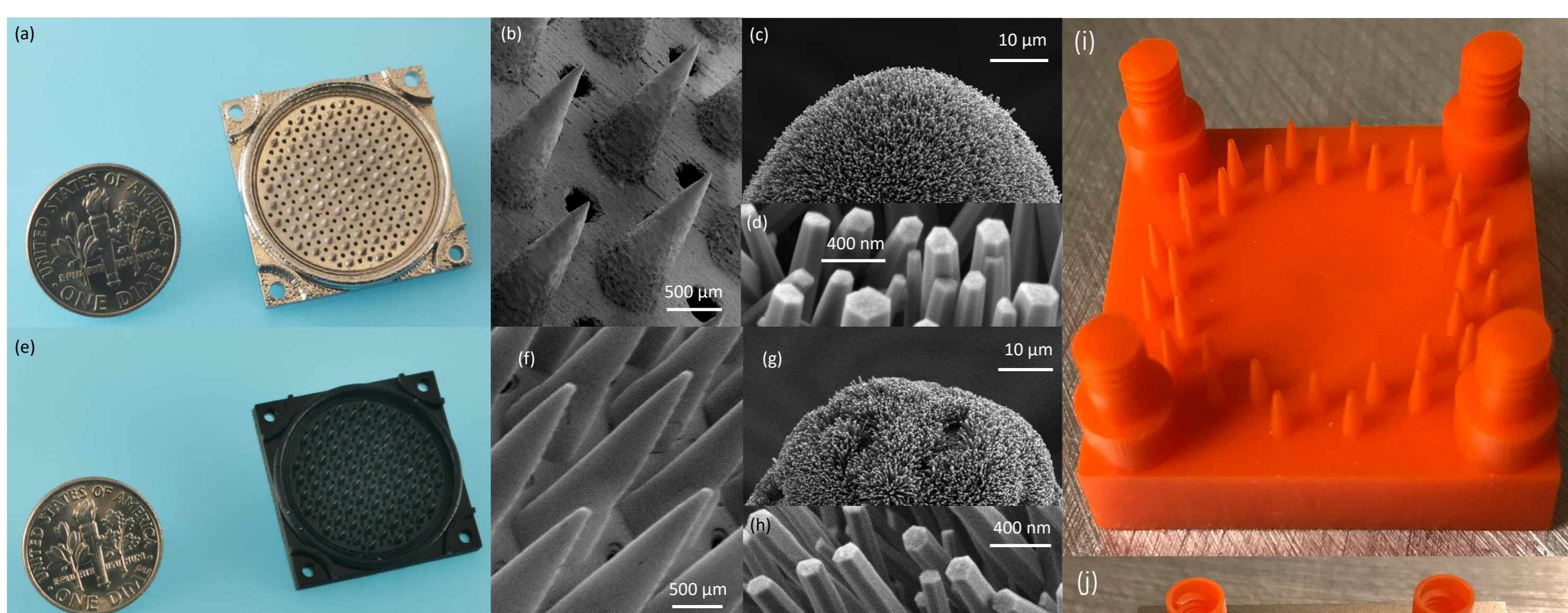


Figure 3. Fabricated electro spray arrays. (a) Optical image of 3D-printed externally fed electro spray emitter array made of SS 316L next to a US dime, (b) close-up SEM image of a cluster of emitters, (c) close-up SEM image of an emitter tip conformally coated with a dense ZnONW forest, and (d) close-up SEM image of the ZnONW forest. (e) Optical image of 3D-printed externally fed electro spray emitter array made of FTD-IB next to a US dime, (f) close-up SEM image of a cluster of emitters, (g) close-up SEM image of an emitter tip conformally coated with a dense ZnONW forest, and (h) close-up SEM image of the ZnONW forest. (i) Optical image of 3D-printed internally fed electro spray array, (j) internally fed electro spray array with integrated extractor electrode. In (i) and (j), the size of the square block is 29 mm.

Device Characterization

Externally fed electro spray thruster

Externally fed emitters operate with a low flow rate, hence emitting pure ions and droplets with a small mass-to-charge ratio. This leads to high specific impulse but low thrust compared to internally fed emitters, which operate with a relatively high flow rate and emit larger droplets.

To estimate thrust and specific impulse of our externally fed electro spray thrusters, we measured current-voltage characteristic (Figure 4a, 4b), mass spectra of emitted plume (Figure 4c, 4d), and beam divergence data using the ionic liquid EMI-BF₄ as a propellant. The mass spectrometry showed there is only one peak for each polarity which corresponds to EMI⁺ ion and BF₄⁻ ion, meaning that only pure ions are emitted. The maximum per-emitter thrust and specific impulse are estimated to be 191.3 nN and 139.9 nN (Figure 5a, 5c), and 9.26×10^3 s and 1.22×10^4 s (Figure 5b, 5d) for SS 316L emitters and FTD-IB emitters, respectively.

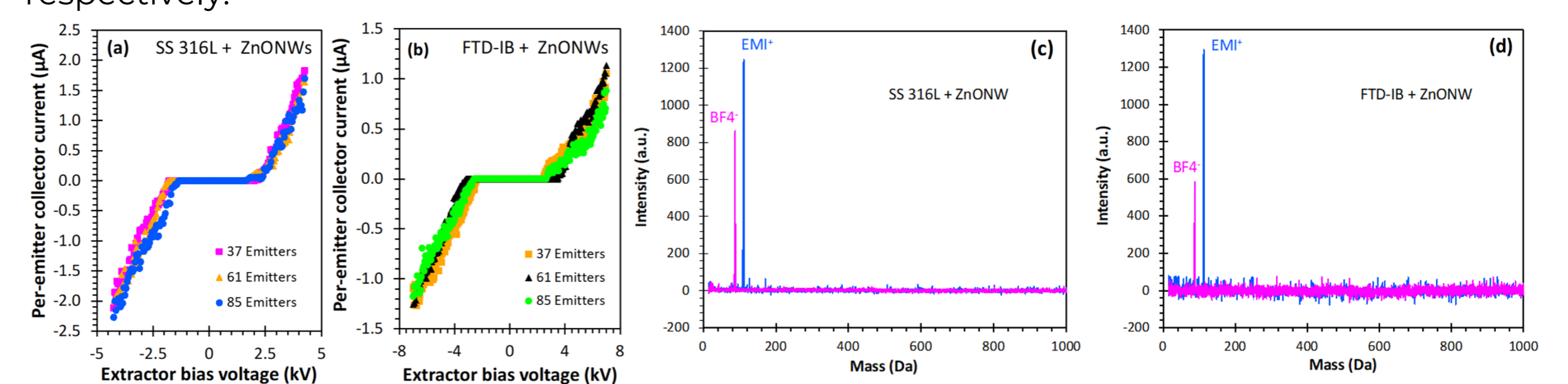


Figure 4. Current-voltage characteristics and mass spectra of emitted plume. Per-emitter collected current versus extractor bias for devices with (a) SS 316L emitting electrode and with (b) FTD-IB emitting electrode. Mass spectra of devices with (c) SS 316L emitting electrode and (d) FTD-IB emitting electrode.

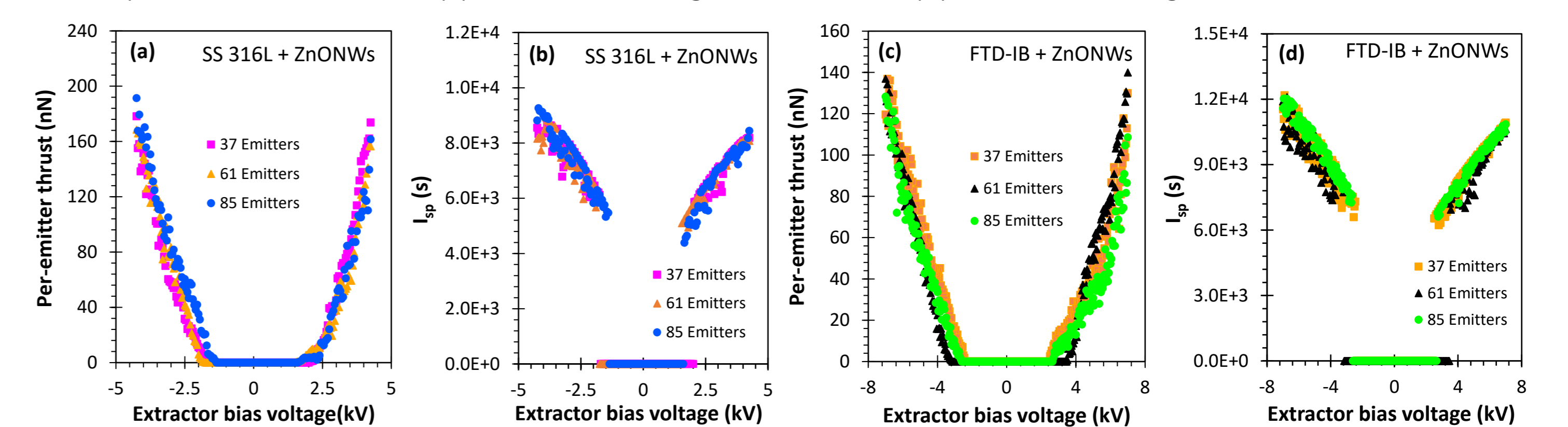


Figure 5. Estimated thrust and specific impulse using $I-V$, mass spectrometry, and plume divergence data. (a) Estimated per-emitter thrust versus extractor bias voltage and (b) estimated specific impulse versus extractor bias voltage for devices with 3D-printed SS 316L electro spray emitters. (c) Estimated per-emitter thrust versus extractor bias voltage and (d) estimated specific impulse versus extractor bias voltage for devices with 3D-printed FTD-IB electro spray emitters.

Internally fed electro spray thruster

The characterization of internally fed electro spray thruster is still in progress; we are currently testing a device with one emitter. Unlike the externally fed emitters that are voltage-controlled, the current from an internally fed emitter is controlled by modulating the flow rate with fixed bias voltage. Our devices are pressure-fed using a home-built system that can pressurize the propellant tank from vacuum to about 140 psi. The estimated thrust and specific impulse from the test that used 35 psi on the propellant tank (Figure 6) are 33 μ N and 52 s, assuming 100 % of propulsive efficiency (two orders of magnitude more thrust compared to the externally-fed emitters). Further work includes testing larger arrays and conducting mass spectrometry of the plume.

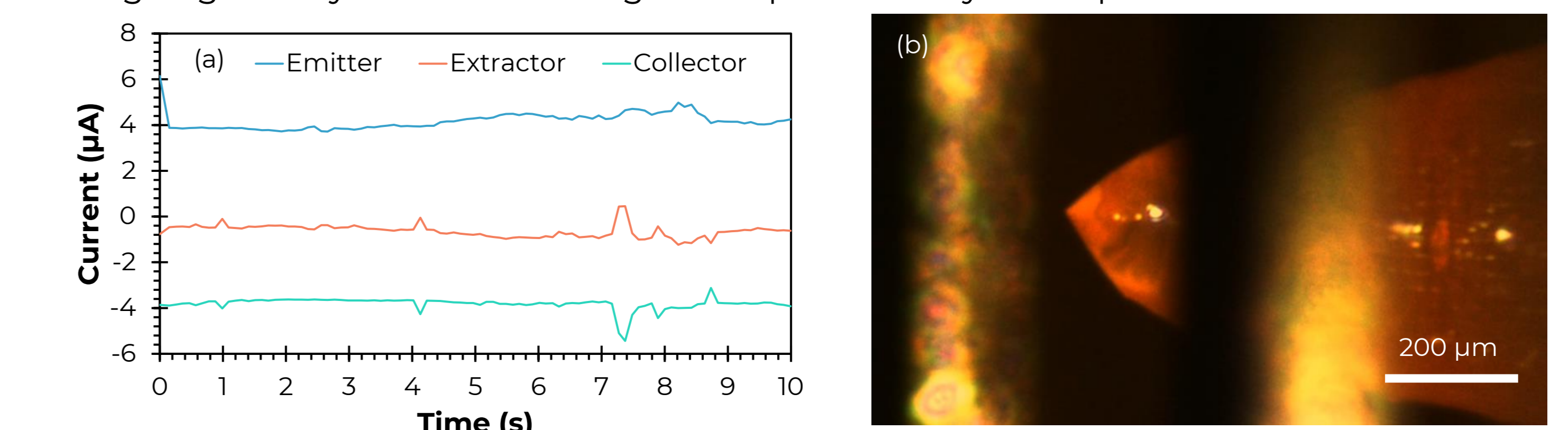


Figure 6. Current vs. time data from an internally fed emitter while applying 35 psi on the propellant tank and 2000 V, 0 V, and -1000 V on emitter, extractor, and collector electrodes, respectively. (a) Current measured at each electrode; the extractor electrode attains ~100% transmission of the emitter plume. (b) A Taylor cone formed on the emitter.

Further Reading

- D. Olvera-Trejo and L. F. Velásquez-García, "Additively Manufactured MEMS Multiplexed Coaxial Electro spray Sources for High-Throughput, Uniform Generation of Core-Shell Microparticles," *Lab on a Chip*, vol. 16, no. 21, pp. 4121-4132, Oct. 2016.
- D. V. Melo Máximo and L. F. Velásquez-García, "Additively Manufactured Electrohydrodynamic Ionic Liquid Pure-Ion Sources for Nanosatellite Propulsion," *Additive Manufacturing*, vol. 36, p. 101719, Dec. 2020.
- E. García-López, D. Olvera-Trejo, and L. F. Velásquez-García, "3-D Printed Multiplexed Electro spinning Sources for Large-Scale Production of Aligned Nanofiber Mats with Small Diameter Spread," *Nanotechnology*, vol. 28, no. 42, p. 425302, Oct. 2017.

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