Enabling Independent Interplanetary CubeSats with Staged Electrospray Propulsion

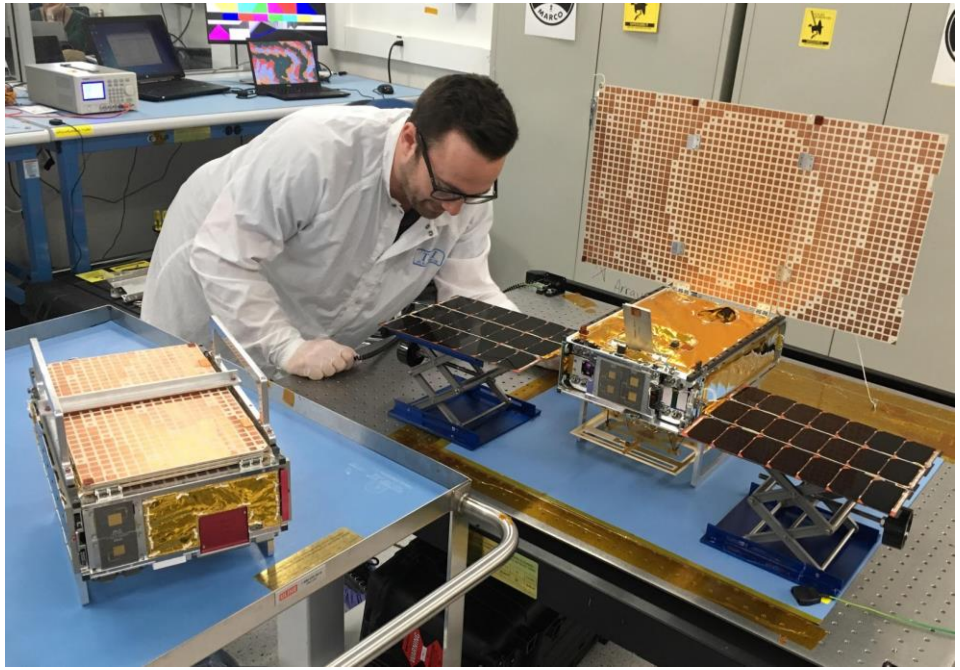
Gustav M. Pettersson, Oliver Jia-Richards, and Paulo C. Lozano
Massachusetts Institute of Technology

2021 Interplanetary Small Satellite Conference

MIT SPL
SPACE PROPULSION LAB

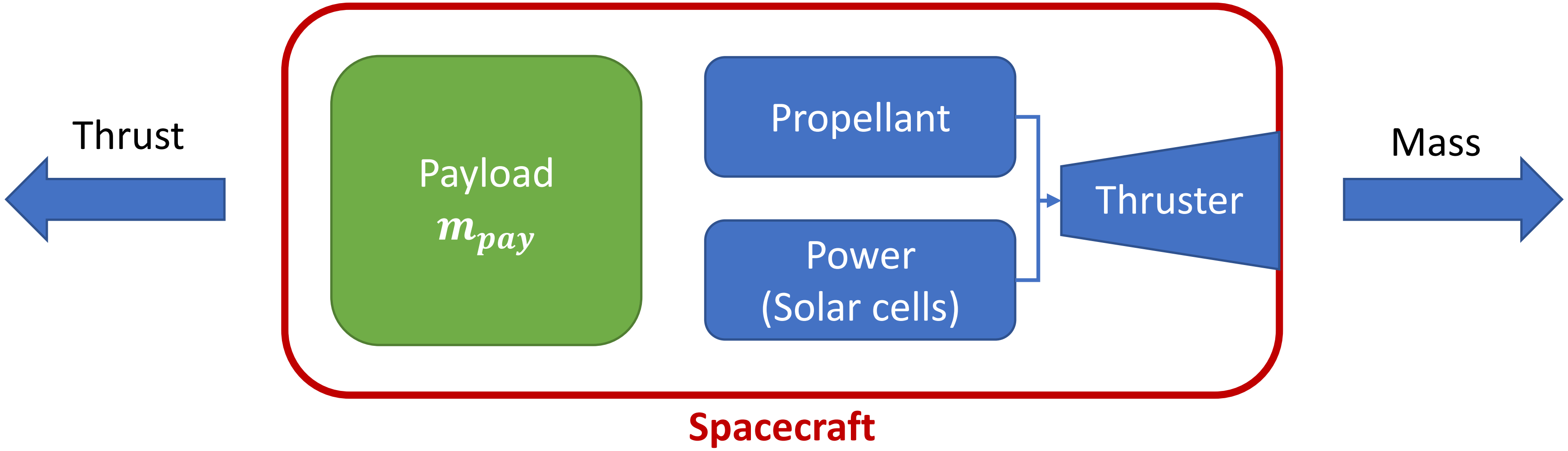
Independent Interplanetary CubeSats

- Small satellite revolution in Earth orbit
  - Lower costs
  - Faster development
  - **Why not in deep-space?**
- Deep-space and interplanetary missions
  - Endless opportunity for discovery
  - Prospecting for resources
- So far not independent
  - "Hitchhiking" limits opportunities
  - Considered secondary to the mission
- **Effective propulsion is the key enabler**



NASA *MarCo A/B* went to Mars with *InSight*
The only interplanetary CubeSats,
but not independent.

Propulsion Definitions



- Requirements
  - m_0: Spacecraft initial mass
    - 12 kg for 6U CubeSat
  - ΔV: How far you need to go
  - α: Specific power of generation
    - **Varies $^1/_{R^2}$ with distance to sun**

- Propulsion parameters
  - I_{sp}: Specific impulse
  - P: Power
  - m_{dry}: Dry mass
- Payload m_{pay} delivered
  - Everything except prop. or power

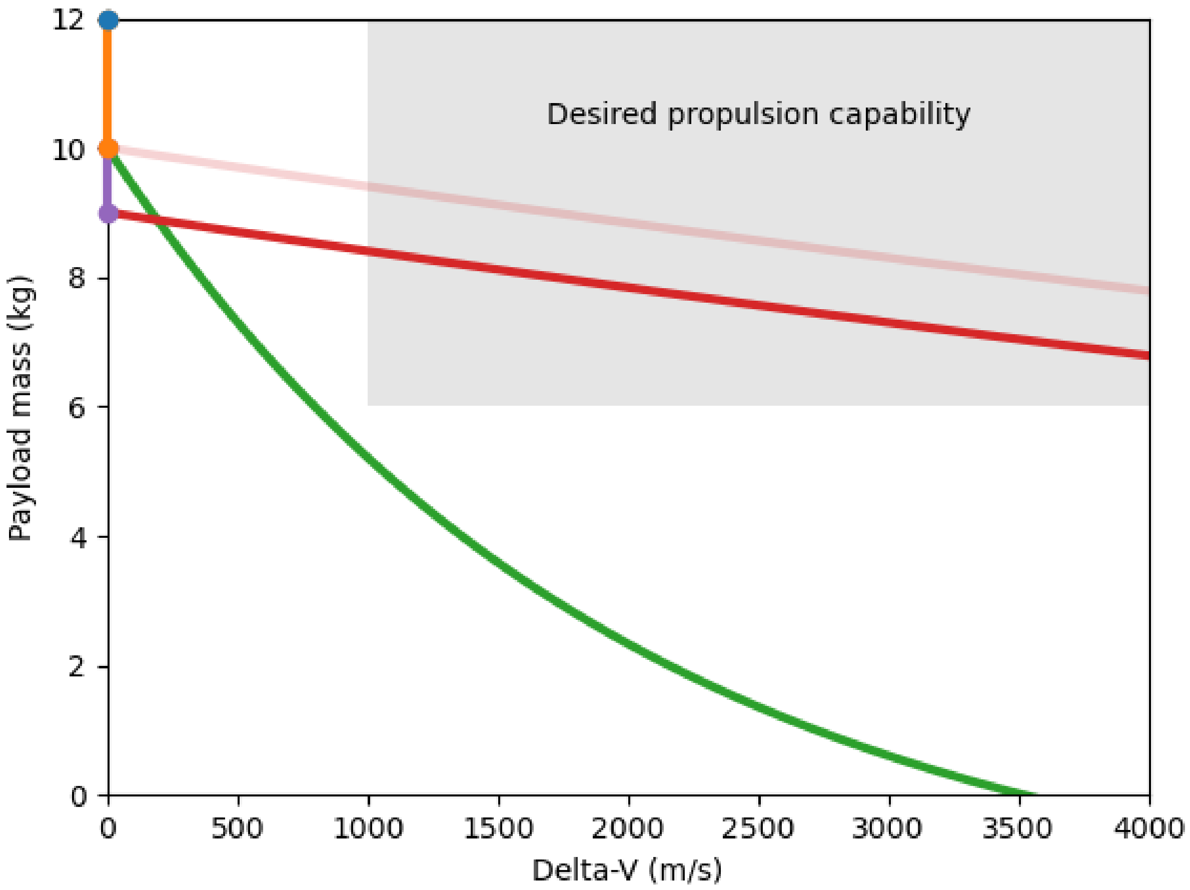
Payload Capability Example

$$\boldsymbol{m_{pay}} =$$

Initial mass
(6U CubeSat)
$\boldsymbol{m_0 = 12\ \mathrm{kg}}$

Propulsion
dry mass
$\boldsymbol{m_{dry} = 2\ \mathrm{kg}}$

Propellant
(Chemical)
$\boldsymbol{I_{sp} = 200\ \mathrm{s}}$

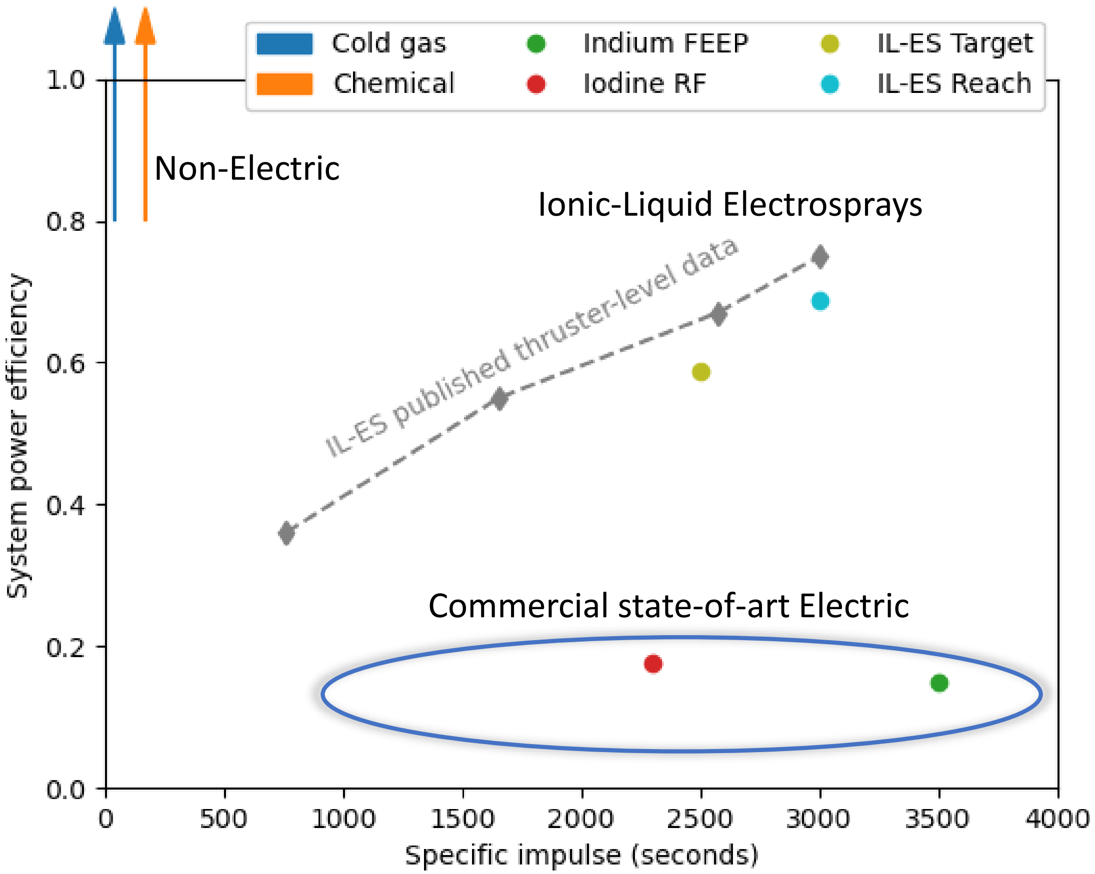


Propellant
(Electric)
$\boldsymbol{I_{sp} = 2000\ \mathrm{s}}$

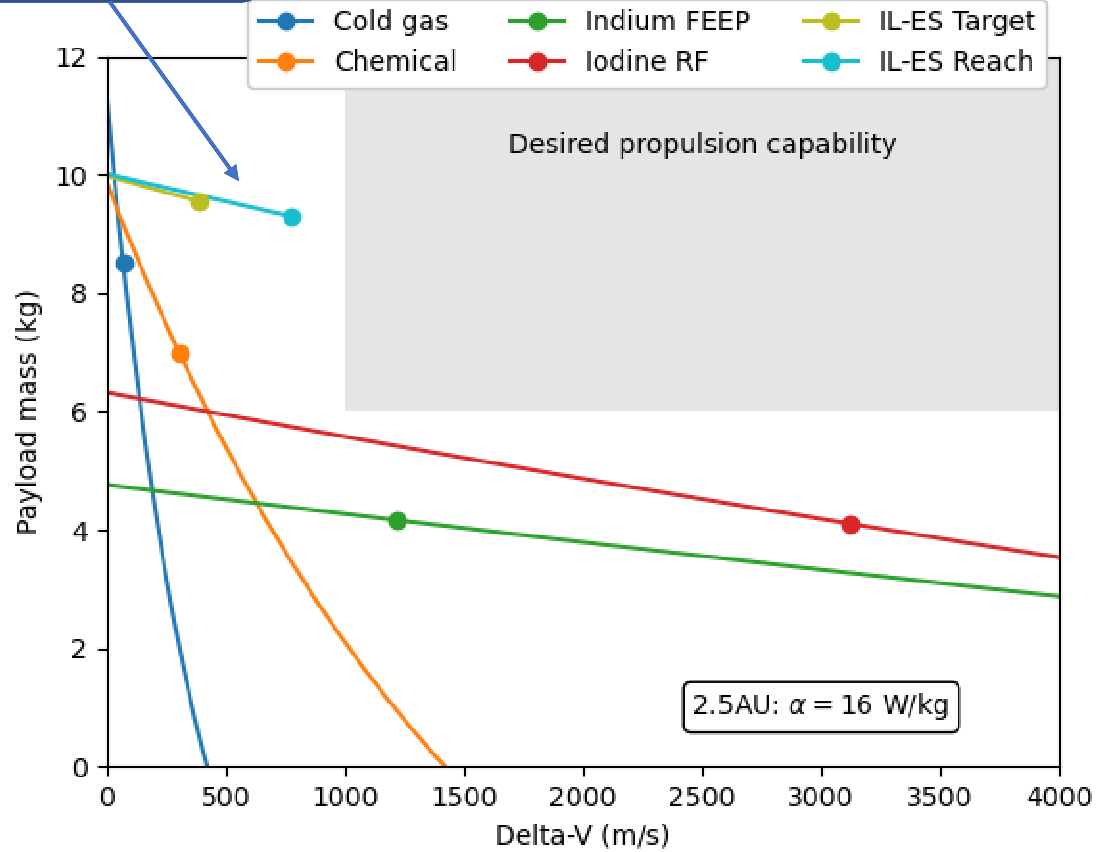
Power system
$\boldsymbol{P = 100\ \mathrm{W}}$
$\boldsymbol{\alpha = 100\ \mathrm{W/kg}}$

(For I_{sp} in m/s multiply with g=9.81 m/s^2)

Challenges to Deep-Space CubeSat Propulsion



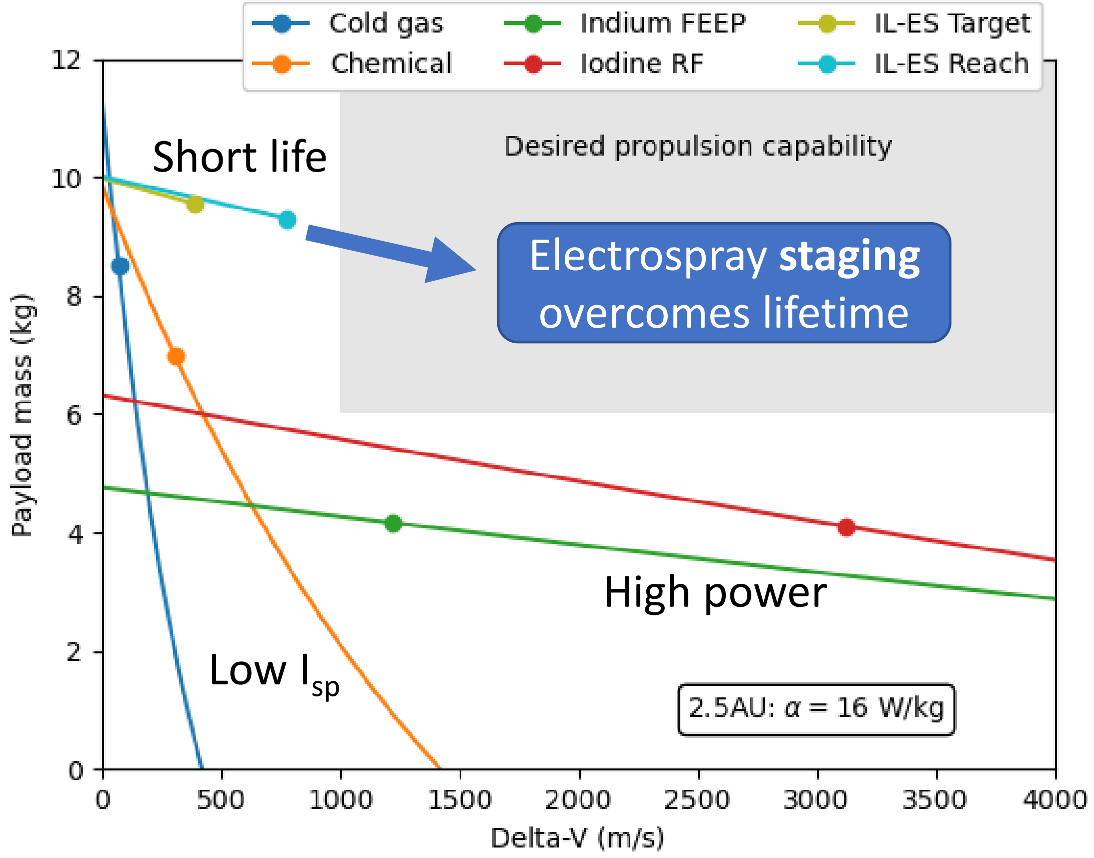
Electrospray **lifetime limit**



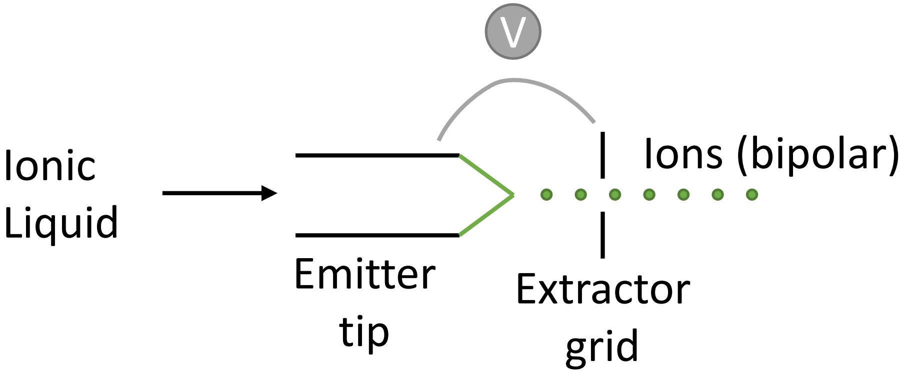
IL-ES data: (Krejci et al., 2017; Petro et al., 2020)

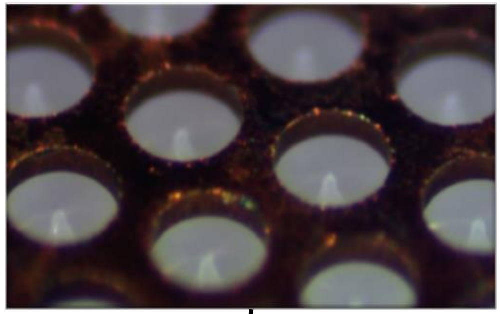
CubeSat Propulsion Situation

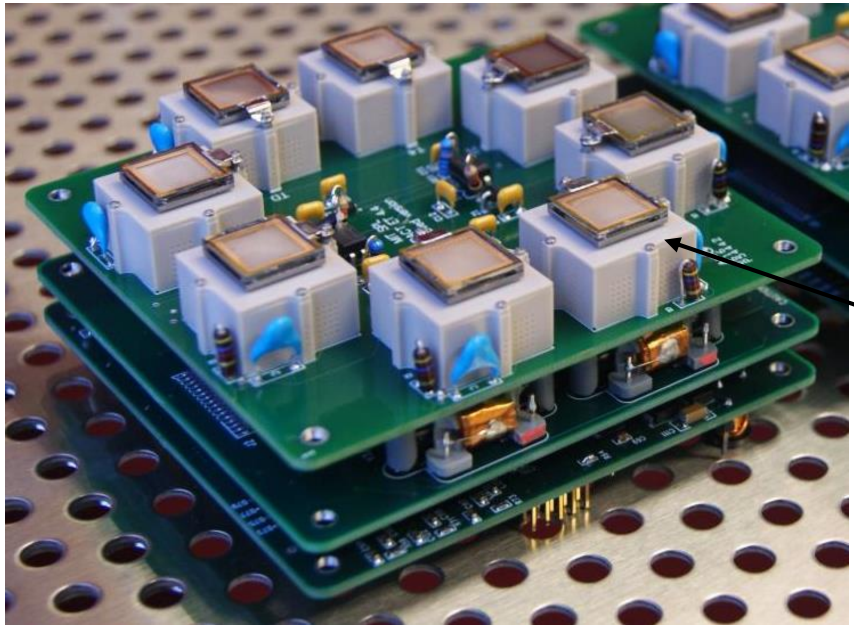
- Near-Earth: Competent systems available!
- Deep-Space: More work.
  - High specific impulse (I_{sp})
  - Low power
  - Long lifetimes
  - **All three required**
- Key message:
  - **Staging overcomes IL-ES lifetime**
  - IL-ES known high efficiency and I_{sp}
  - **Deep-space unlocked**

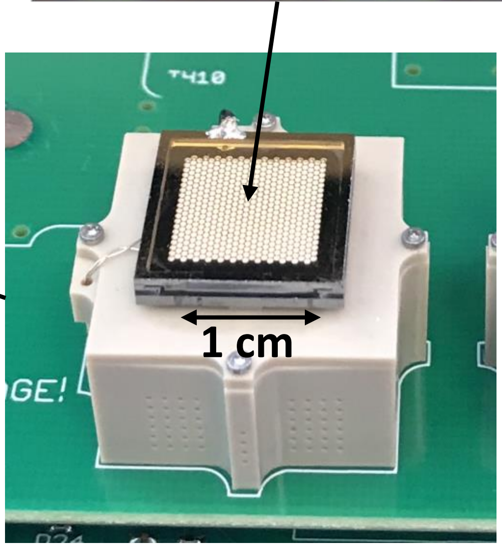


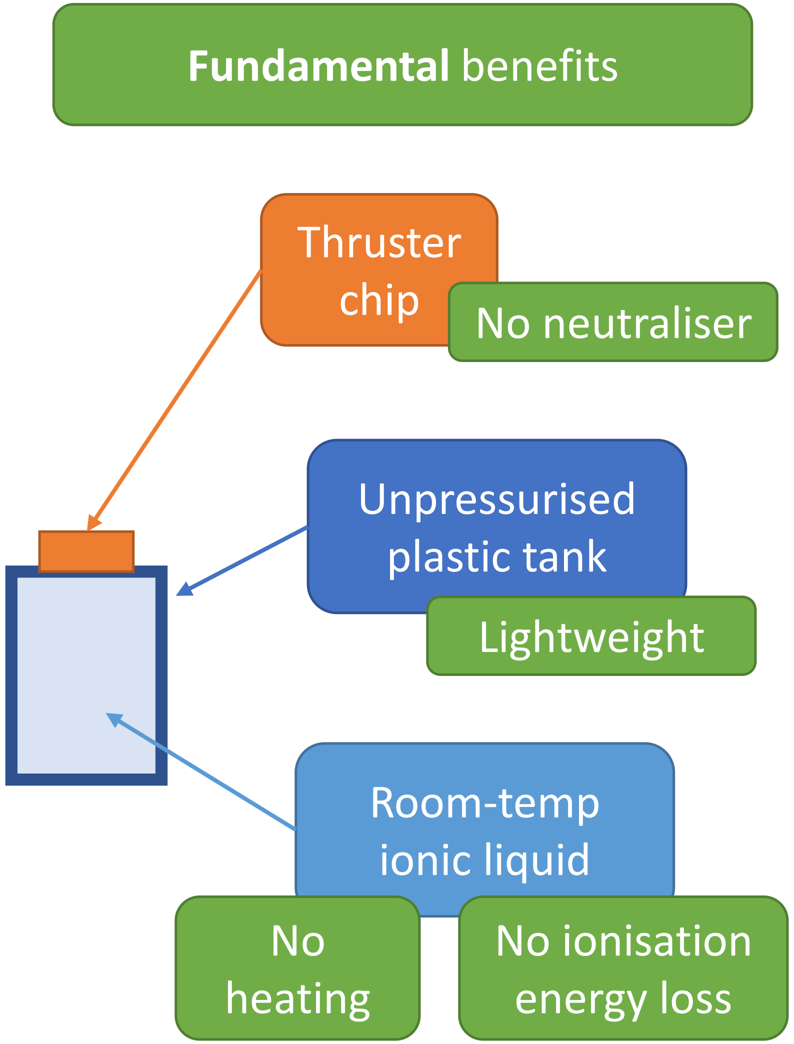
Electrosprays are Fundamentally Efficient











Fundamental benefits

Thruster chip

No neutraliser

Unpressurised plastic tank

Lightweight

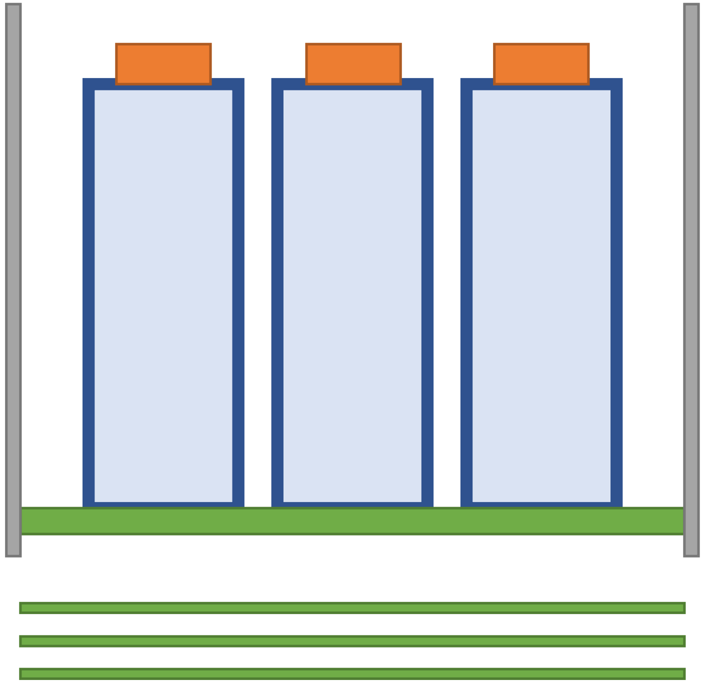
Room-temp ionic liquid

No heating

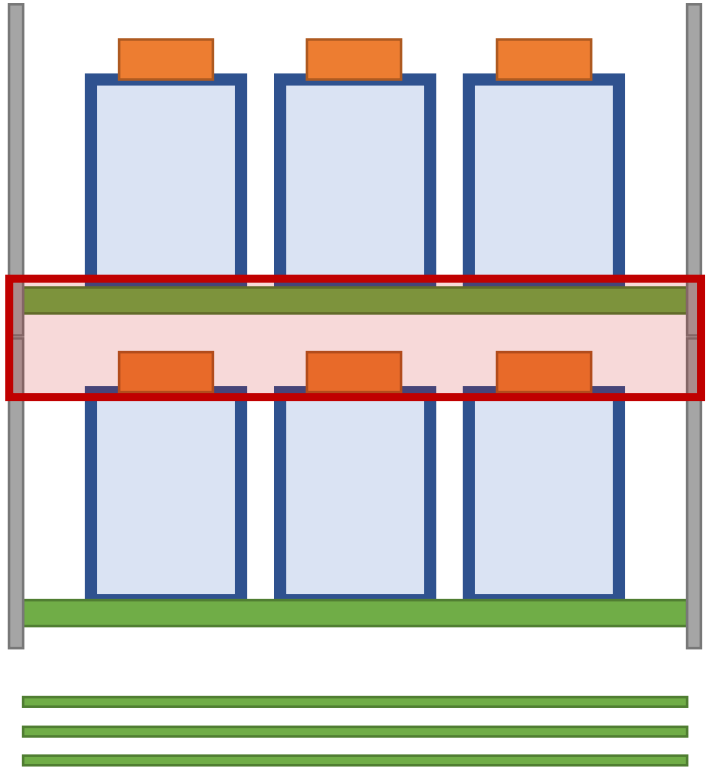
No ionisation energy loss

Staging Architecture and Penalty

“Traditional” IL-Electrospray stack



Two-stage IL-Electrospray stack



Staging penalty

Fundamentally light, compact

Small staging penalty

Staged Electrosprays Becoming Reality

- Theoretical work and feasibility
  - (Krejci, Gomez-Jenkins, and Lozano, 2019), (Jia-Richards et al., 2020)
- Proof of concept lab demonstration
  - (Jia-Richards et al., 2019)

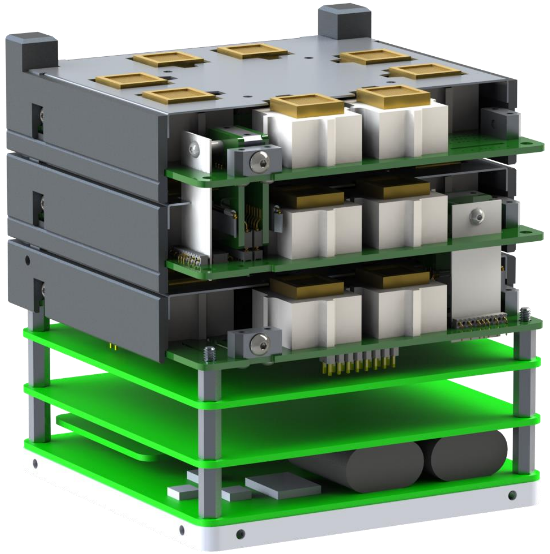
STEP-1: Staged Electrospray Pathfinder 1

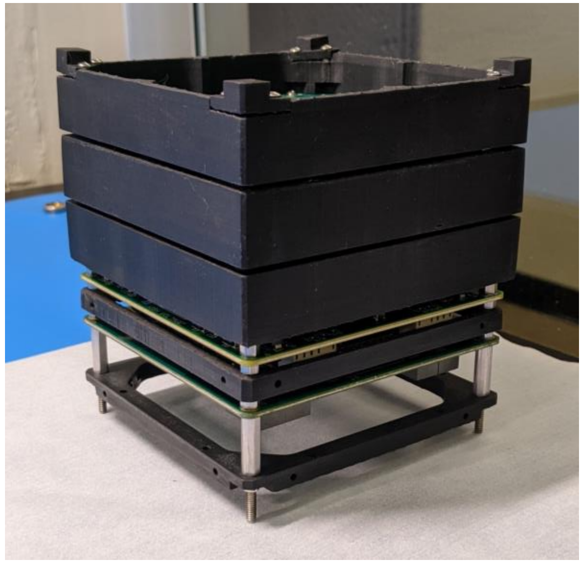
- System optimisation and integration
  - Prove functionality
  - Measure staging penalty and performance
- Qualification and demonstration

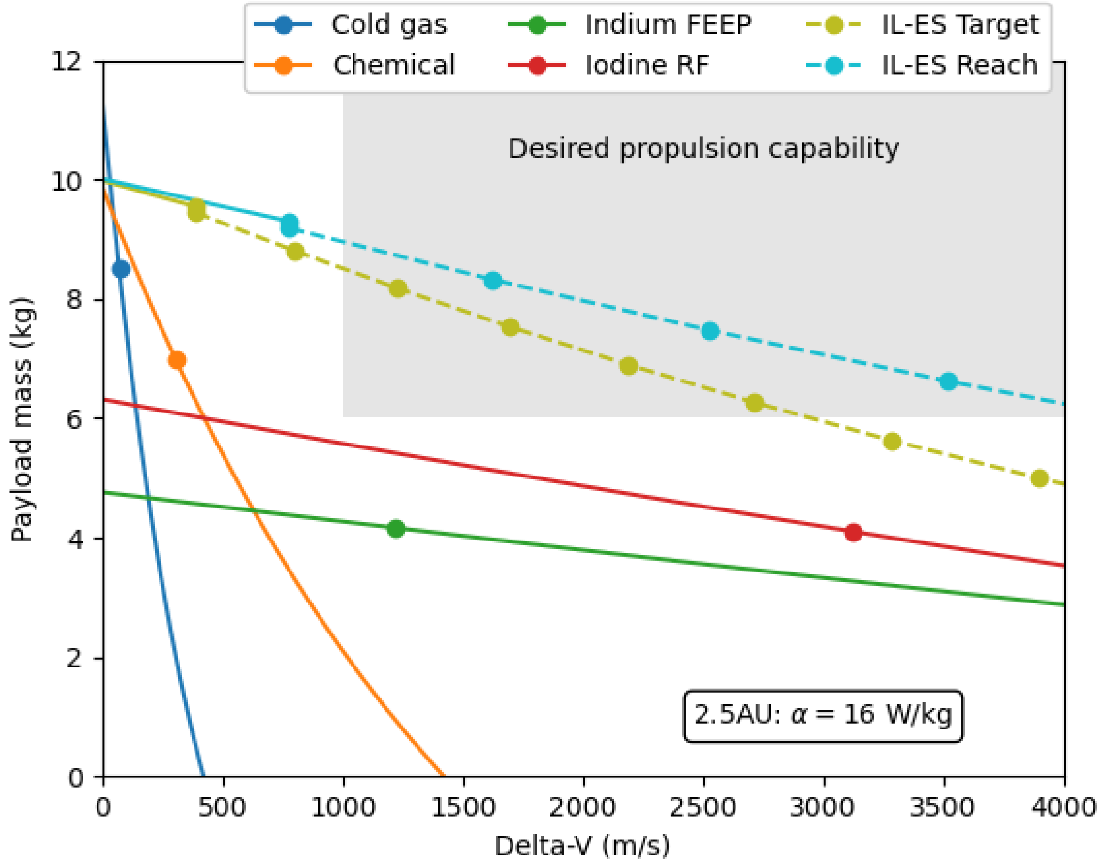
Preliminary Results

- STEP-1 preliminary results
  - **<150g mass penalty** per stage
  - <15mm height penalty per stage
  - Arbitrary number of stages

Preliminary performance results:
(Scaled from STEP-1 3U to 6U)

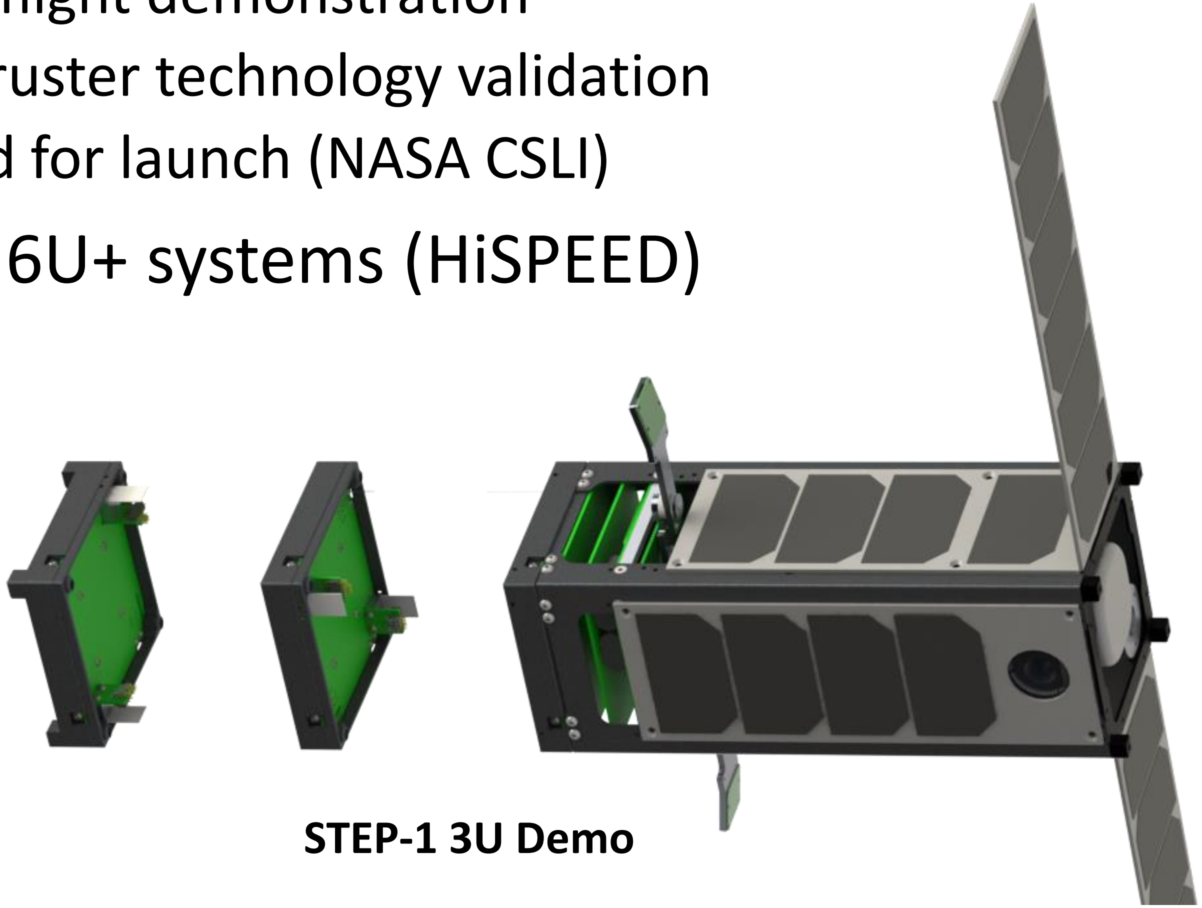




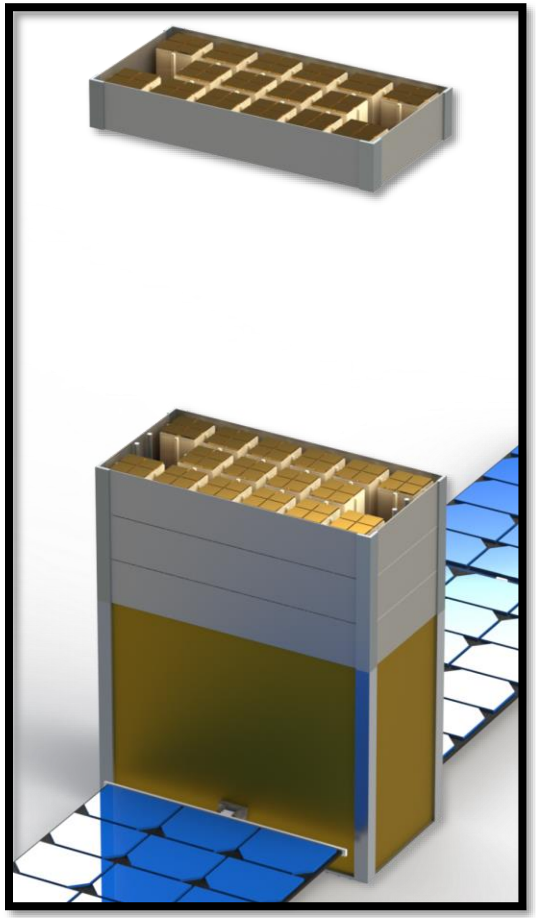


Future Work

- STEP-1 3U CubeSat Flight
    - Staging flight demonstration
    - Core thruster technology validation
    - Selected for launch (NASA CSLI)
- Scaling to 6U+ systems (HiSPEED)



STEP-1 3U Demo



HiSPEED 6U Explorer

Acknowledgements

NASA

Small Spacecraft Technology Program (SSTP)
SmallSat Technology Partnerships (STP)

DOD

Department of Defence

AFOSR

Air Force Office of Scientific Research

STEP-1 technical management in

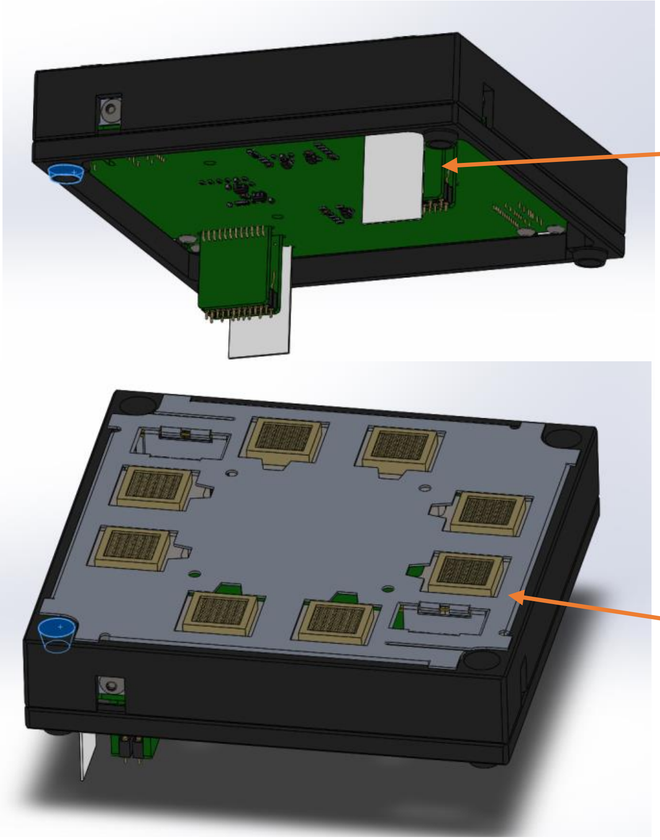
VALISPACE

References

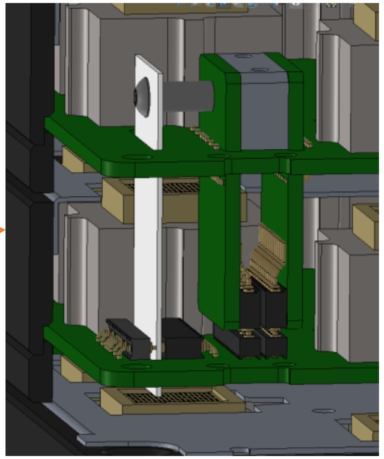
- Krejci, D., M. Gomez Jenkins, and P. Lozano. "Staging of electric propulsion systems: Enabling an interplanetary Cubesat." *Acta Astronautica* 160 (2019): 175-182.
- Jia-Richards, O., and P. C. Lozano. "Laboratory Demonstration of a Staging System for Electrospray Thrusters." (2019).
- Petro, E. et al. "Characterization of the TILE Electrospray Emitters." In *AIAA Propulsion and Energy 2020 Forum*, 2020.
- Krejci, D. et al. "Emission characteristics of passively fed electrospray microthrusters with propellant reservoirs." *Journal of Spacecraft and Rockets* 54, no. 2 (2017): 447-458.
- Jia-Richards, O. et al. "Feasibility of a Deep-Space CubeSat Mission with a Stage-Based Electrospray Propulsion System." In *2020 IEEE Aerospace Conference*, 2020.

Extras

STEP-1 Design

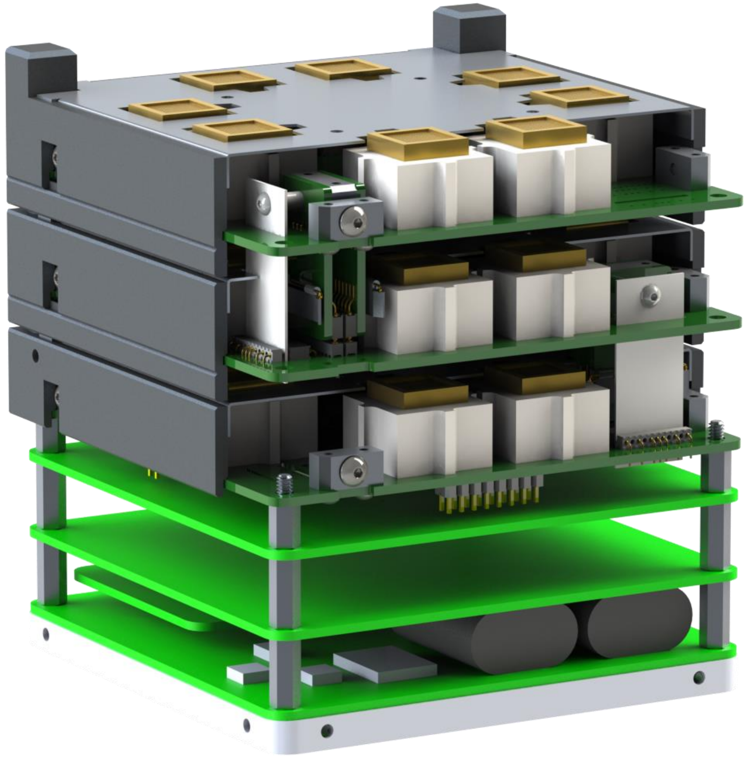


Conical surface for alignment and force transfer. Integrated separation spring. Stainless steel wire hold-down.



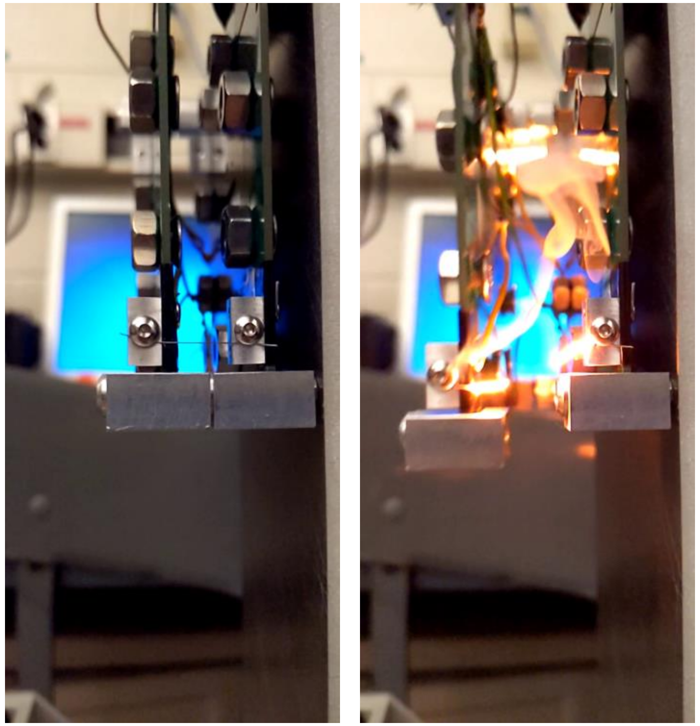
Electrical interstage and physical lower stage inhibit

Individual stage layout identical to previous system

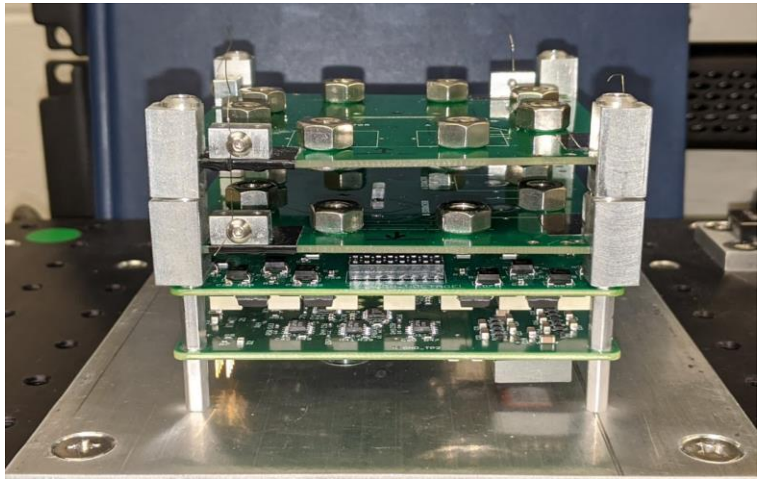


Three-stage stack with heritage power electronics

STEP-1 Testing

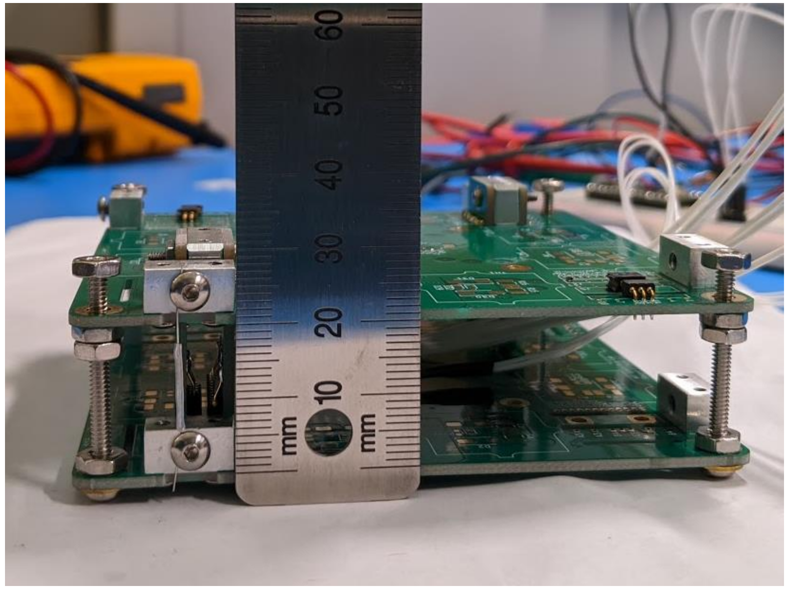


First staging test



Vibrated to 11g RMS

2019:
Mechanical design
and testing



Full interstage and electronics

2020:
Electronics and
integration

Power Trade-Off and Efficiency

- Thrust: $F = \dot{m} I_{sp}$
- Jet power: $P_J = \frac{1}{2} \dot{m} I_{sp}^2 = \frac{1}{2} F I_{sp}$
- Efficiency: $\eta = \frac{P_J}{P} = \frac{\dot{m} I_{sp}^2}{2P} = \frac{F I_{sp}}{2P}$
- Electrical power: $P = \frac{F I_{sp}}{2\eta}$

$$\boldsymbol{m_0 \mathrm{e}^{-\Delta V / I_{sp}} - \alpha^{-1} P}$$

$$\boldsymbol{m_0 \mathrm{e}^{-\Delta V / I_{sp}} - \alpha^{-1} \frac{F I_{sp}}{2\eta}}$$

- Specific impulse = Impulse per mass
  - International: N s / kg = m/s
  - American: lb s / lb = s
  - Multiply I_{sp} in s with $g = 9.81\ \mathrm{m/s^2}$

Commercial System Performance

Name	F (mN)	Isp (s)	P (W)	Wet (kg)	Impulse (Ns)	Tank struct mass fraction*
Iodine RF	1.25	2300	80	2.9	35,000	30%
Indium FEEP	2x0.35	3500	2x40	2x1.42	2x7200	30%
Cold gas		40		3.49	755	30%
Chemical		169		5.0	3320	30%

*Assumed change in dry mass to extend payload—delta-V diagram