iEPSat: CubeSat propelled to lunar space by ionic liquid electrospray thrusters

David Krejci, Paulo Heredia and Paulo Lozano

Interplanetary Small Satellite Conference, Pasadena, CA, April 25-26, 2016

Massachusetts Institute of Technology

MIT AEROASTRO

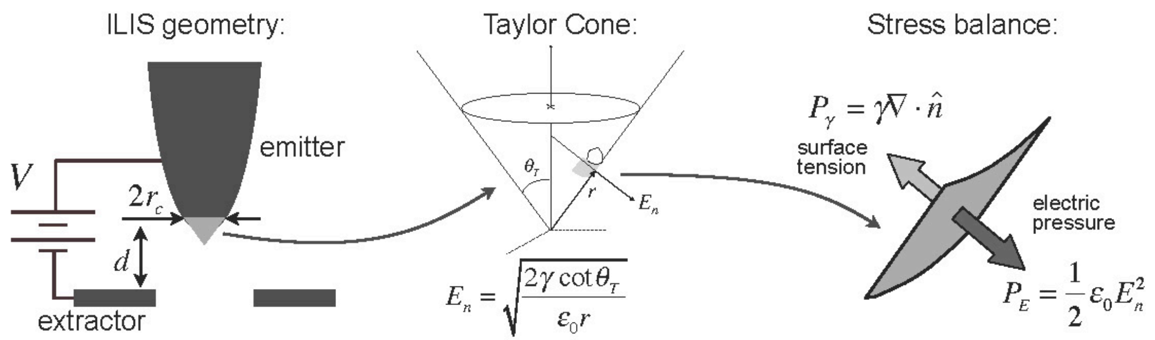
space propulsion laboratory
Massachusetts Institute of Technology

Agenda

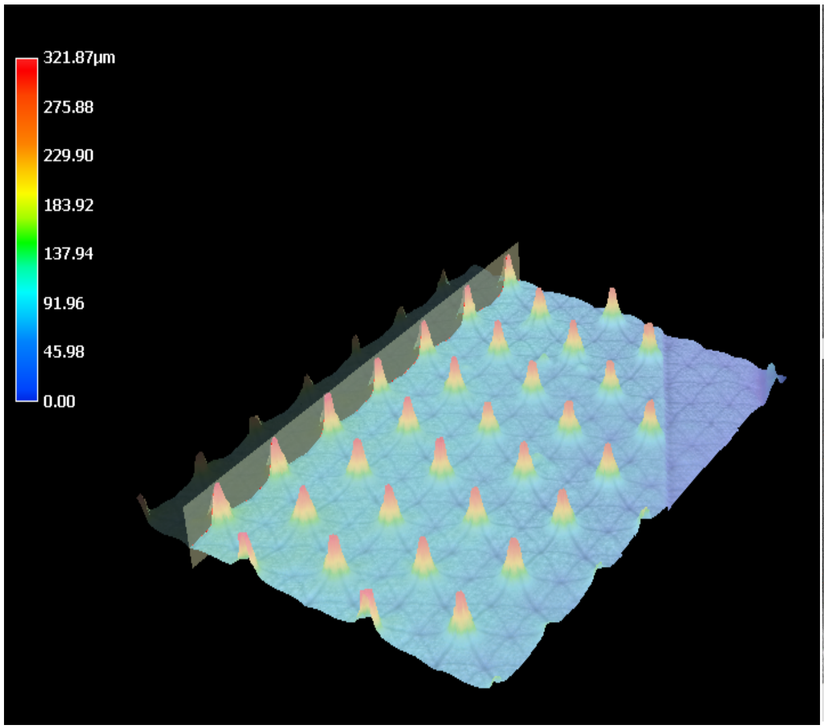
- Electrospray principle, thruster design and operation
- Current propulsion modules
- Performance characterization of current emitters
- Future propulsion module studies for high ΔV scenarios

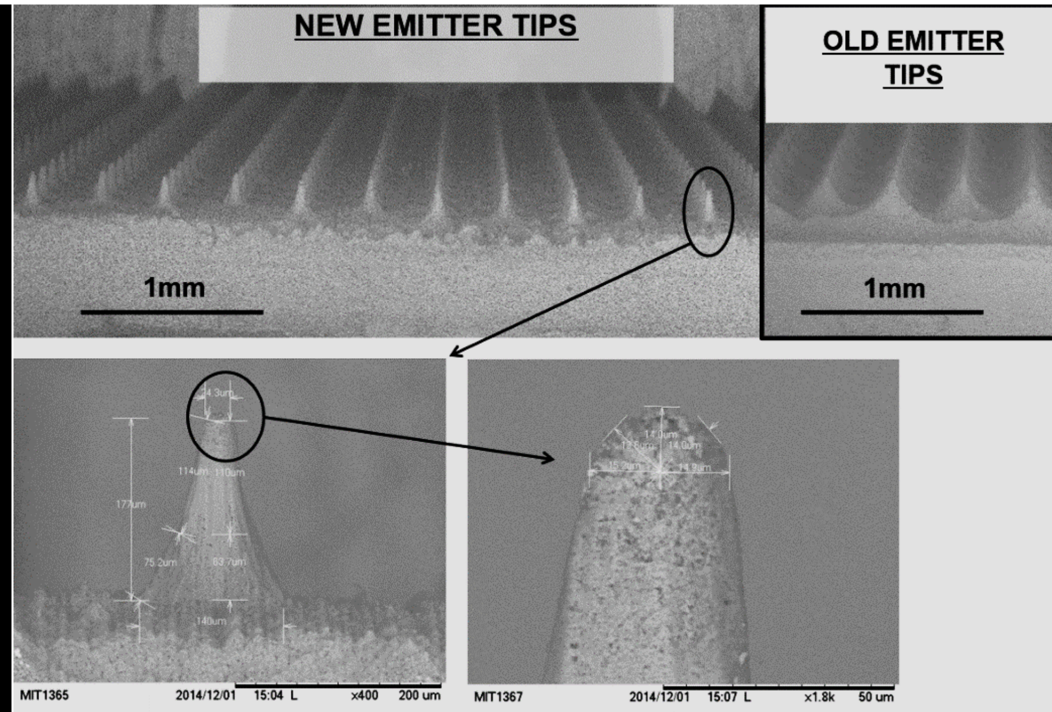
Ionic liquid electrospray

- Room temperature molten salts
- Zero vapor pressure liquids
- Relatively high conductivities
- Stable over a wide temperature range
- Ion extraction for E*~1.6×10^9V/m
- 100s of nN per emitter tip → array



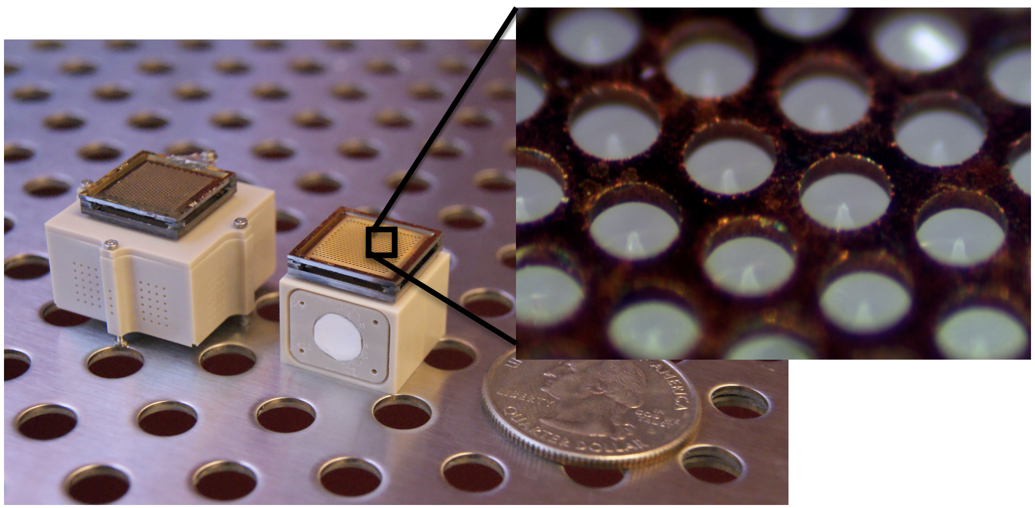
Emitter arrays

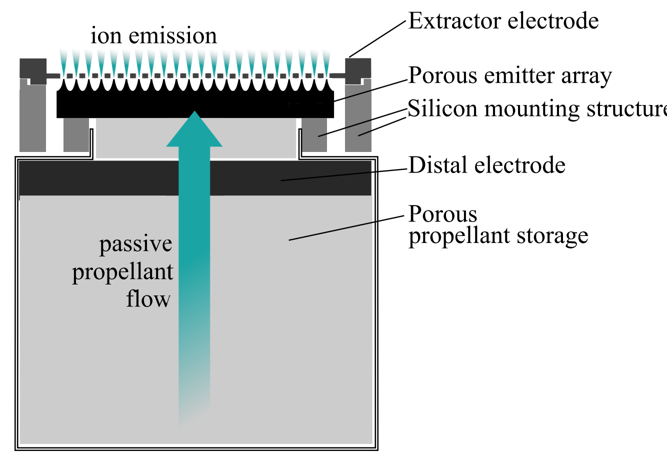




iEPS thruster design

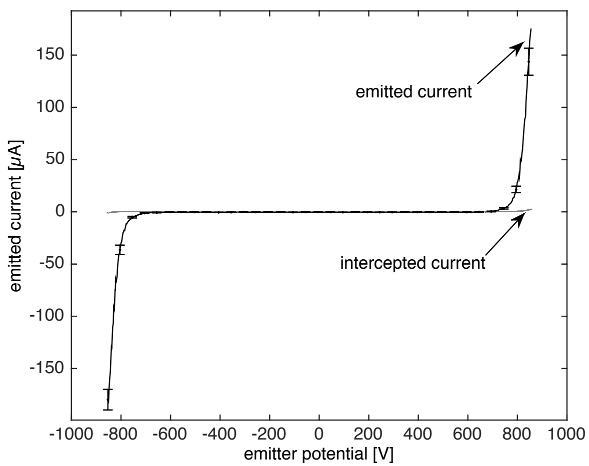
- Entirely passive devices
- Positive and negative ion emission -> self neutralization
- Porous glass emitter chip in silicon frame packaging for aperture alignment
- 480 emitter tips in 1cm^2



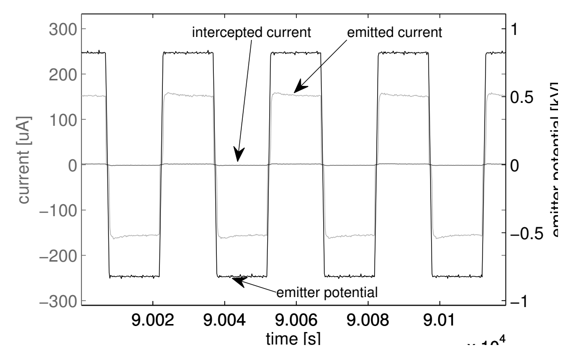


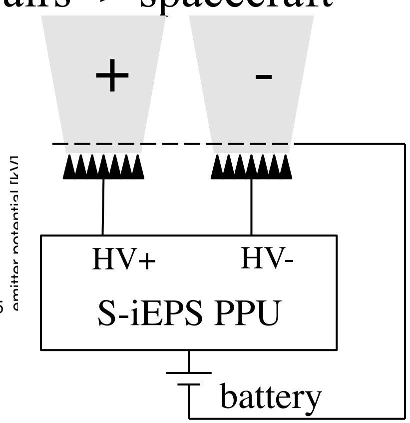
iEPS thruster: Operation

- Emission current as a function of applied voltage
- Determines operational point of emitter



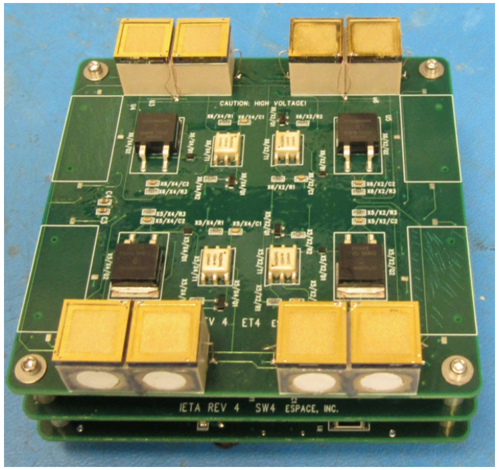
- Low frequency polarity alternation
  - Prevent electrochemical decay
  - Maintain charge balance in propellant reservoir
  - Operate thrusters in pairs -> spacecraft neutralization

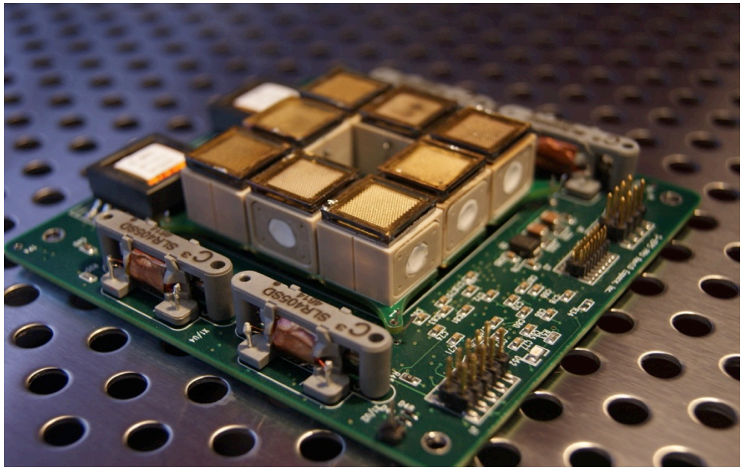




Previous propulsion modules

- Attitude control configuration
- Single axis propulsion module (2.1cm total height, ~100g, including PPU)
  - 50h continuous thrust test (Aerospace Corporation[1])
  - <2W, 50% total efficiency (low side to thrust)

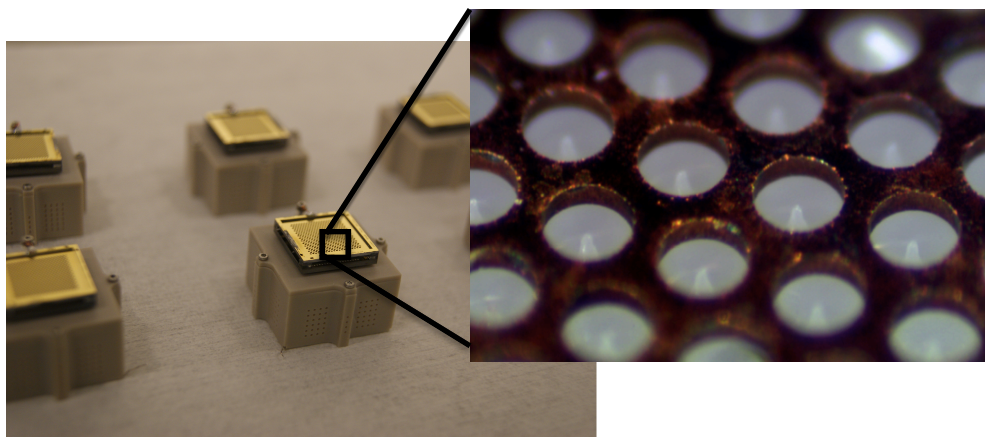




[1]) Krejci, D., Mier Hicks, F., Fucetola, C., Lozano, P., Hsu Schouten, A., and Martel, F., "Design and Characterization of a Scalable ion Electrospray Propulsion System," 34th International Electric Propulsion Conference, No. IEPC-20150149, Hyogo-Kobe, Japan, 2015.

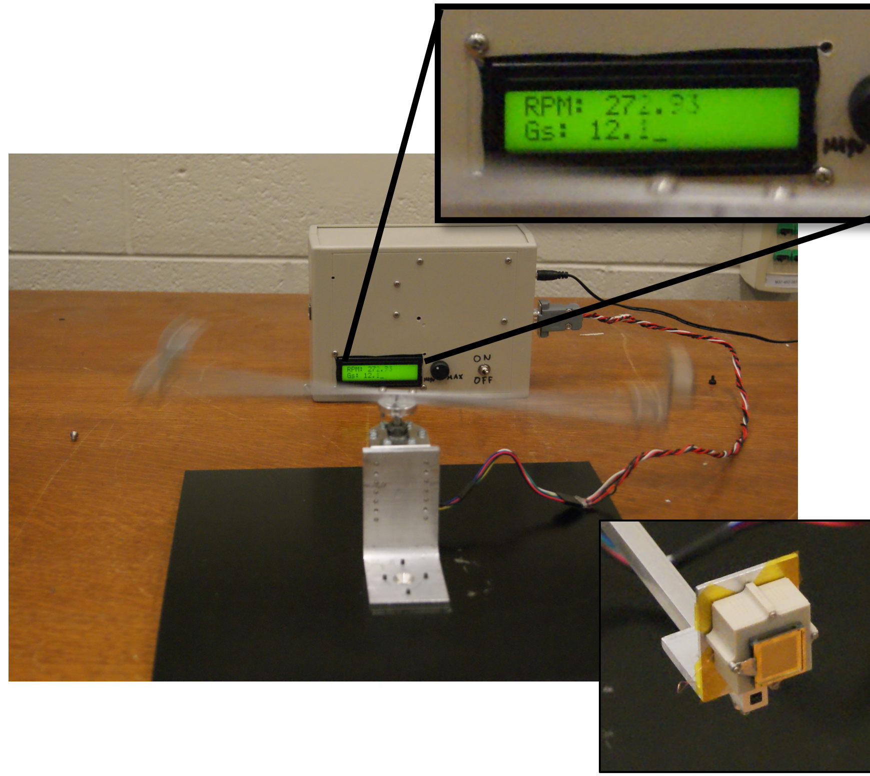
Current thruster design

- Scalable propellant tank: liquid feed flow independent of tank saturation
- Robustness: Confinement of liquid during degassing process
- Nominal ion emission currents at <1000V



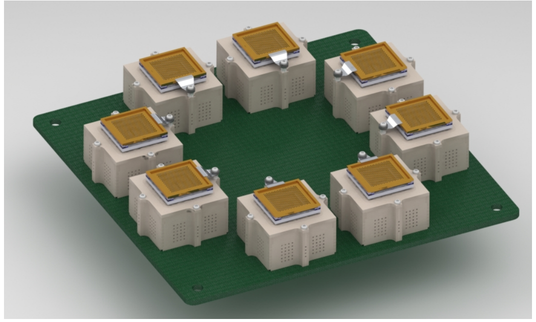
Current thruster efforts

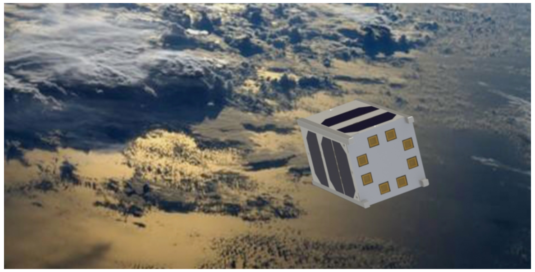
- Scalable propellant tank
- Robustness
  - Static G
  - Vibration
  - Thermal cycling
  - Degassing

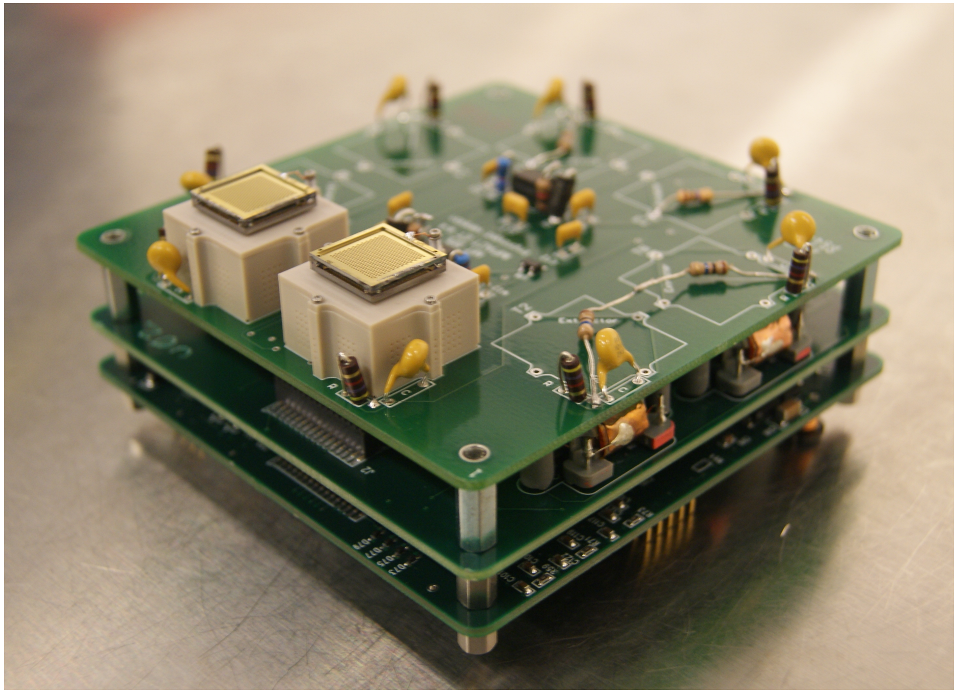


Current propulsion module design

- Targeting 1.5U Cubesats
- Attitude control capability
- Dynamic thruster paring

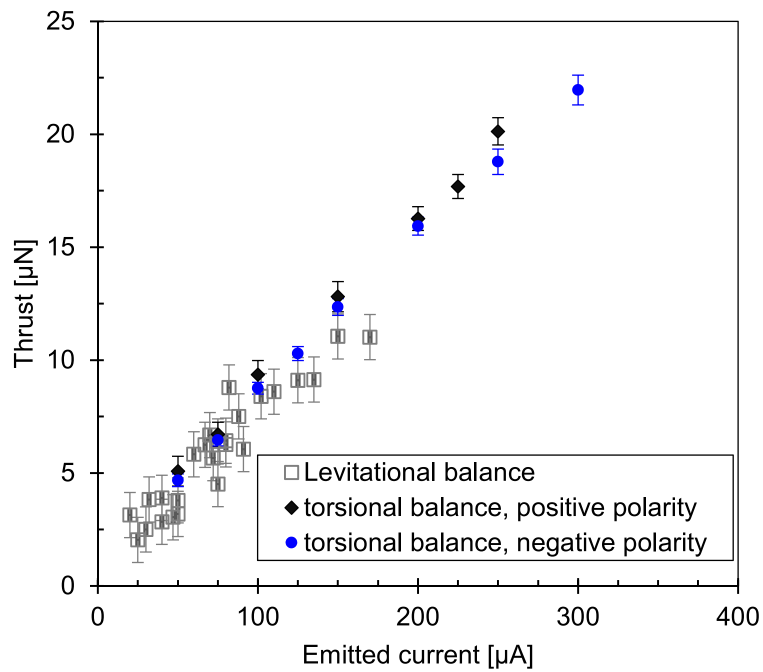






Engineering module

Thrust measurements (per emitter)



- Torsonal balance data recorded at NASA GRC

from: *Krejci, Mier Hicks, Thomas, Haag, Lozano, Emission characteristics of passively fed electrospray microthrusters with propellant reservoirs, submitted to AIAA Journal of Spacecraft and Rockets*

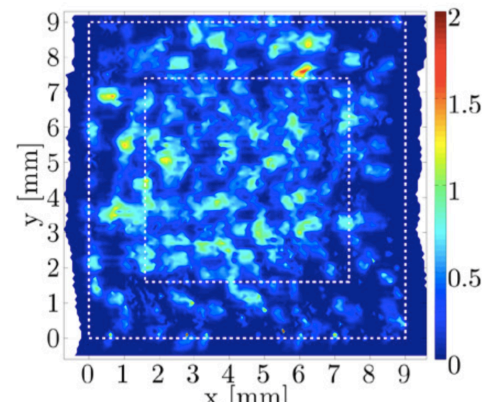
Current iEPS vesion: characterization efforts

- Very high grid transparency: up to 99%
- Spatial beam distribution: Large opening angles ~60deg half opening angle

  → *Strong effect on Isp and efficiency*
- Retarding potential analysis (RPA)

  Energy efficiency
- Beam composition from Time of Flight: showed presence of droplets

  → *Strong effect on Isp and efficiency*



Spatial emission profile, 150uA

from: Guerra, Krejci, Lozano, J Phys D: Appl. Phys., 49

Current iEPS version efficiency summary

	emission polarity	
	positive	negative
transmission efficiency η_{tr}	0.981 ± 0.006	0.982 ± 0.011
angular efficiency η_{θ}	0.801 ± 0.055	0.828 ± 0.045
energy efficiency η_E	0.887 ± 0.061	0.912 ± 0.048
polydispersive efficiency η_P	0.8859	0.8597
Overall thruster efficiency η_T	**0.606 ± 0.096**	**0.626 ± 0.086**

$$\eta_T = \eta_i \eta_{tr}^2 \eta_\theta \eta_E \eta_p$$

- While efficiency is still high, presence of droplets and angular distribution decrease Isp significantly

Current S-iEPS version characterization summary

- Specific impulse (not accounting for beam spreading)

Experiment type	Comment	Specific impulse [s] ± standard deviation	Max. experiment error margin [s]
Longduration	Initial operation	1167 ± 21	±79
	172h average	1717	±112
Time **of Flight**	positive polarity	1150 ± 40	±188
	negative polarity	1247 ± 20	±168

- True specific impulse: directly measured, combining thrust measurements and propellant consumption measurements[3]

	Specific impulse [s]
Directly measured	758.9 ± 40.7

- Thruster efficiency:

	emission polarity	
	positive	polarity
Overall thruster efficiency η_T	0.606 ± 0.096	0.626 ± 0.086

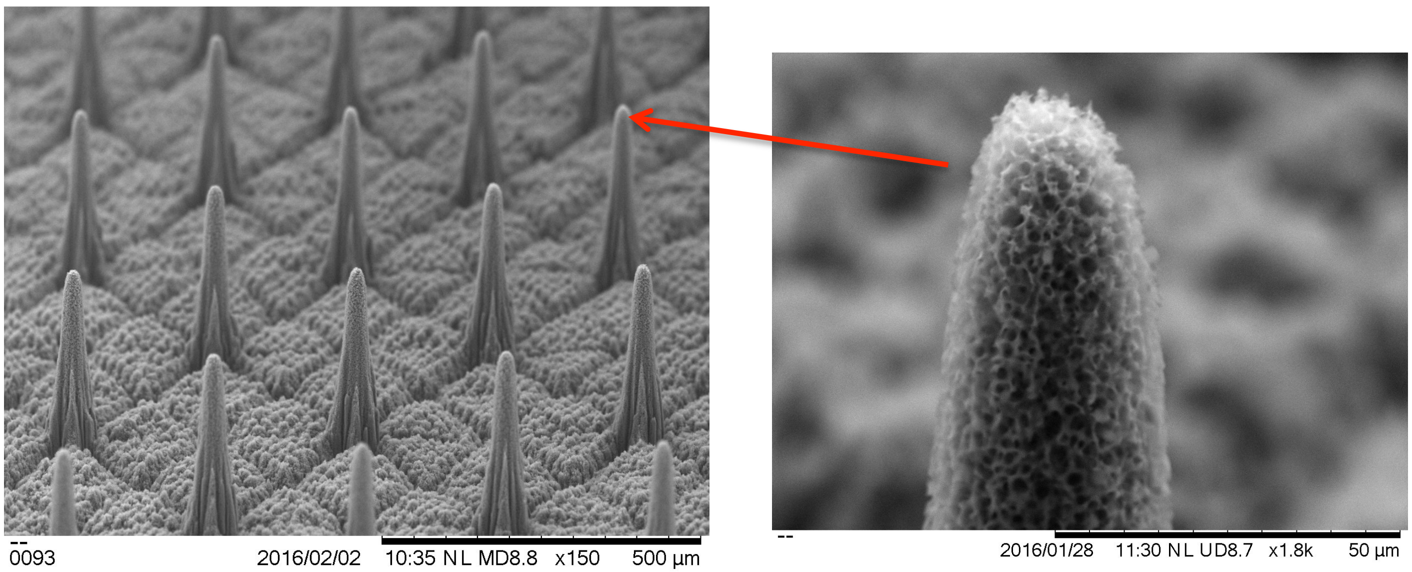
- PPU: Peak efficiency:

	Thrust [μN]	Current [mA]
Measured	74 ± 3.7	1.175
Interpolated	81.5 ± 4.1	1.2

3) *Krejci, Mier Hicks, Thomas, Haag, Lozano, Emission characteristics of passively fed electrospray microthrusters with propellant reservoirs, submitted to AIAA Journal of Spacecraft and Rockets*

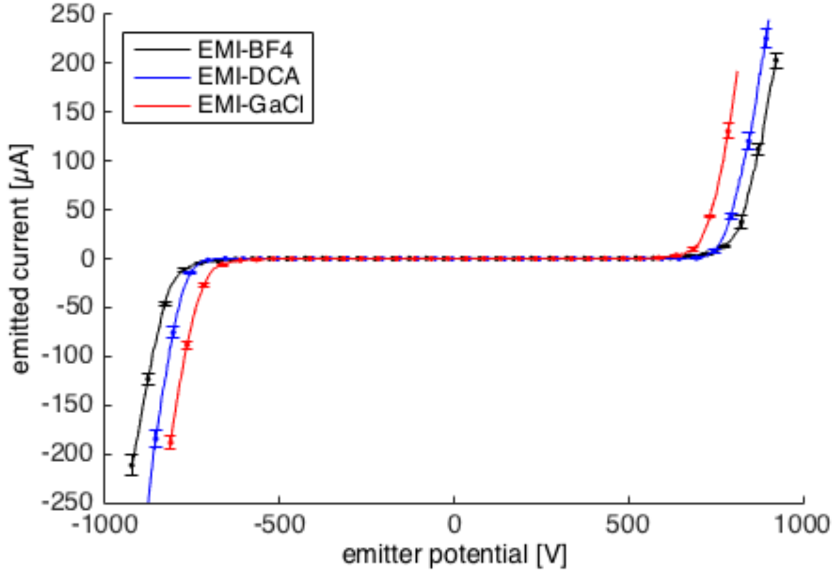
Future developments

- New emitter materials with controlled pore distribution
- Minimizes droplet contribution, increases Isp



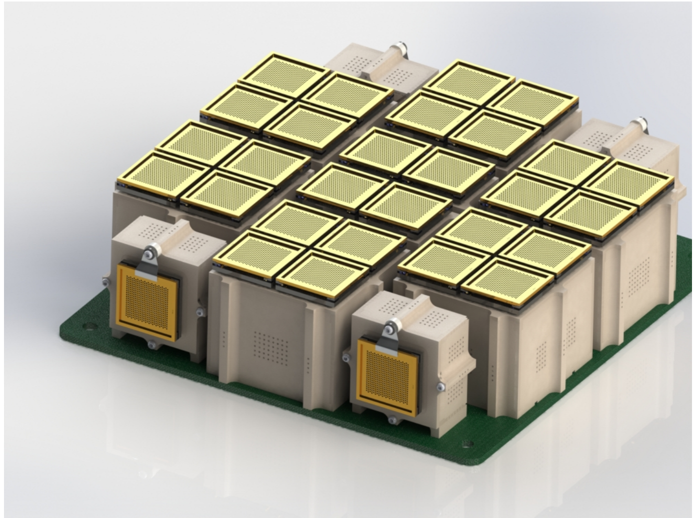
iEPS alternative propellants

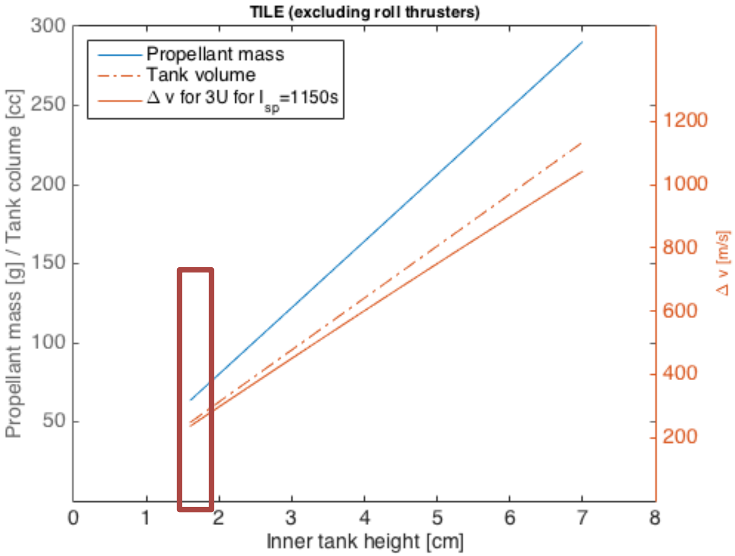
- Studied: EMI-DCA, EMI-GaCl4, EMI-Im
- Indicate significant capability for future improvements



Propulsion modules design studies

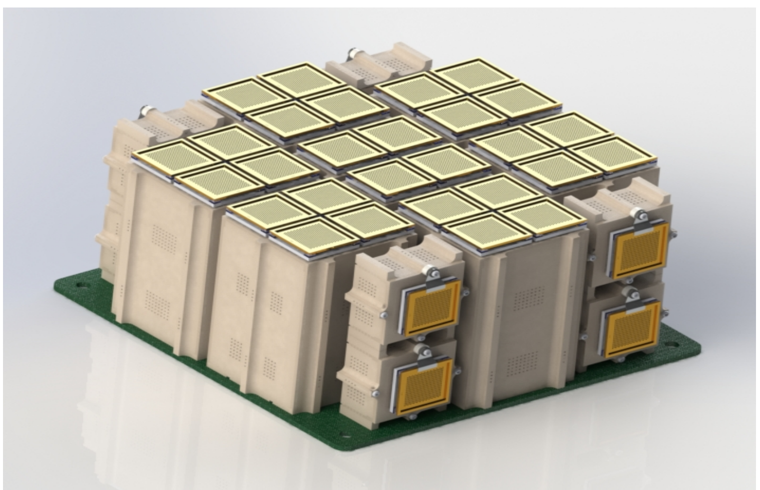
- Scalable tank design, emitter clustering
- Roll capability
- Change in emitter substrate material to achieve lifetime and increase performance

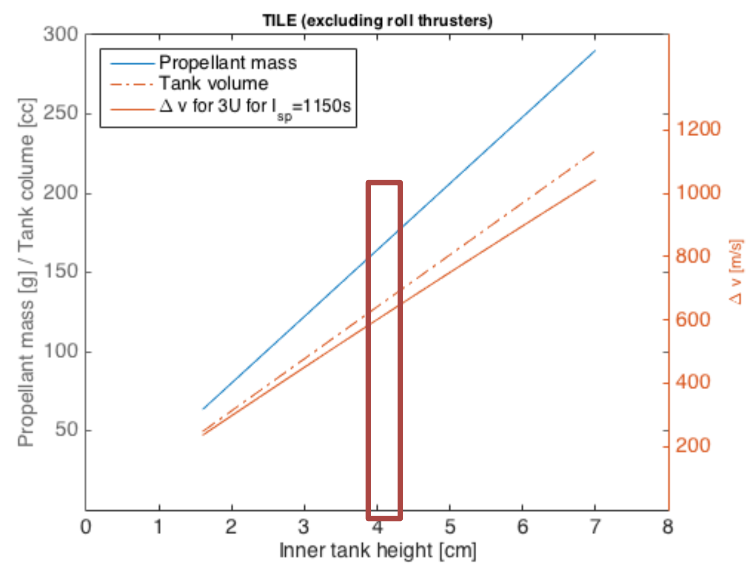




Propulsion modules design studies

- Increased delta V module
- Change in emitter substrate material to achieve lifetime and increase performance





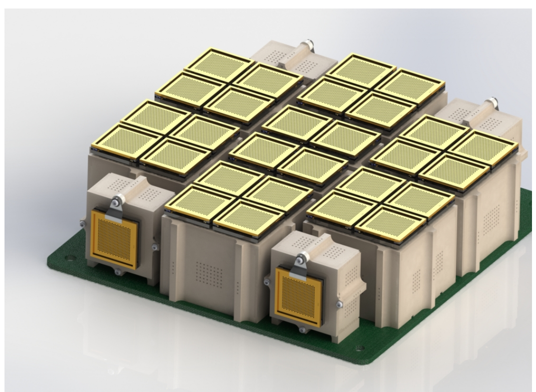
Application

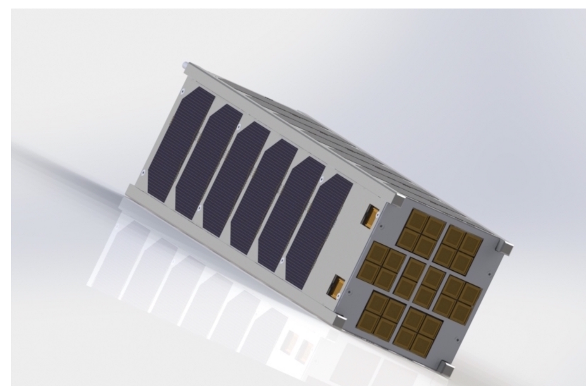
- GMAT simulations
  - 3U Cubesat baseline, dry mass 3kg
  - Isp=1150sec (still lots of room for improvement)
  - 2 thrust levels: 0.35mN and .7mN
  - Assuming perfect thrust vector alignment

Applications: LEO orbit raising

- 300km orbit raising to 700km, 51deg inclination
- Not accounting for drag in this simulation

Thrust [mN]	Burn time [d]	Propellant consumption [g]
0.35	20.6	55.3
0.7	10.7	55.3



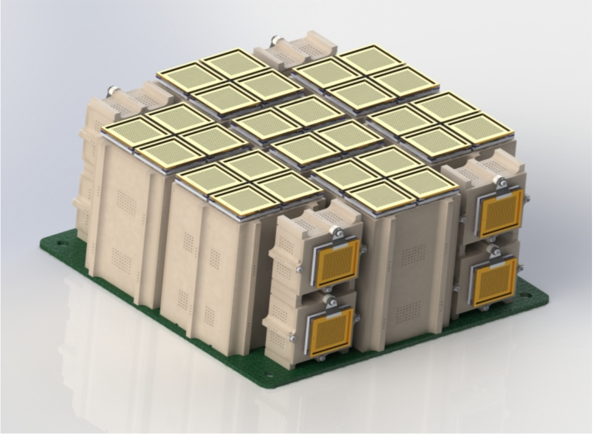


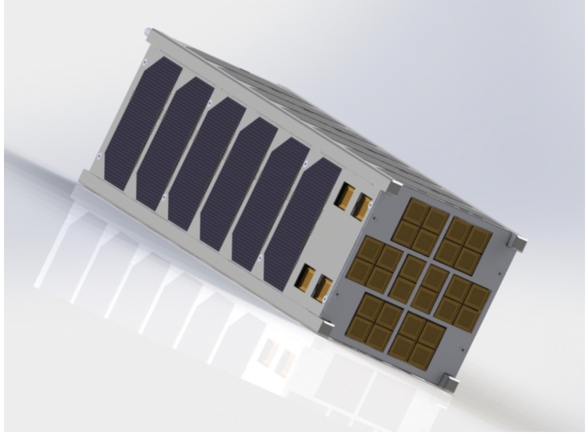
- propulsion module ~1/5 of satellite

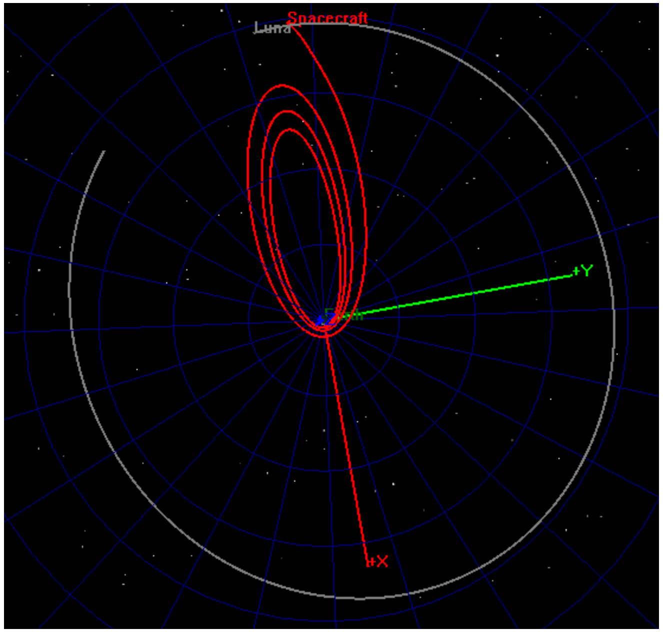
Applications: Elliptical launch orbit

- Assuming a launch opportunity similar to TESS

Thrust [mN]	Burn time [d]	Propellant consumption [g]
0.35	50	130.4
0.7	23	123.3





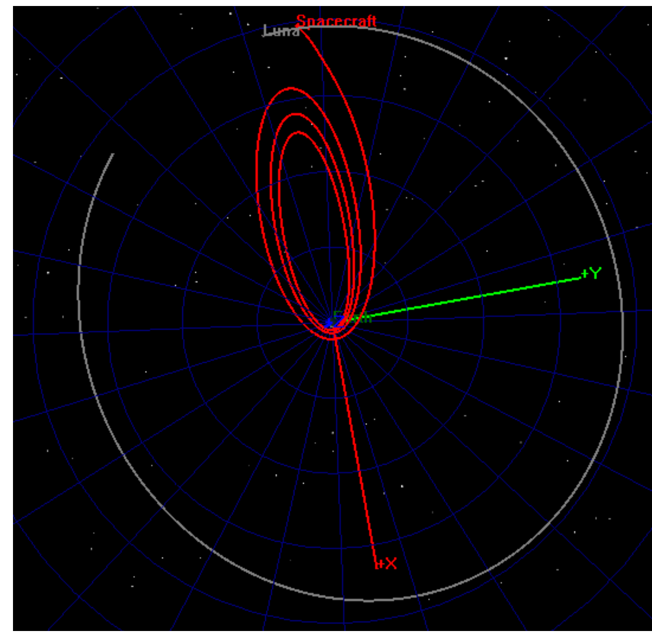


- propulsion module ~1/4 of satellite

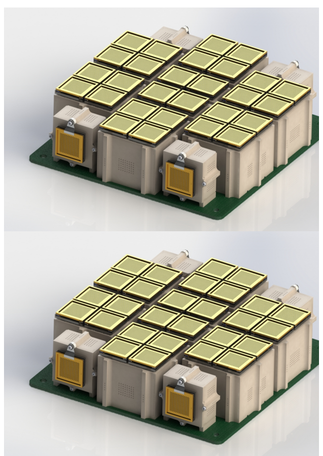
Applications: Elliptical launch orbit

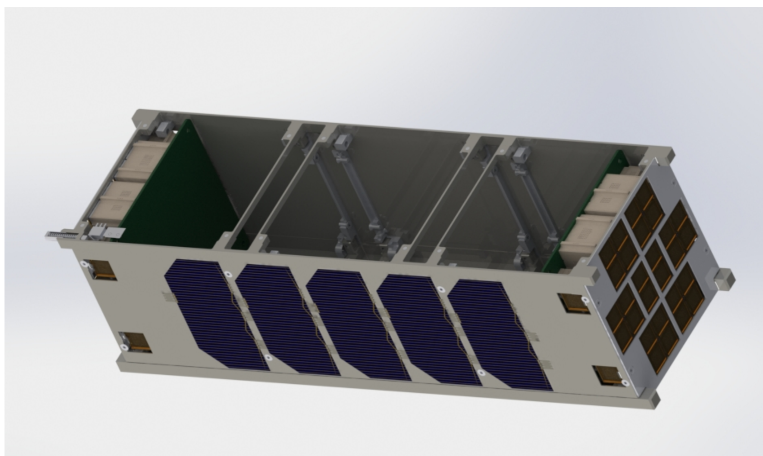
- Assuming a launch opportunity similar to TESS

Thrust [mN]	Burn time [d]	Propellant consumption [g]
0.35	50	130.4
0.7	23	123.3



- Reduces lifetime requirement



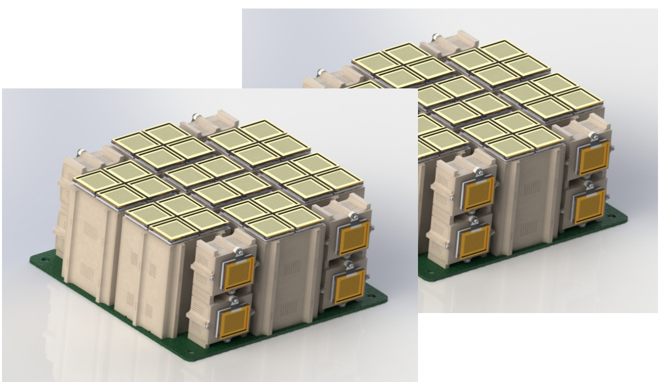


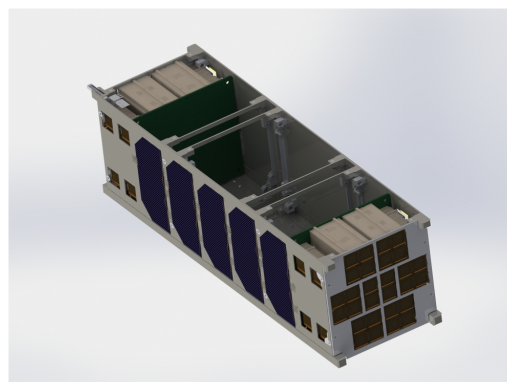
- propulsion module ~1/3 of satellite

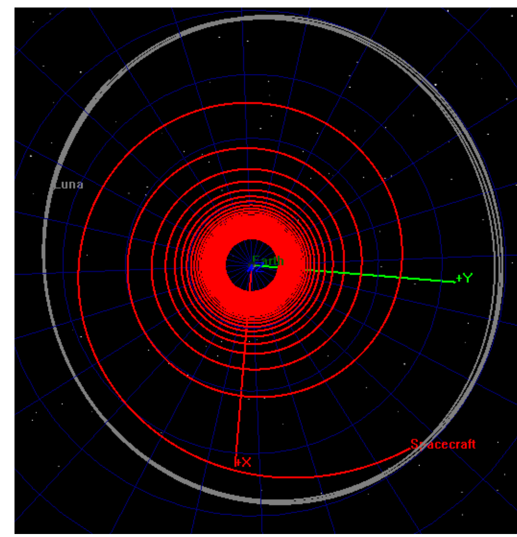
Applications: GEO to lunar space

- Assuming piggyback to GEO, autonomous orbit raising to lunar space
- Assumed thruster performance improvement to Isp=2500s

Specific impulse [s]	Thrust [mN]	Burn time [d]	Propellant consumption [g]
1150	0.35	223	600
	0.7	112	600
2500	**0.35**	**212.7**	**267**
	0.7	**108.2**	**267**







- propulsion module ~1/2 of satellite

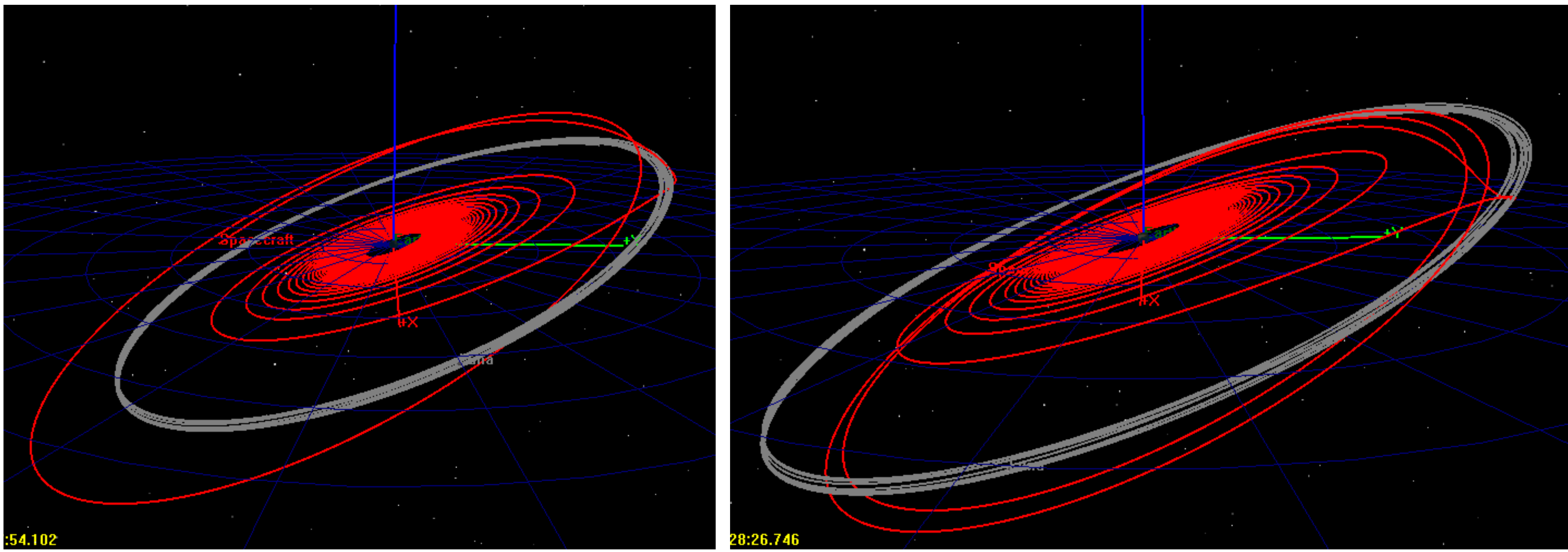
Conclusion

- Current porous glass emitter cause droplet emission
- Are sufficient for significant LEO orbit raising capability with propulsion module ~1/5 of satellite
- Up-scaled modules with moderately improved emission properties (target Isp~1150s, achievable with decreased beam spreading) are capable to reach lunar space for suitable launch orbit with propulsion module ~1/4-1/3 of satellite
- Performance improvement to Isp~2500s (significant droplet content reduction and decreased beam spreading) allows autonomous orbit raising from GEO to lunar space, with propulsion module ~1/2 of satellite

Thank you

Backup slides

- ~6000km approach



Backup slides