Energy Harvesting on Spacecraft Using Electrodynamic Tethers

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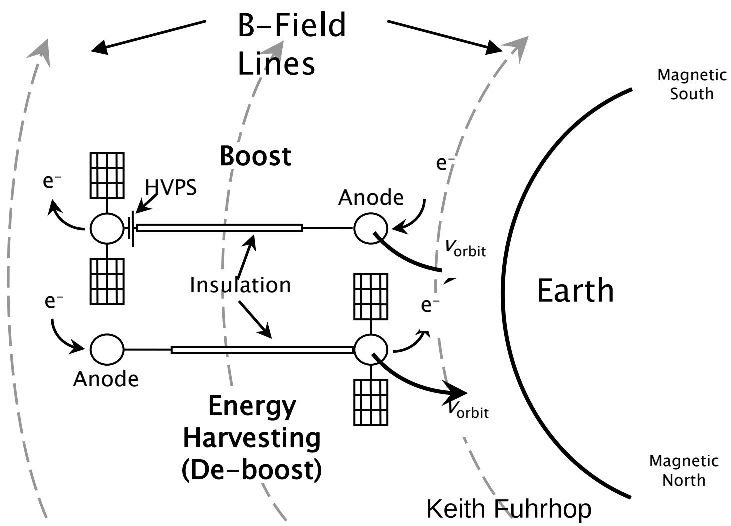
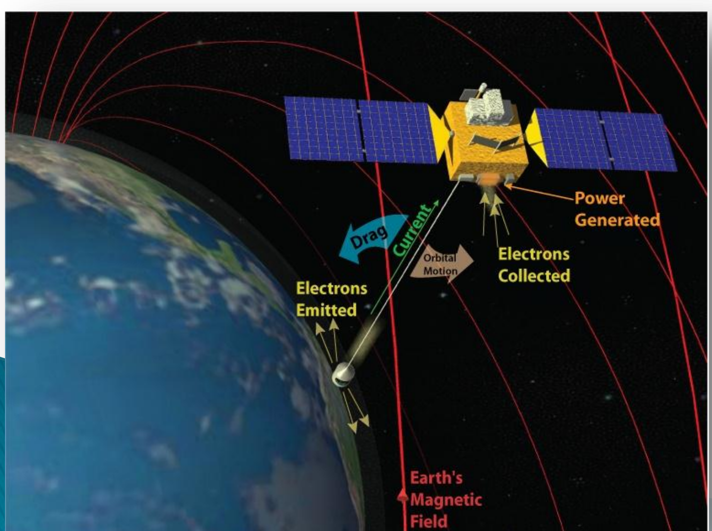
Benefits of EDTs include ability to generate power and thrust





- <u>Generate power</u> onboard spacecraft
  - Up to *kilowatts*
- Same system can be used to provide <u>propulsion</u>
  - Change inclination, altitude, etc.
  - Reboost and deboost
  - No consumable propellant
- Generate significant power when other sources are <u>not available</u>
  - Dark side of the Earth
  - Thrust when power is available
- Uses orbital energy as the storage "battery"

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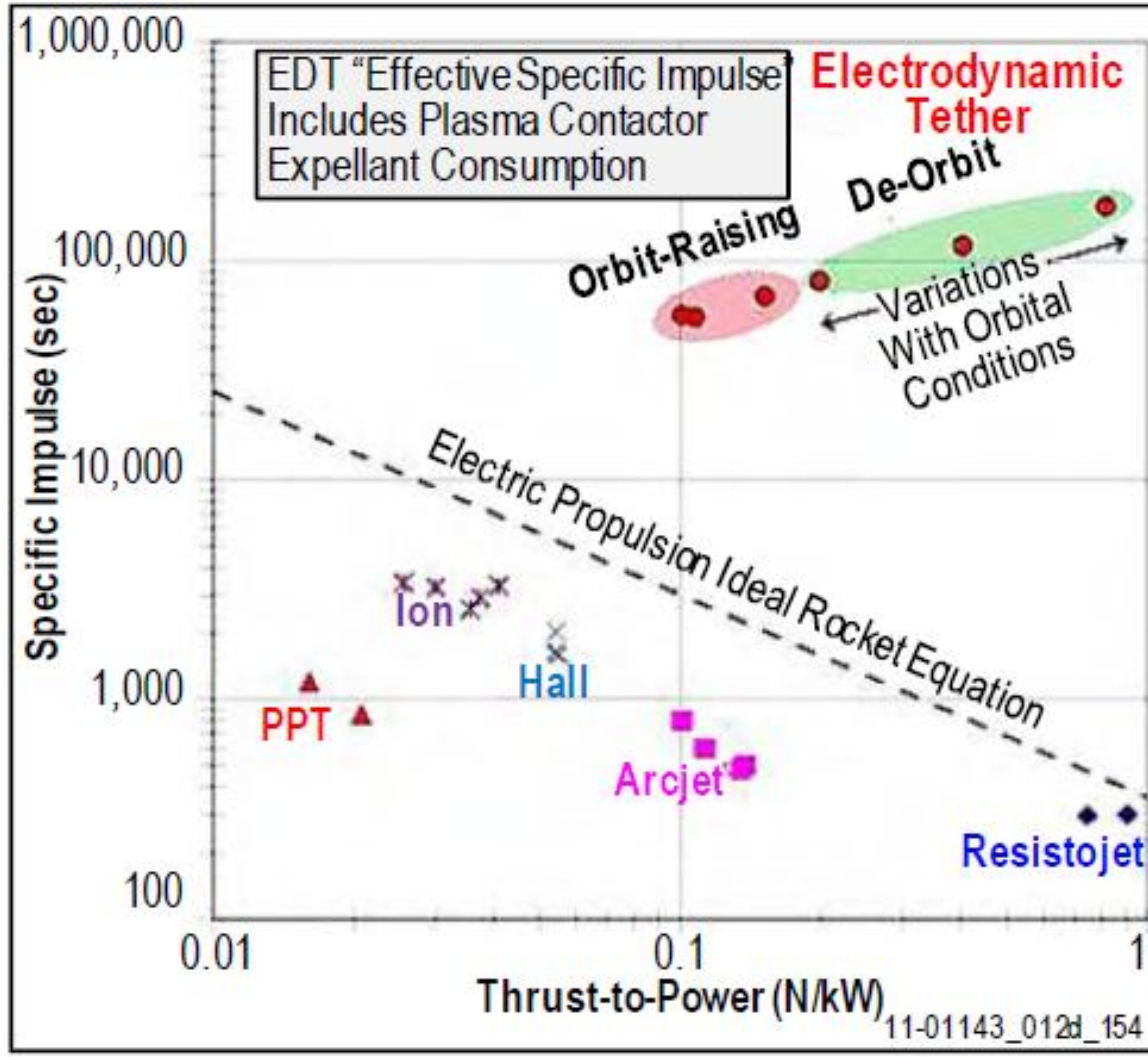
EDT vs. Electric Propulsion

<u>EDTs provide</u>

- **High thrust-to-power**
- **Extremely high specific impulse performance**

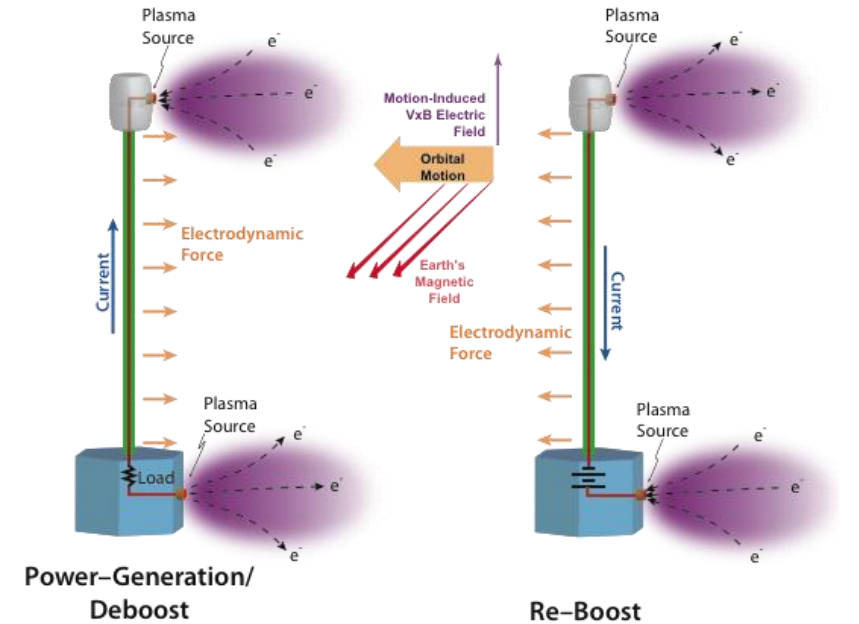


ED Tether Architectures for "Orbital Battery" Operations

- **Re-boost mode converts solar energy into orbital energy**
- **De-boost/Generation mode converts orbital energy into electrical power**
- **Requires capability to drive current both up and down tether**

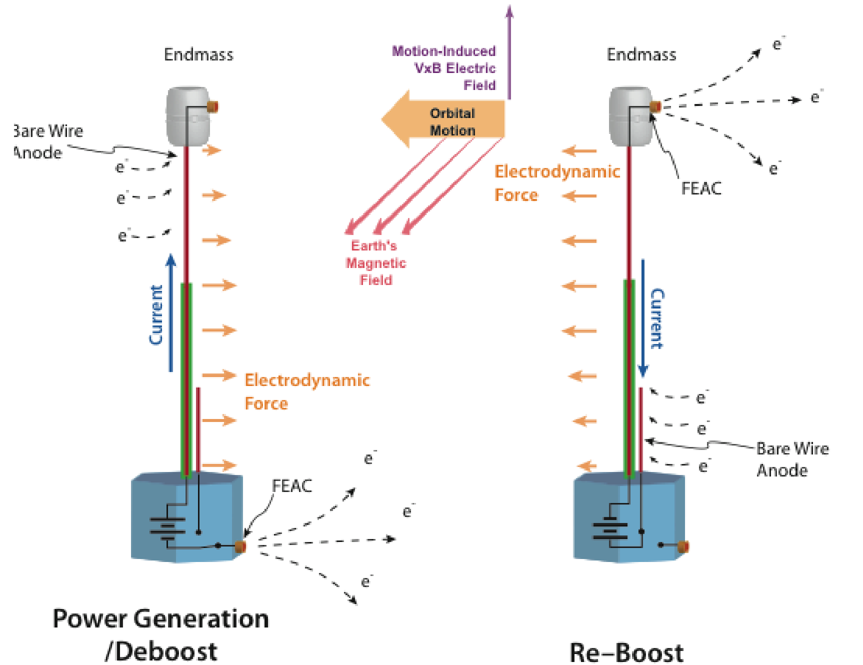
Dual-Plasma Generator

- Hollow Cathode Plasma Contactors or SOLEX devices generate plasma 'ball' to enable low-impedance electrical connection to ionospheric plasma
- High TRL, but requires small mass flow of expellant



Bare Wire Anode + FEACs

- Bare wire anodes used to collect electrons from ionosphere, and Field Emission Array Cathodes used to emit electrons
- No consumables, but lower TRL

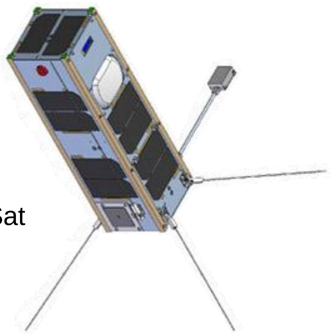


Research Accomplishments FY11-12

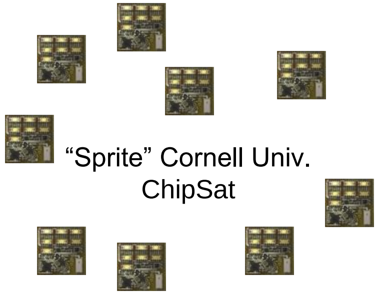
- Began experimental investigations on EDT components for CubeSat-class EHEDT systems
  - LEO plasma chamber set up and characterized
  - Component testing begun
- Performed femtosat-class trade studies and concept development
- Participated in PROPEL EDT mission design

Satellite Classification

"small" satellite
~100+ kg

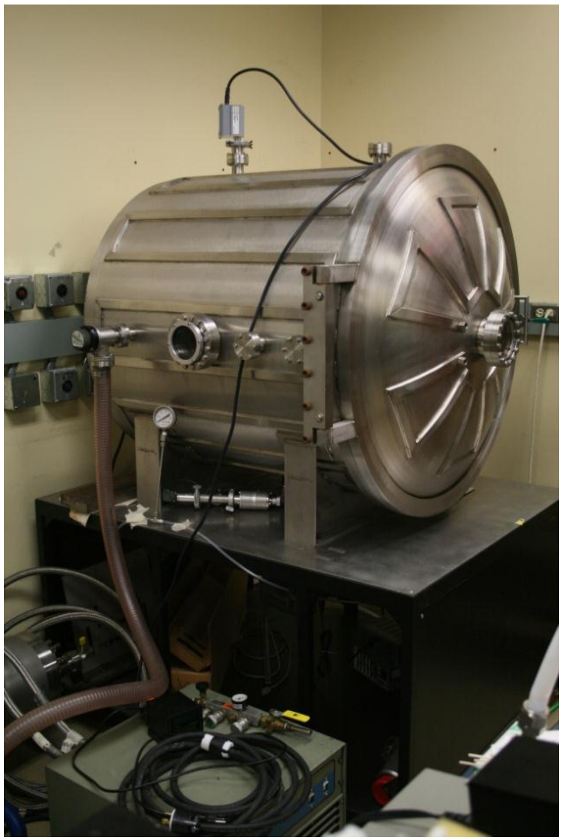


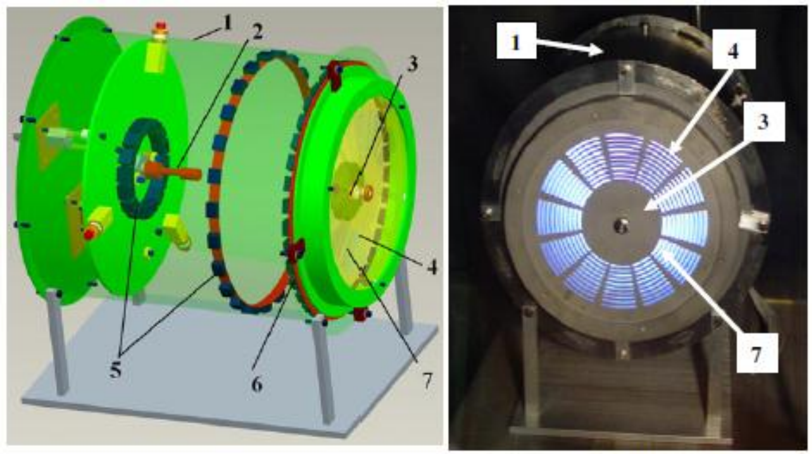
"nano" satellite
1 to 10 kg



"pico" satellite
<1 kg

Ongoing laboratory experiments are evaluating key components

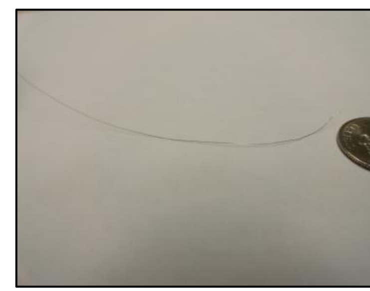




(a) (b)

Figure 3. (*a*) Plasma source CAD model: 1—discharge chamber outer wall, 2—hollow cathode, 3—inner part of the magnetic filter, 4—neutral density grids, 5—Sm–Co magnets, 6—outer part of the magnetic filter, 7—coaxial plasma expansion region. (*b*) Photograph of the plasma source during operation.

Field Emitter



Tether Materials

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Rationale for Experiments

- For small-scale systems, such as those used on CubeSats (<10 kg) and femtosatellites (<100 g), it may be difficult to make simplifying approximations such as assumption of thin or thick current collecting sheath
- Hence, experiments are necessary in order to properly characterize devices at this scale
- Our objective is to compare measured current-voltage characteristic to theoretical value giving upper bound, lower bound, and most exact current collection

Low Earth Orbit (LEO) Environment

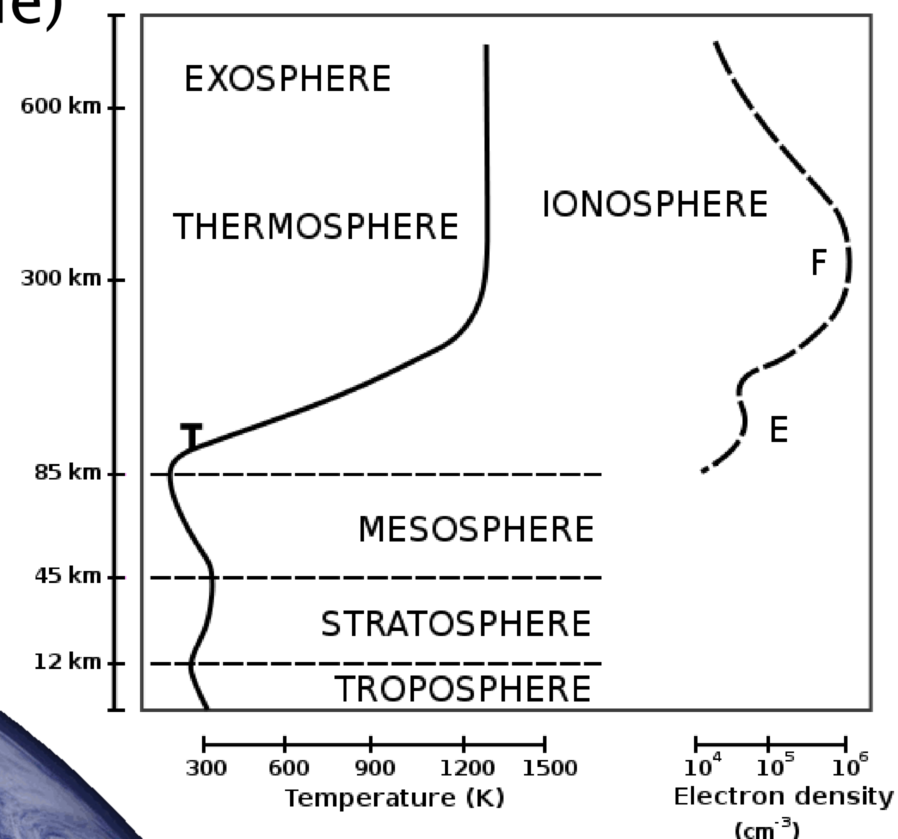
Temperature (order of magnitude)

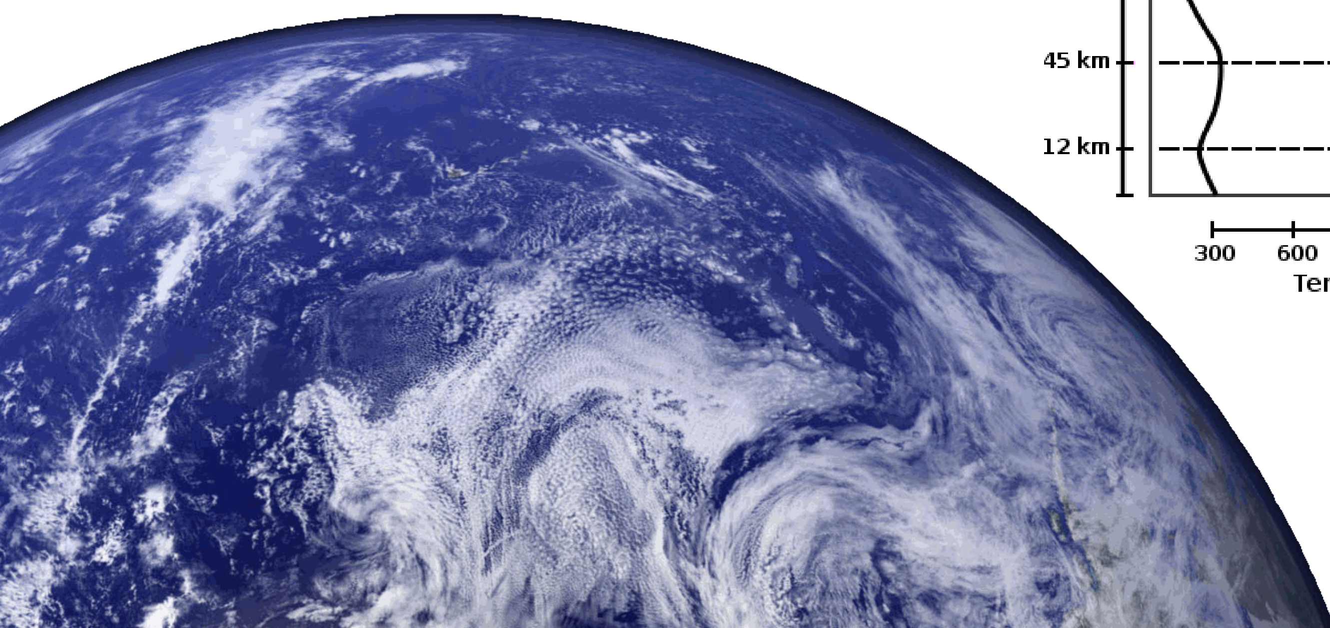
Electrons ~ 0.1 eV

Ions ~5 eV (streaming)

Density (order of magnitude)

10^{10}–10^{12} m^{-3}



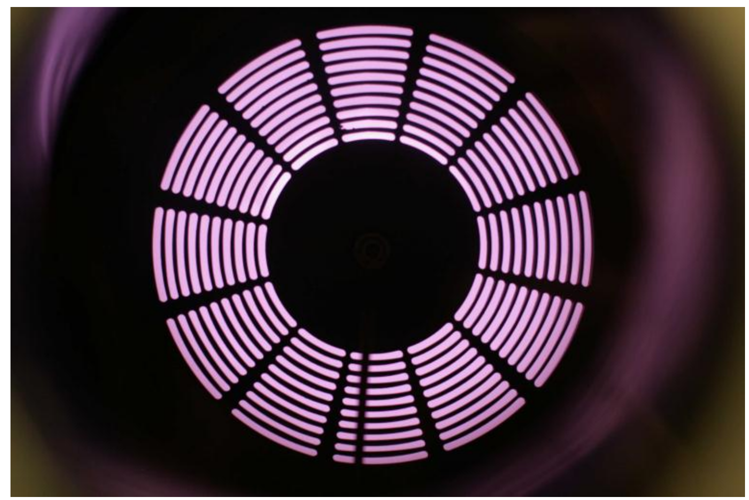


Plasma Source

Magnetic Filter Plasma Source (CSU)

Electron Temperature
0.1 to 0.5 eV

Ion Temperature
5 to 10 eV



Argon glow

What to Test and Why?

- Materials
  - Conductivity (I–V characteristics)
  - Dual purpose: shared resources on small satellites
- Geometries
  - Non-ideal geometries (e.g., built-up CubeSats)
  - Contactors with small volume (or low in mass) and high surface area
- Devices
  - Active or passive charge exchange
  - Mission-derived or hardware-limited

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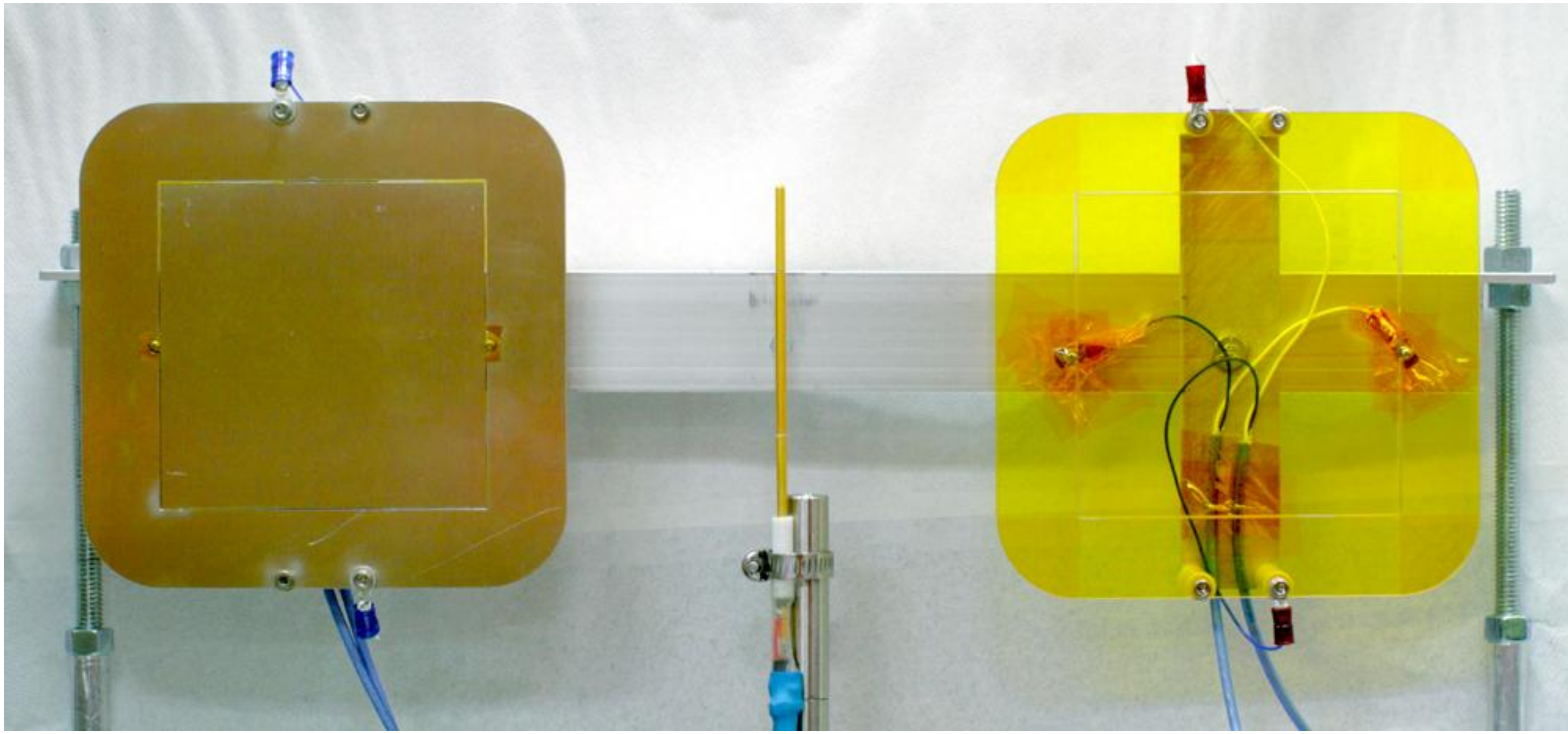
Test Articles

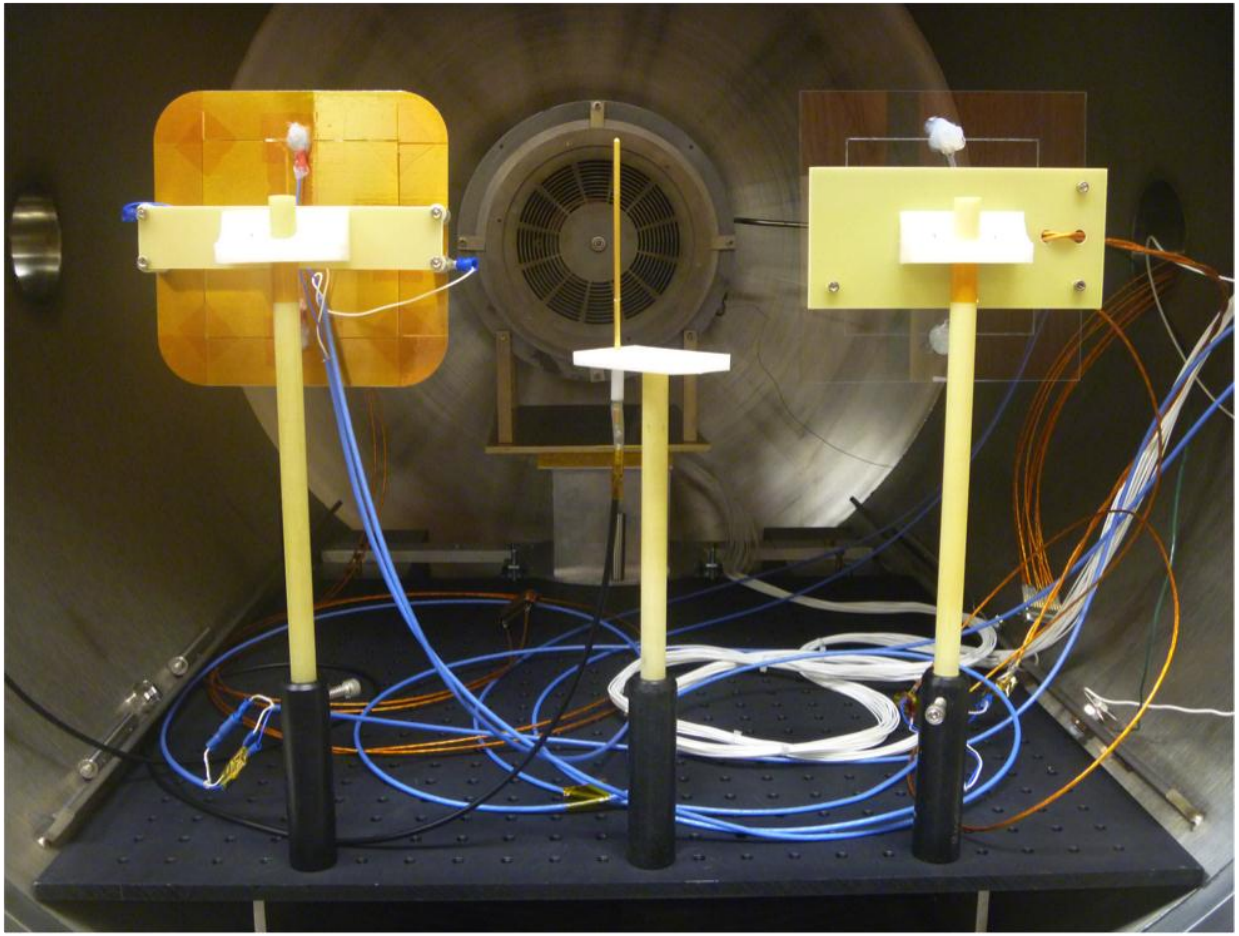


Aluminum
(Chromate Converted)

Langmuir Probe
(with guards)

ITO Coating
(Indium Tin Oxide)

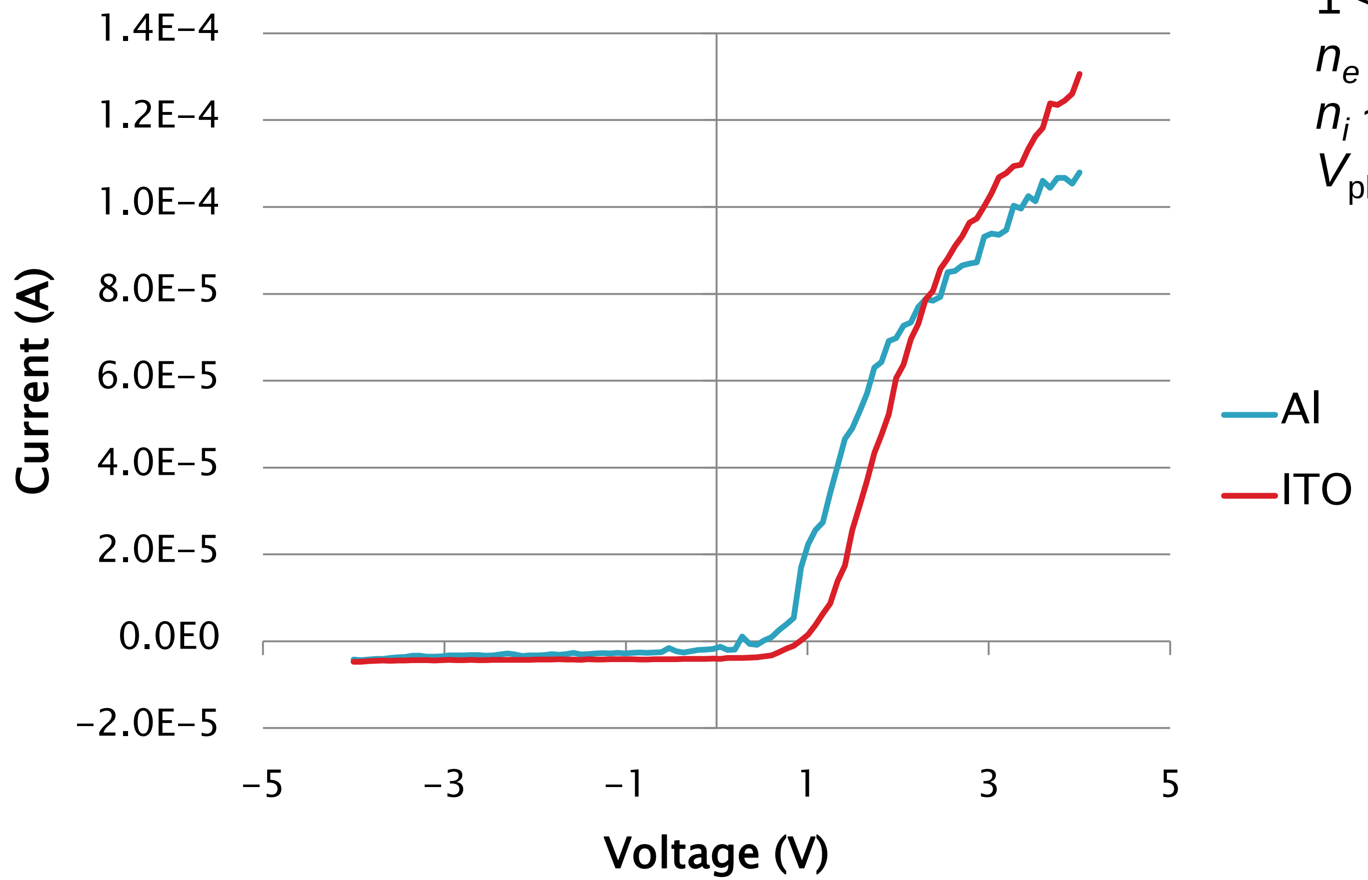
ITO Testing



Alodine Aluminum
~5 Ω/sq

Indium Tin Oxide (ITO)
~15 Ω/sq

Comparison Between Alodined Aluminum and Indium Tin Oxide
Low Earth orbit plasma environment



Plasma Environment:

$T_e \sim 0.2$ eV

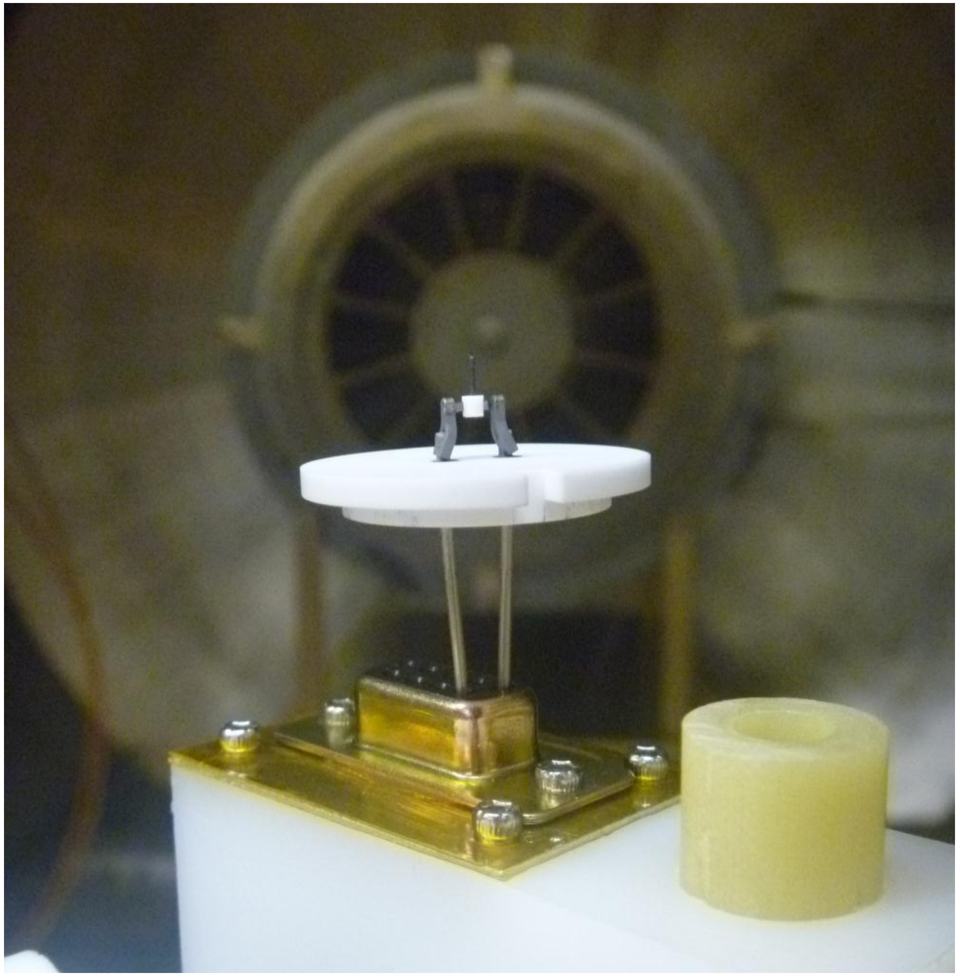
$1 < T_i < 5$ eV

$n_e \sim 10^{11}\ m^{-3}$

$n_i \sim 10^{12}\ m^{-3}$

$V_{plasma} \sim 1.0$ V

Lanthanum Hexaboride (LaB_6) Cathode Testing



Experimental setup: Plasma source approximately 0.5 m away

Image from Kimball Physics

90° cone, 15-micron microflat

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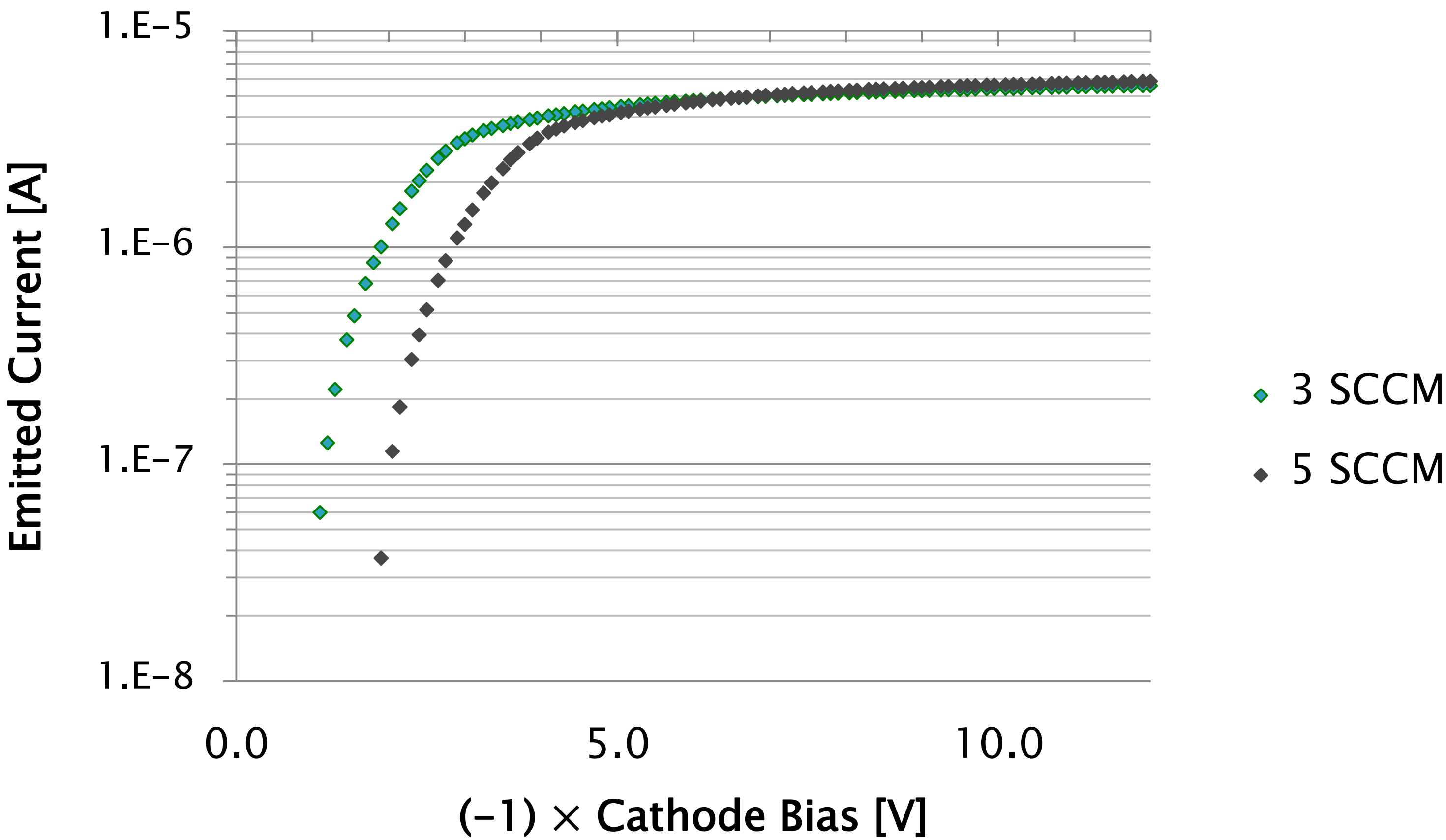
Space Charge and Thermionic Limits of a LaB_6 Cathode in a LEO-like Environment

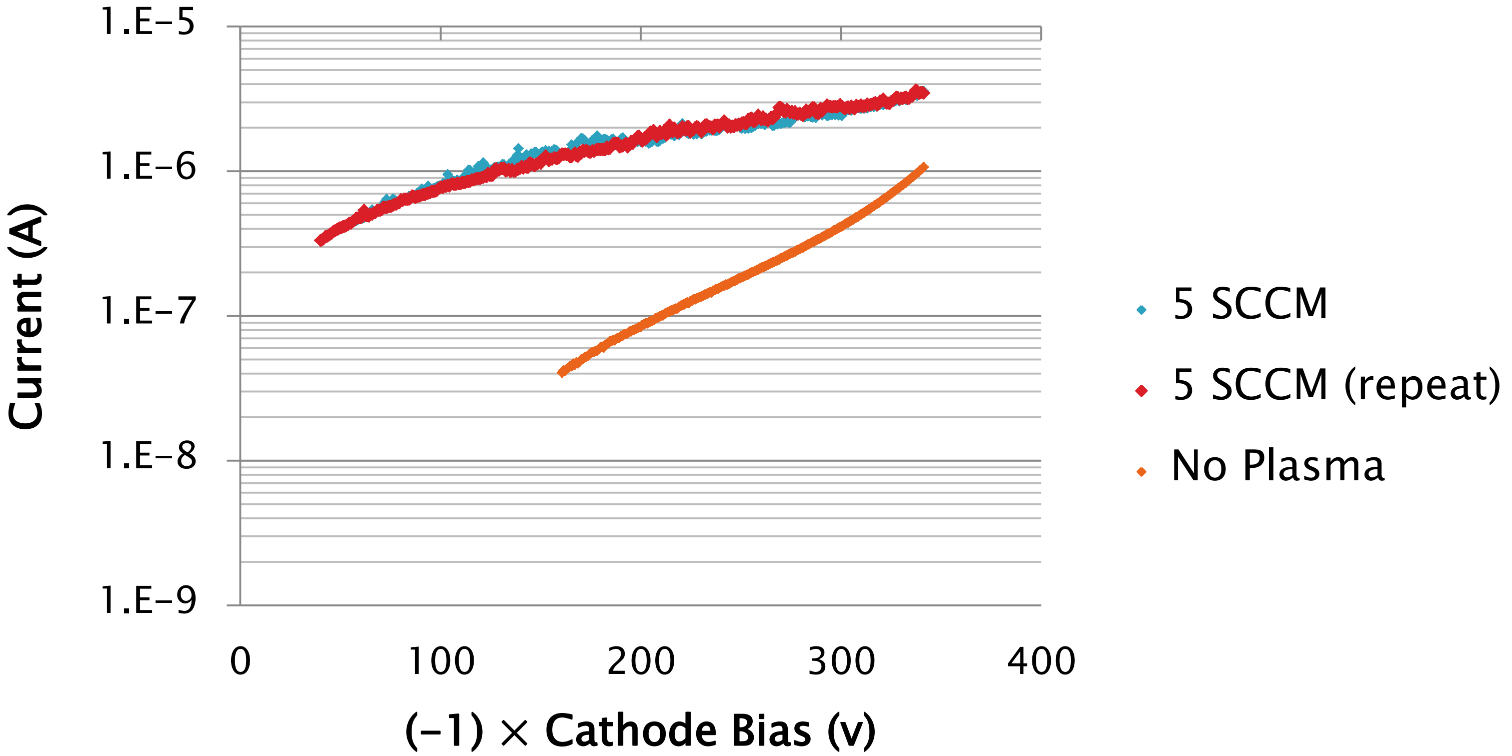
Heater: 1.50 A, 2.2V (3.3 W)

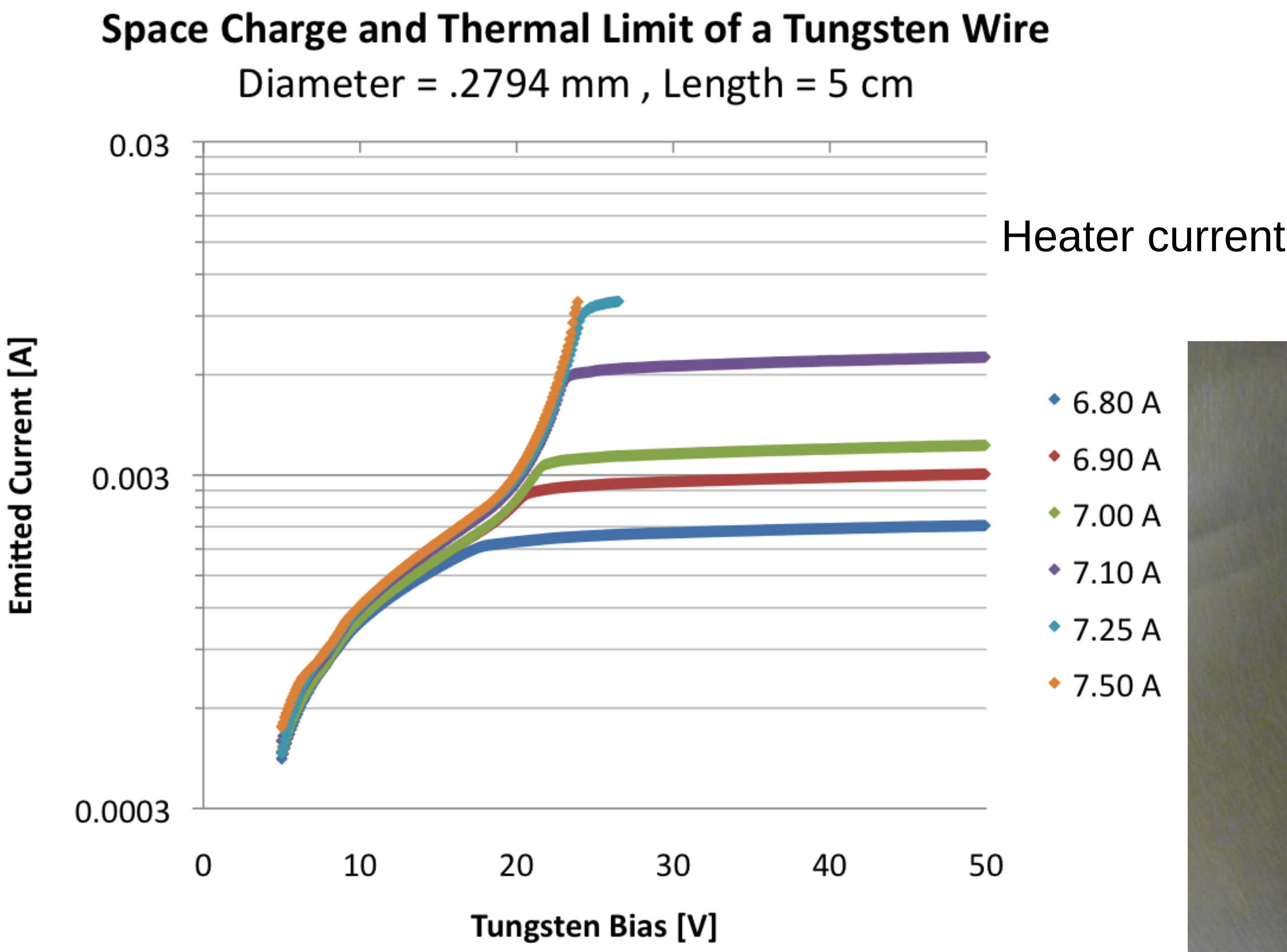


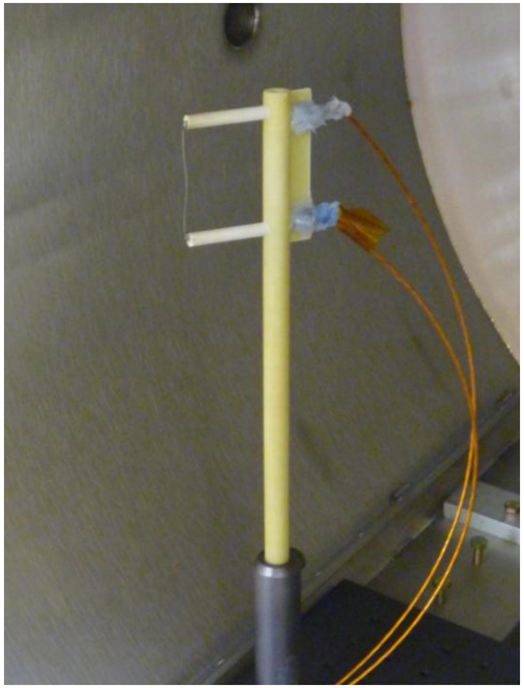
Low Power Electron Emission from Lanthanum Hexaboride (LaB_6) Cathode

Heater: 0.300 A, 0.577V (0.1731 W)

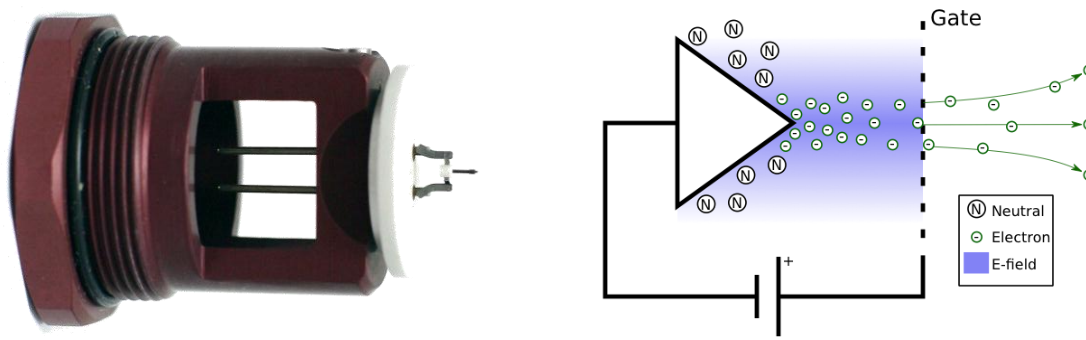
Low Earth orbit plasma environment



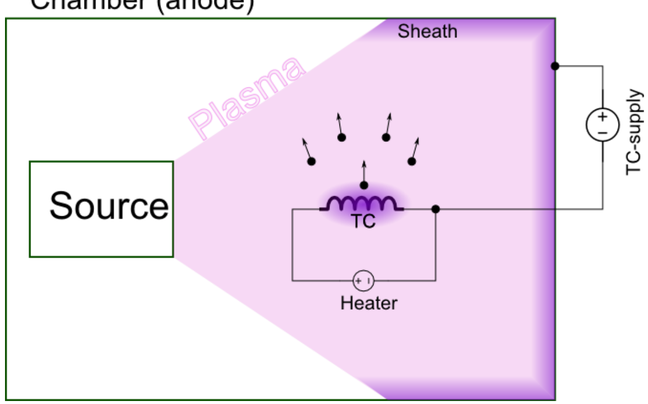

Space Charge and Thermal Limit of a Tungsten Wire
Diameter = .2794 mm , Length = 5 cm
0.03
0.003
0.0003
Emitted Current [A]
0
10
20
30
40
50
Tungsten Bias [V]
Heater current
6.80 A
6.90 A
7.00 A
7.10 A
7.25 A
7.50 A



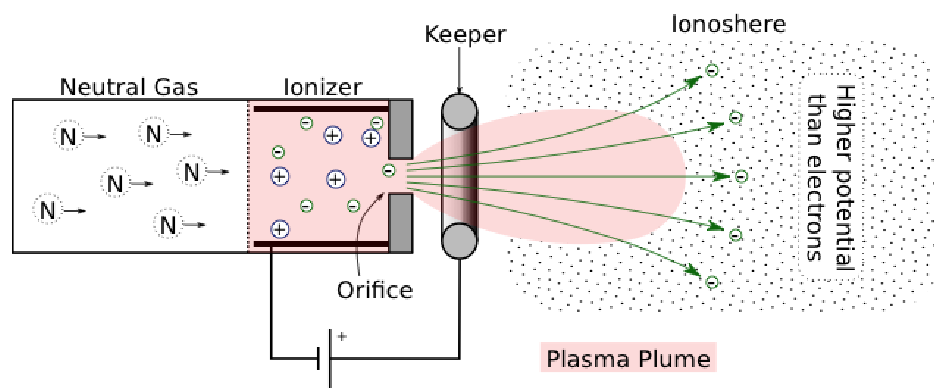
Future Work: Electron Emitters



Field Emitters or Emitter Arrays



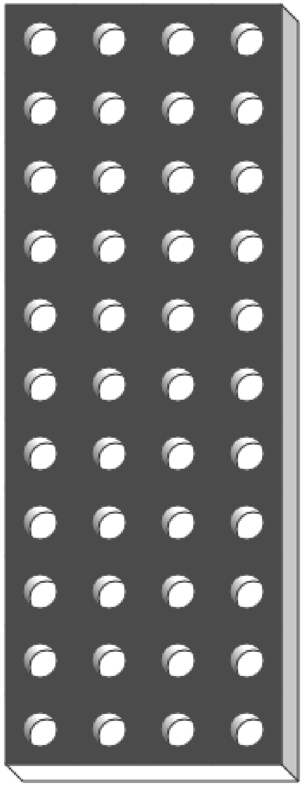
Thermionic Cathode



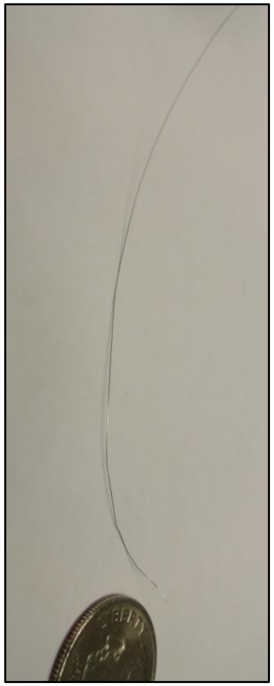
Hollow Cathode

Future Work: Tethers

Hoytether



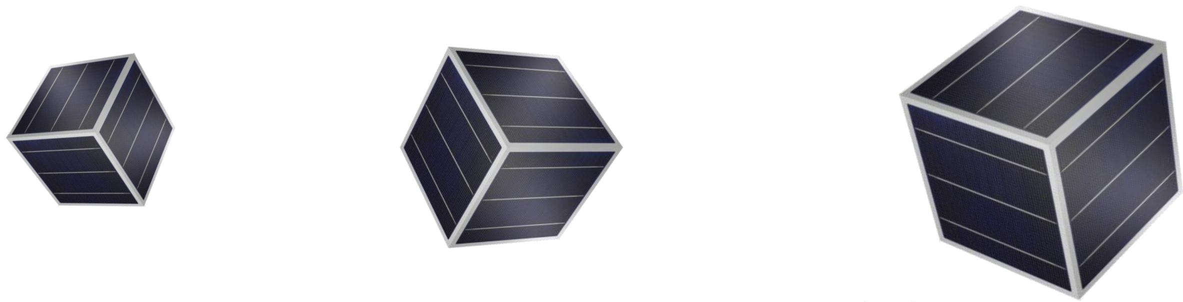
Slotted Tape

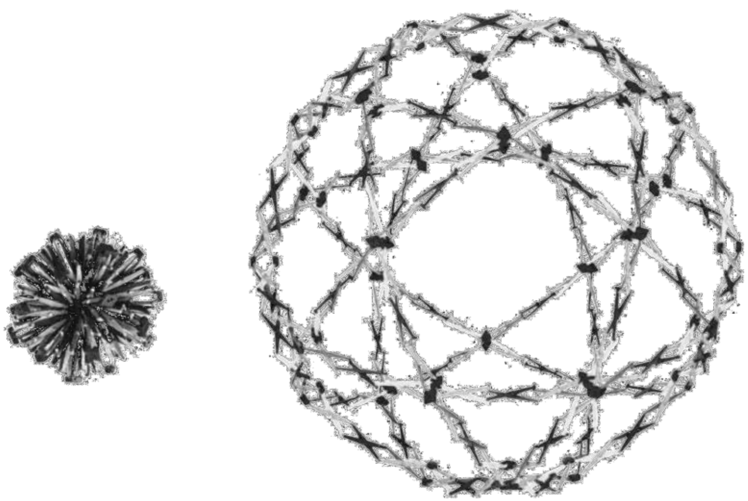


50 micron diameter monel (femtosat)

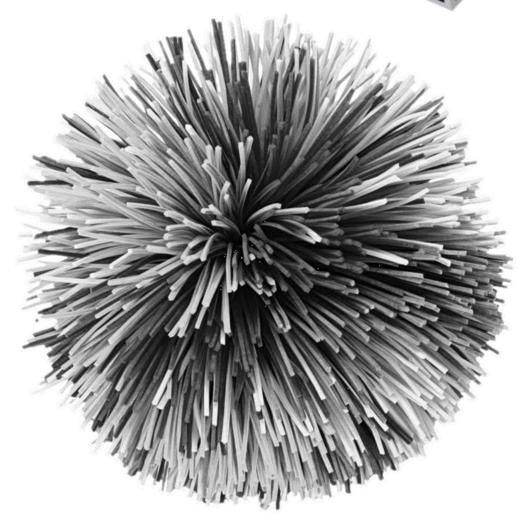
Future Work: Complex Geometries

From
Ideal Surface ➔ Cube ➔ Satellite Model





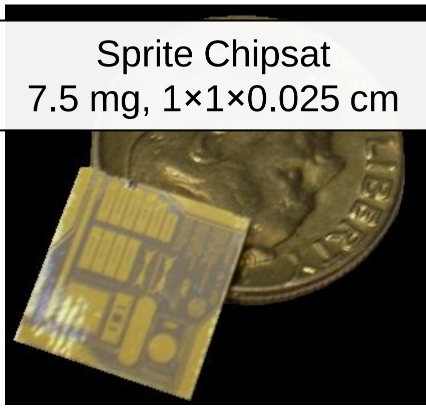
Hoberman Sphere



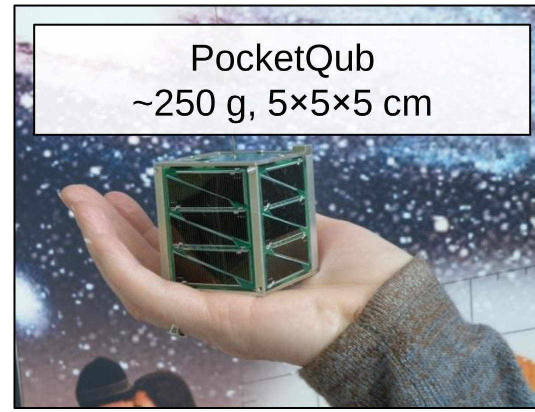
Koosh Ball

What is a *picosat* and a *femtosat*?

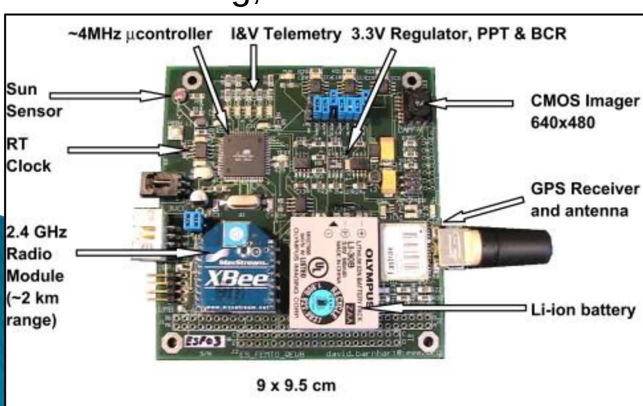
- Picosatellites (1 kg–100 g) and femtosatellites (<100 g) are the next steps in satellite miniaturization → think of flying your smartphone with highly capable, enhanced MEMS sensors


Sprite Chipsat
7.5 mg, 1×1×0.025 cm

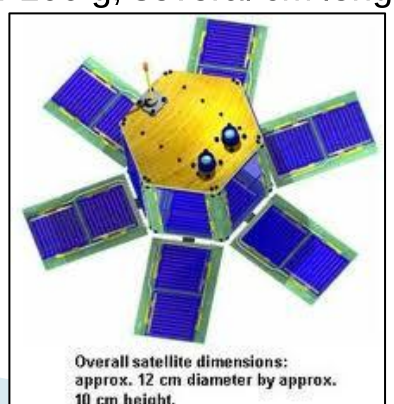

Picosat 1 and 2
250 g, few cm length


PocketQub
~250 g, 5×5×5 cm

PCBSat
~300 g, 9×9.5×2.5 cm



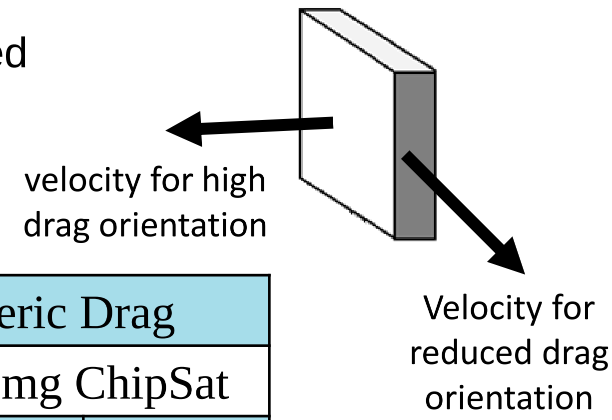
PalmSat
Few 100 g, several cm length



CubeSat
1 kg, 10×10×10 cm

The Need for Propulsion

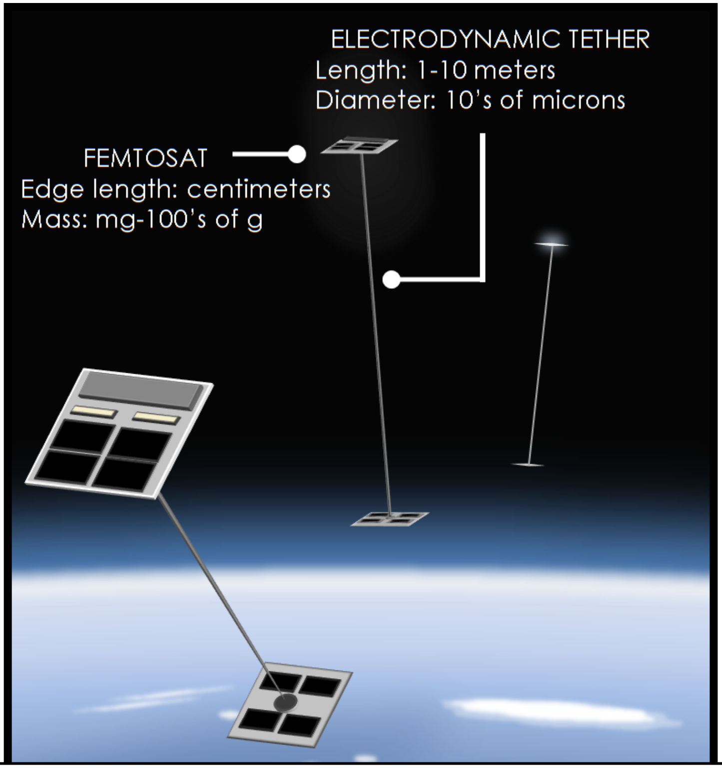
- Small size & mass enable large *swarms* or *fleets* to be launched
- Missions using "fleets" of pico- and femtosats would require coordination/maneuverability (propulsion)



A Rough Estimate of Satellite Lifetime due to Atmospheric Drag					
Parameters	3-kg CubeSat	8-g ChipSat		7.5-mg ChipSat	
Configuration	3-1000 cm^3 cubes, stacked upright	Low drag	High Drag	Low Drag	High Drag
Ballistic Coeff.	45	95	2.5	13.6	0.03
Alt = 300 km	a month	**a month**	hours	**several days**	~
Alt = 400 km	several months	**several months**	days	**several weeks**	hours
Alt = 500 km	~1 year	**~1-2 years**	weeks	**several months**	hours

Early concepts also have no propellant and a high area/mass ratio, so the orbital lifetime is *short*

Electrodynamic Tethers (EDTs) are Capable of Propellantless Thrusting



Concept of ED tethers with pairs of femtosats as a maneuverable and coordinated fleet

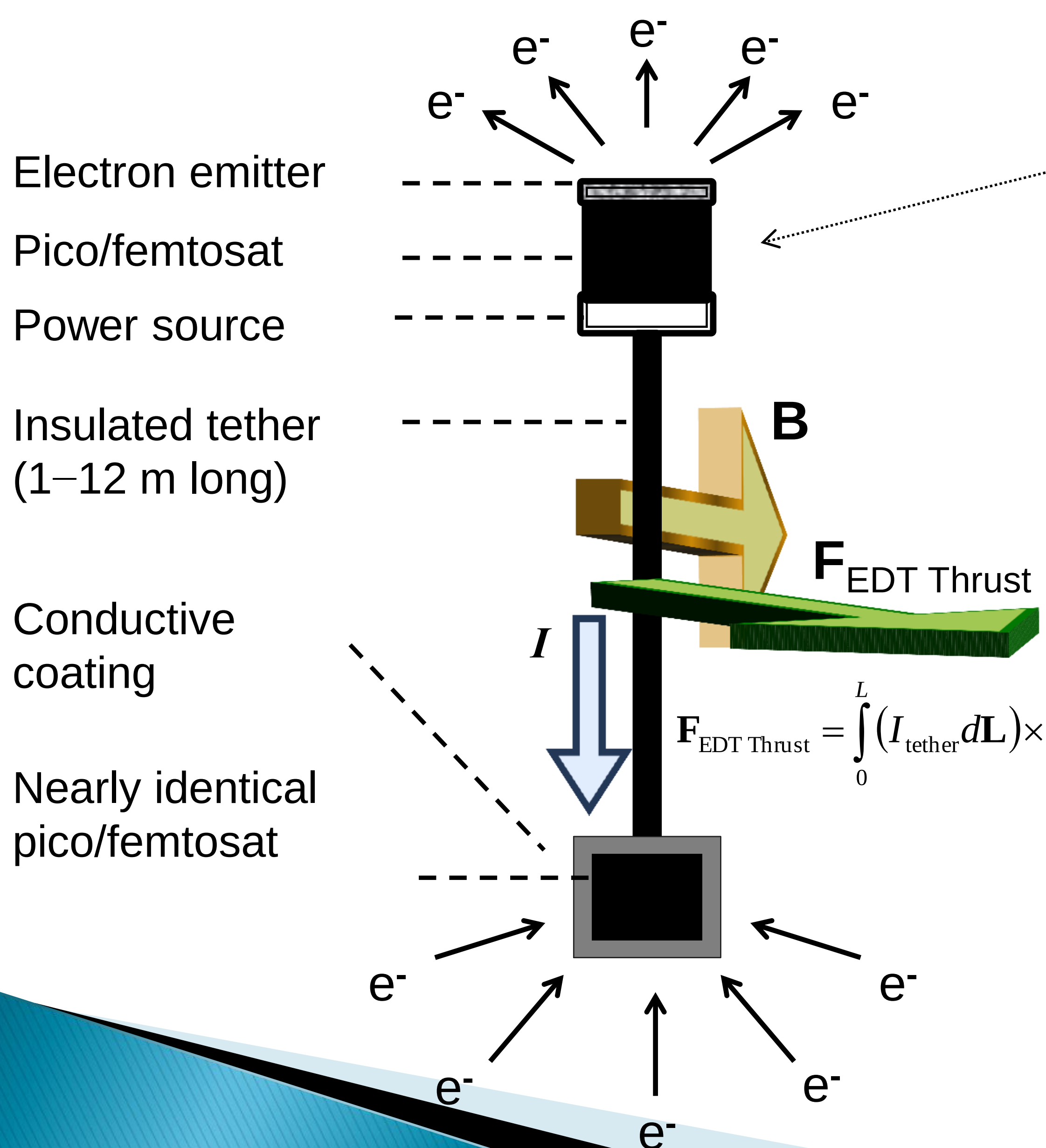
- Electrodynamic Tether (EDT)
  - ✓ A long conductor connected to a spacecraft
- EDT can provide propulsion
  - ✓ Change inclination, altitude, etc.
  - ✓ Reboost and deboost
  - ✓ No consumable propellant
- Additional benefits include:
  - ✓ Providing gravity gradient stability

$$\mathbf{F}_{\text{EDT Thrust}} = \int_0^L \left(I_{\text{tether}} d\mathbf{L}\right) \times \mathbf{B}$$

Research questions:

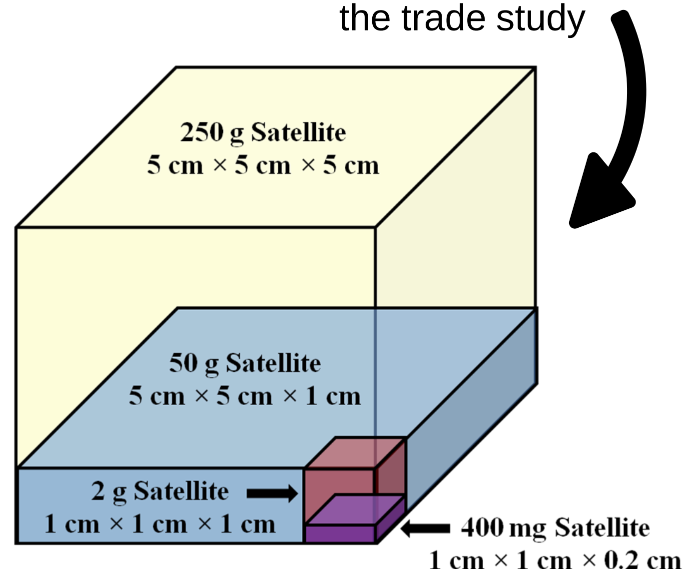
Can electrodynamic tethers provide ultra small satellites with lifetime enhancement and maneuverability? Can it provide other capabilities?

Trade Study System Concept



$$\mathbf{F}_{\text{EDT Thrust}} = \int_0^L (I_{\text{tether}} d\mathbf{L}) \times \mathbf{B}$$

Four satellites are considered in the trade study



Both satellites have

- *solar panel*
- *power supply*
- *electron emitter*
- *capable of collecting electrons on the surface*

System is capable of boost, deboost, and inclination change

Estimate of Power Needed and Available for Drag Make-up

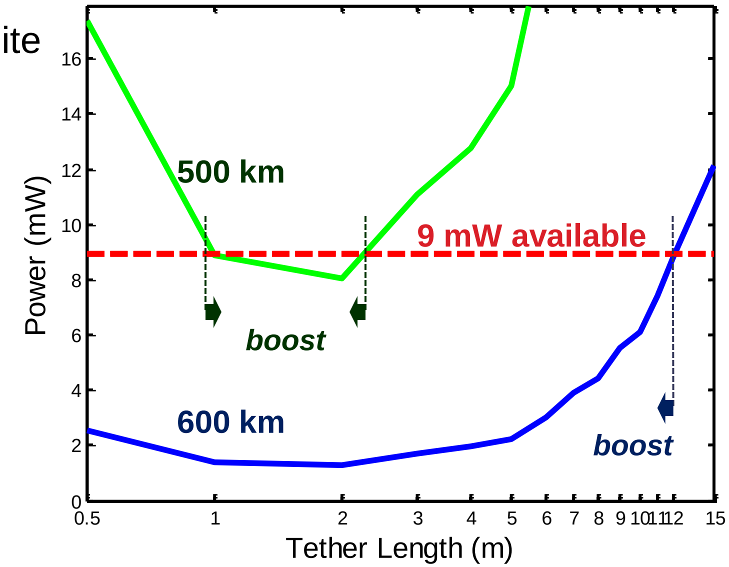
- Estimated that solar cells provide 4.4 mW·cm^{-2} for propulsion

- If more power is available than required for thrust, the EDT can boost

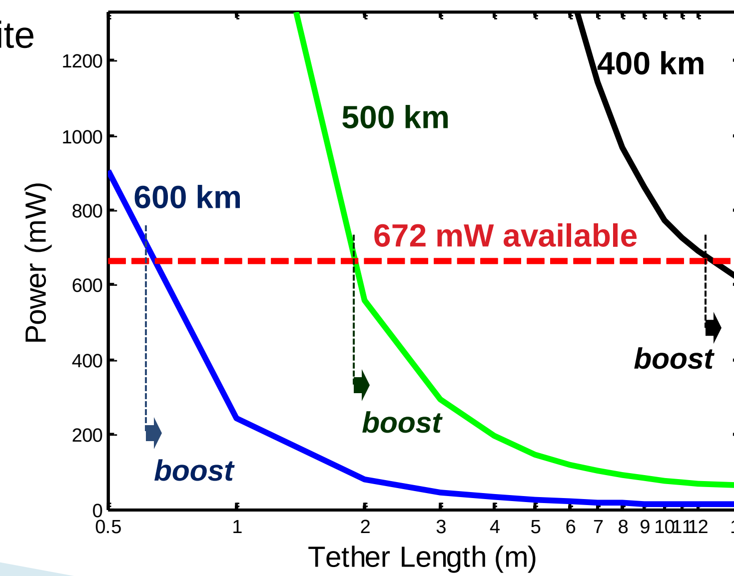
- Figures to the right show power needed for drag make-up at
  - 400 km (**black**)
  - 500 km (**green**)
  - 600 km (**blue**)

  as well as the power available for propulsion (**red**)

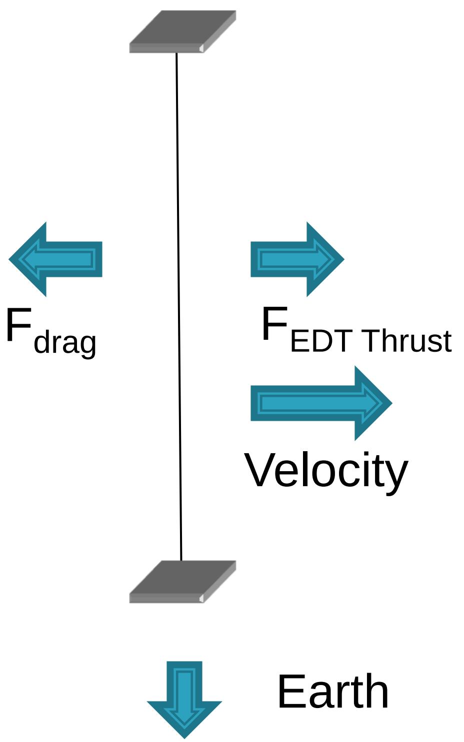
400-mg satellite

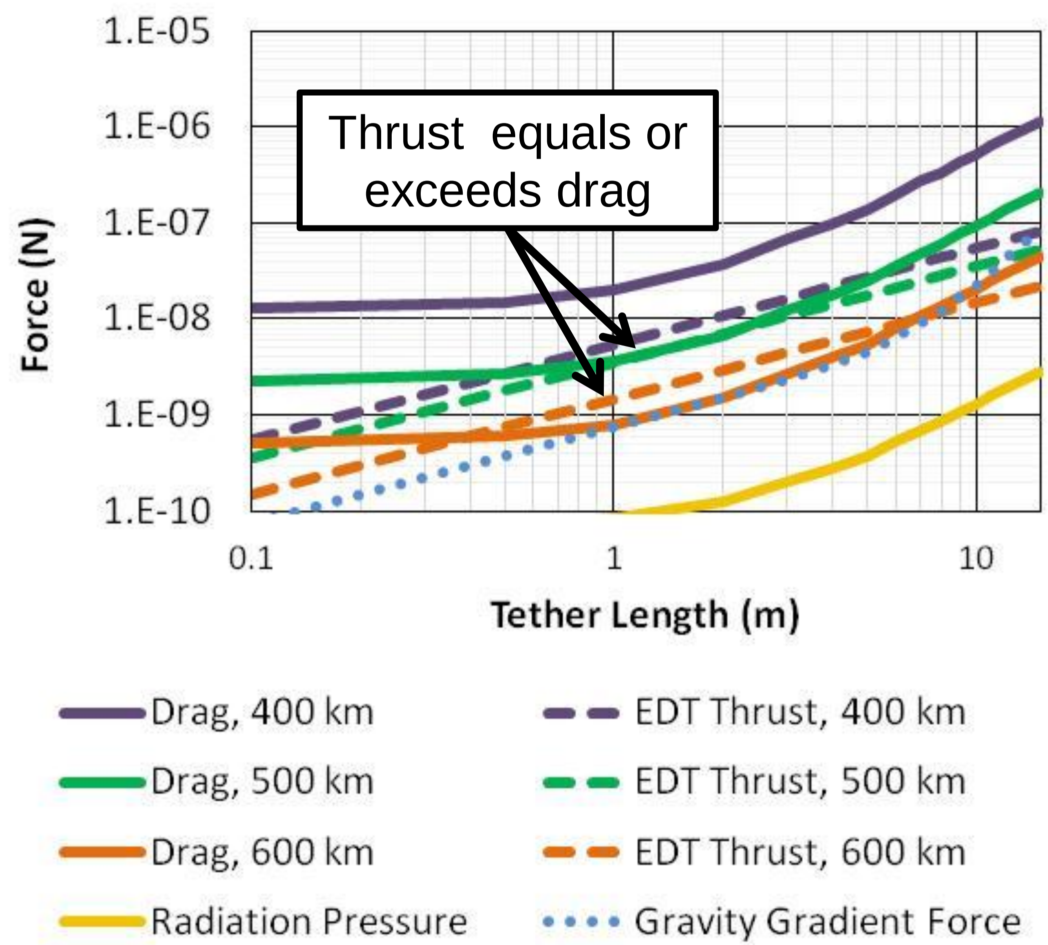


250-g satellite



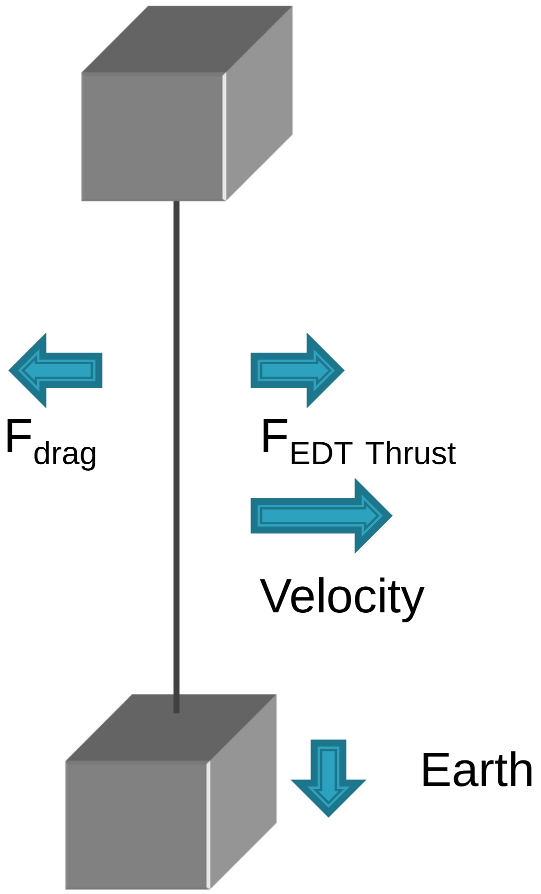
Estimate of Forces on Dual 400-mg Satellites with ED tether

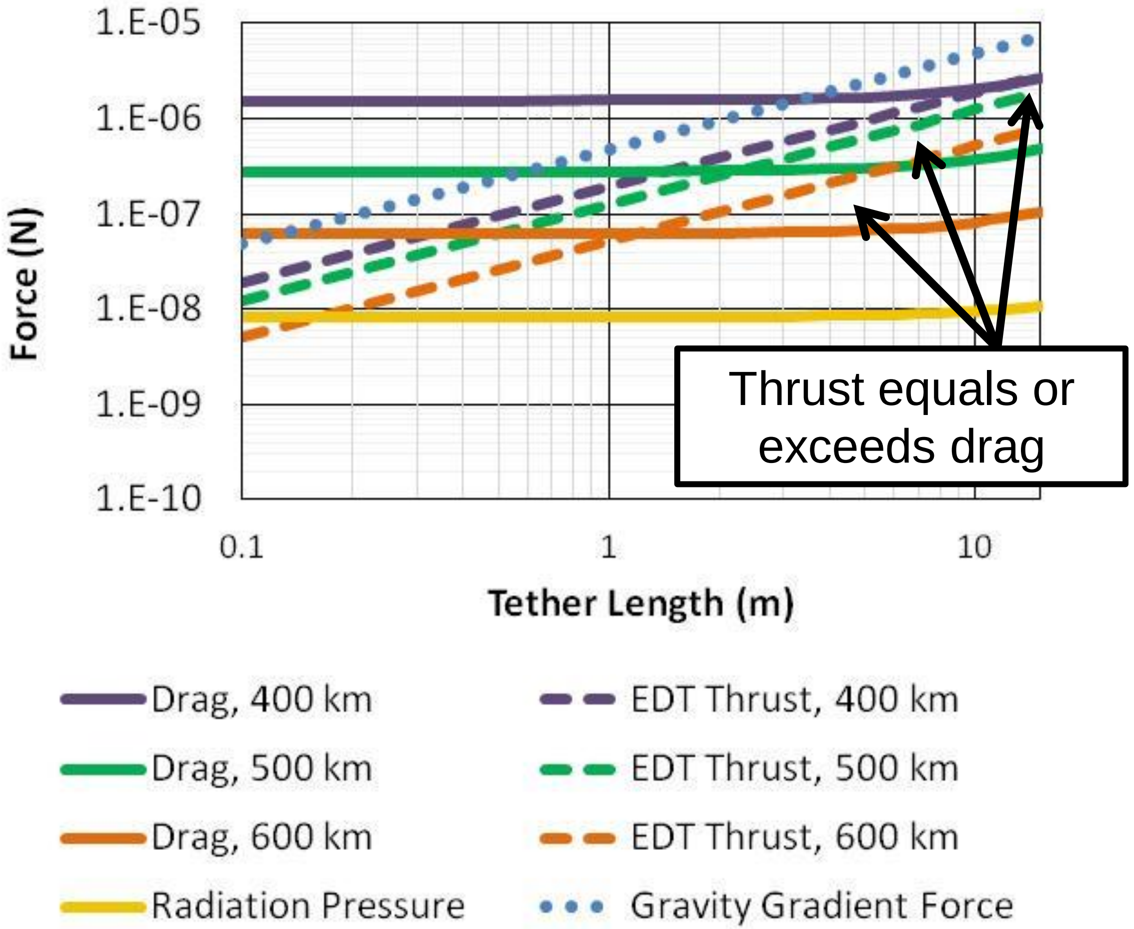




A 1-m EDT gives peak thrust for 400-mg femtosat at 500 km and 600 km. The gravity gradient force is also well below other forces.

Estimate of Forces on Dual 250-g Satellites with ED tether

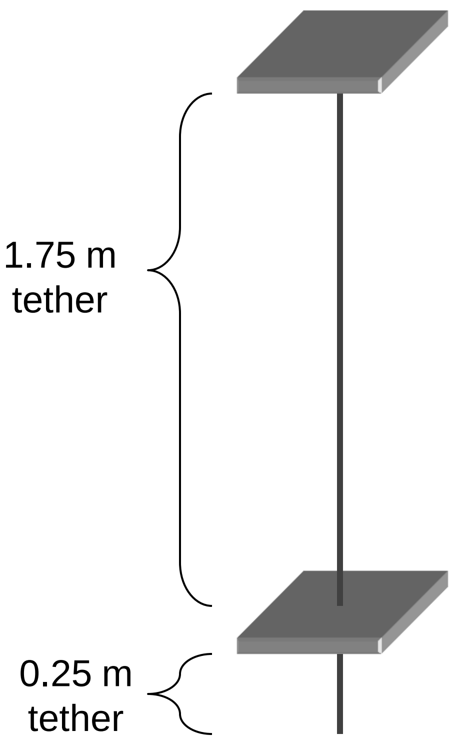




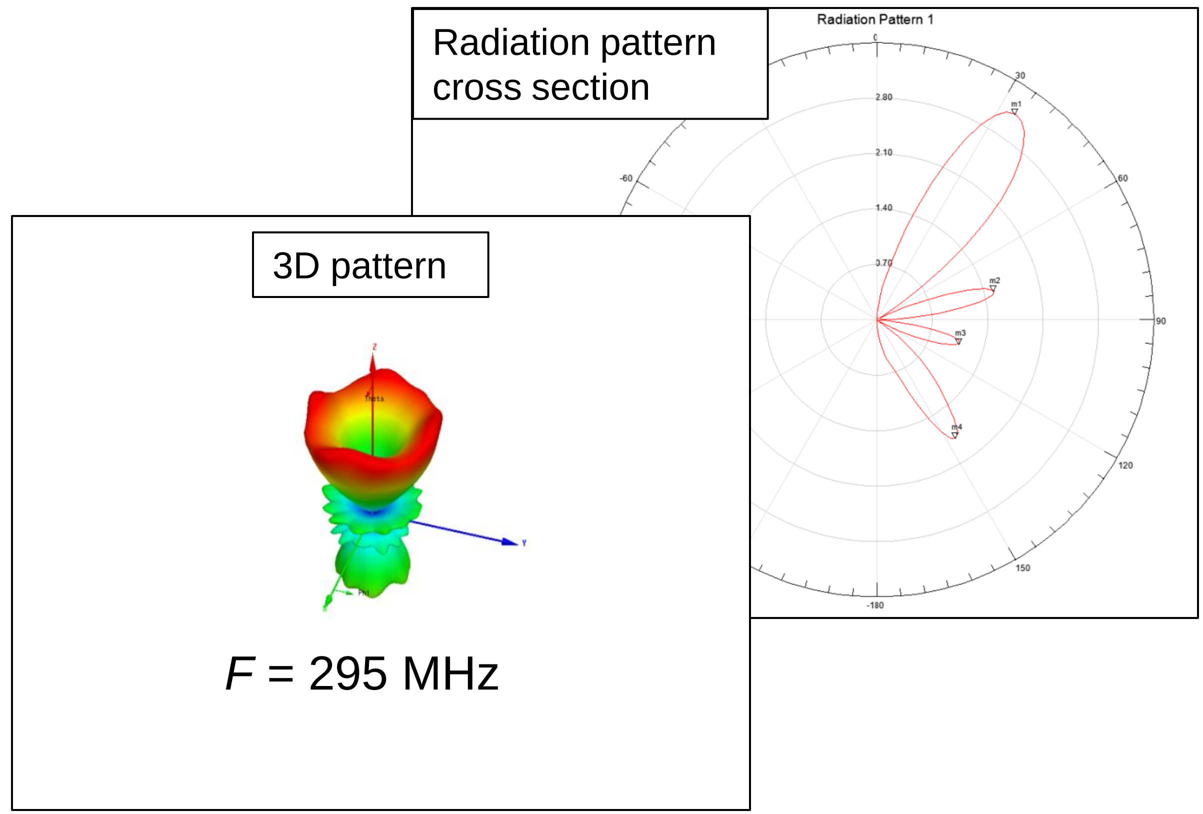
A 12-m EDT gives peak thrust for 250-g picosat at 400 km, 500 km, and 600 km. The gravity gradient force is also comparable to other forces.

Potential of ED Tether to Enhance Communication

Possible ED Tether Architecture for Communication



Simulated ED Tether Radiation Pattern



HFSS was used to model the ED tether as an antenna. We have considered an off-center dipole configuration.

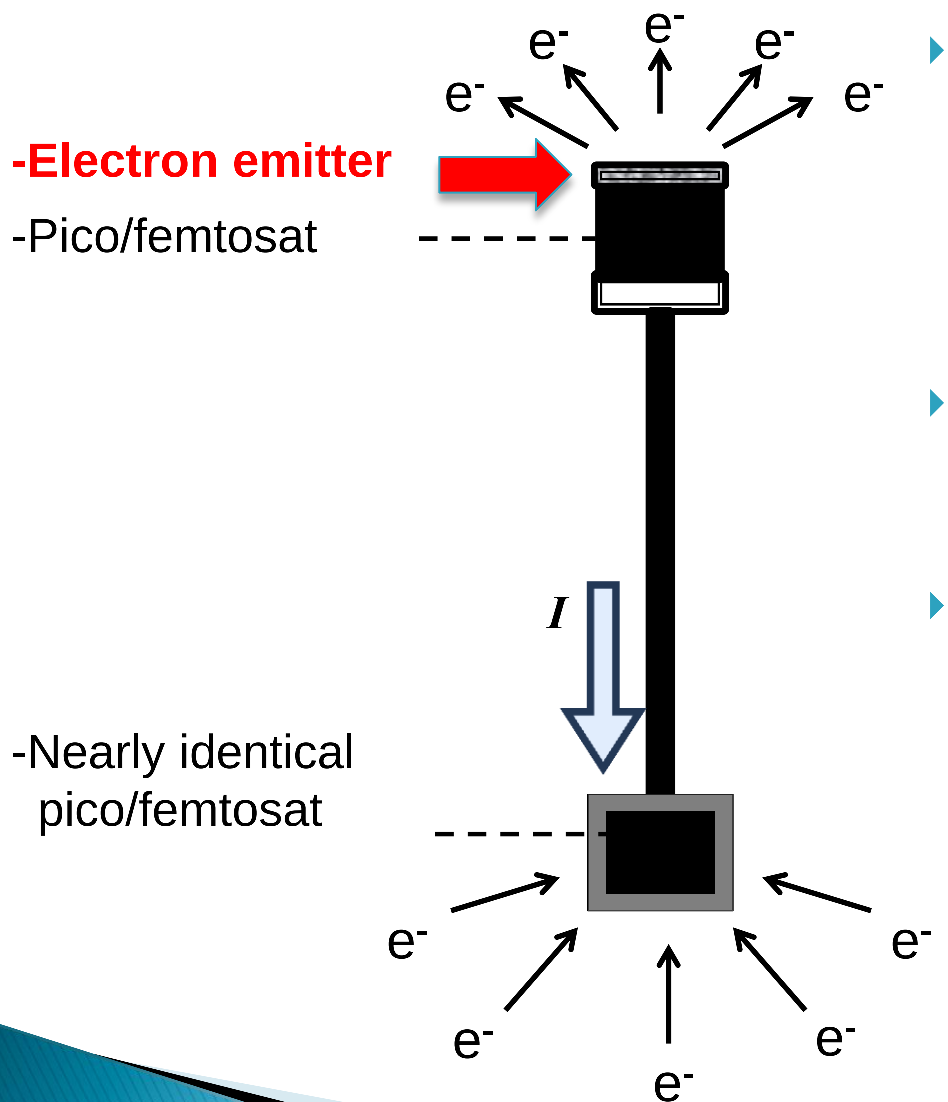
Conclusions

- Insulated EDTs only a few meters long show potential to be used for femtosat and picosat lifetime enhancement and maneuverability
  - Capable of nN to μN thrust levels

- EDT is less able to overcome drag at lower altitudes
  - Due to increased neutral density and decreased plasma density-to-neutral density ratio

Parameter	400 mg	2 g	50 g	250 g
Satellite Dimensions	1 cm × 1 cm × 0.2 cm	1 cm × 1 cm × 1 cm	5 cm × 5 cm × 1 cm	5 cm × 5 cm × 5 cm
Tether	1 m long, 24 μm diam.	4 m long, 70 μm diam.	5 m long, 80 μm diam.	12 m long, 200 μm diam.
Mass	2 mg	12 mg	0.18 g	3 g
Thrust Power	9 mW	27 mW	318 mW	672 mW
Where is gravity gradient significant?	~600 km	~500 km, 600 km	~400 km, 500 km, 600 km	400 km, 500 km, 600 km

Emission Current vs. Emission Area



- Emission current cannot exceed space charge limit (J_{CL}), governed by $$J_{CL} \propto T_0^{3/2}$$
  - T_0 being the initial electron energy
- Electron emitter types
  - Cold cathode
  - Hot filament
- For all femtosatellite sizes and altitudes, necessary emission area is <2% of available emission area even for worst emission technology
  - Smaller femtosatellites require larger percentage of available area for emission

FY13 EHEDT Research Directions

- Finalize EHEDT system and mission studies
  - Characterize overall "round-trip" efficiency of a boost/de-boost "orbital battery" EDT power generation system
  - Characterize performance of de-boost only "orbital energy scavenging" systems
  - Characterize performance and efficiency of orbital plane changes using a boost/de-boost tether system
- Laboratory investigation of tether system elements
- PROPEL mission design efforts

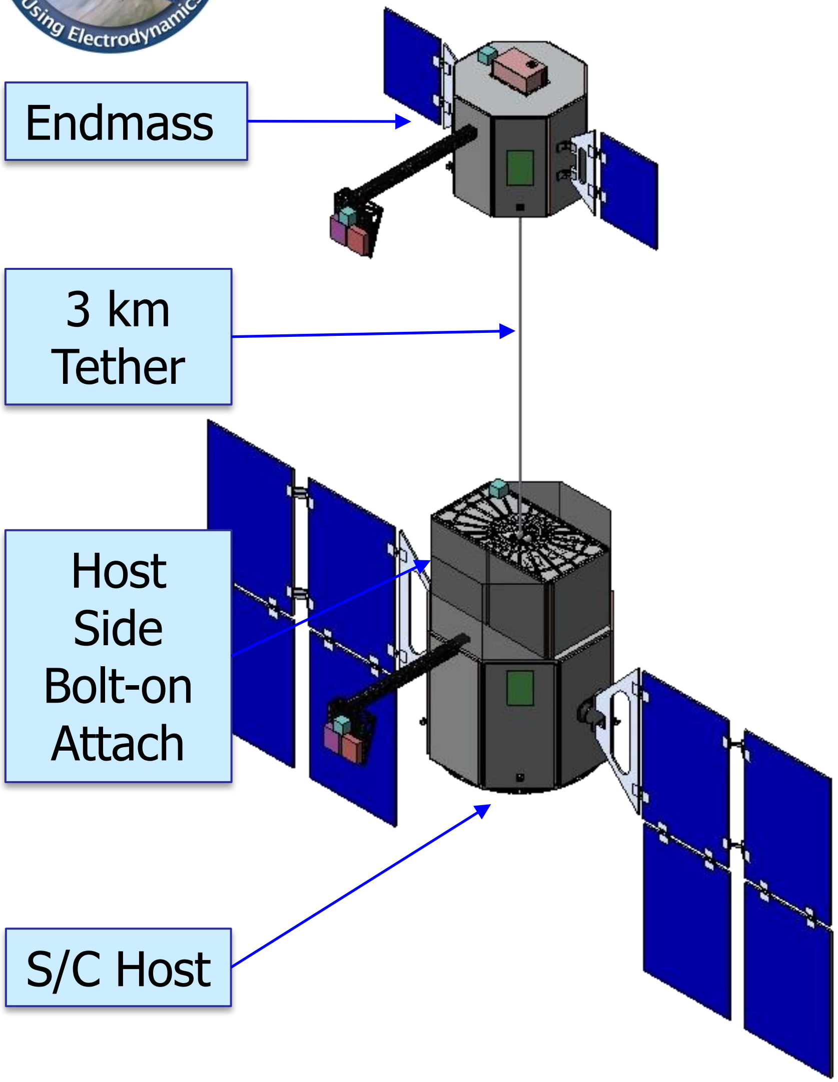
PROPEL Mission Goals

- **Demonstrate capability of ED tether technology to provide robust and safe, near-propellantless propulsion for orbit-raising, de-orbit, plane change, and station keeping, as well as perform orbital power harvesting and formation flight**

- **Fully characterize and validate the performance of an integrated ED tether propulsion system, qualifying it for infusion into future multiple satellite platforms and missions with minimum modification**

"Propulsion using Electrodynamics"

PROPEL Configuration Driven By Goals



- **Need for Bi-polar current flow**
  - Fully insulated conducting tether
  - Hollow Cathode Plasma Contactors (HCPCs) at each end as baseline
  - Plasma sensors at each end for
    - HCPC performance
    - End-Body-to-Ionosphere connection
- **Tether retraction capability at *both* ends for confidence of safety**
- **Bolt-on architecture to Host S/C**

PROPEL Delivers a Space Flight Demonstration of Electrodynamic Tether Propulsion for Rapid Infusion into Future Missions

EDT Questions Driving Mission Design

- What is predictable performance of hollow-cathode plasma contactor (HCPC) to collect current from and emit current to surrounding ionosphere in terms of:
  - Tether current,
  - HCPC parameters, and
  - Ionospheric conditions?

- How does ED tether performance change with increasing current (above 1 A)? How can the tether system be optimized for high current operation?

- What level of forecasting, real-time observation, performance prediction, and integrated simulation are required to enable <u>safe</u> ED tether system maneuvering?

HTV-based PROPEL Mission Design Effort

- The EDT Prop Demo Mission will operate an EDT propulsion system on a flight-proven Host bus in LEO (HTV post ISS mission) and has two goals:
  - Demonstrate EDT technology's capability to provide robust and safe near-propellant-less propulsion for orbit-raising, de-orbit, plane change, and station keeping, as well as perform orbital power harvesting and formation flight
  - Fully characterize and validate the performance of an integrated EDT propulsion system, qualifying it for infusion into future satellite platforms and missions