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An Architecture of Modular Spacecraft with Integrated Structural Electrodynamic Propulsion (ISEP)

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Engineering the Future

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Motivation

- Traditional propulsion uses propellant as reaction mass
- Advantages (of reaction mass propulsion)
  - Can move spacecraft center of mass, on-demand, and relatively quickly
  - Multiple thrusters offer independent and complete control of spacecraft (6DOF)
- Disadvantages
  - Propellant is a finite and mission limiting resource
  - Propellant mass requirements increases exponentially with mission ΔV requirements
  - Propellant may be a source of contamination for optics and solar panels
- Current Architectures of NASA's Vision of Exploration require launching and transporting large masses
- Are there innovative alternatives?

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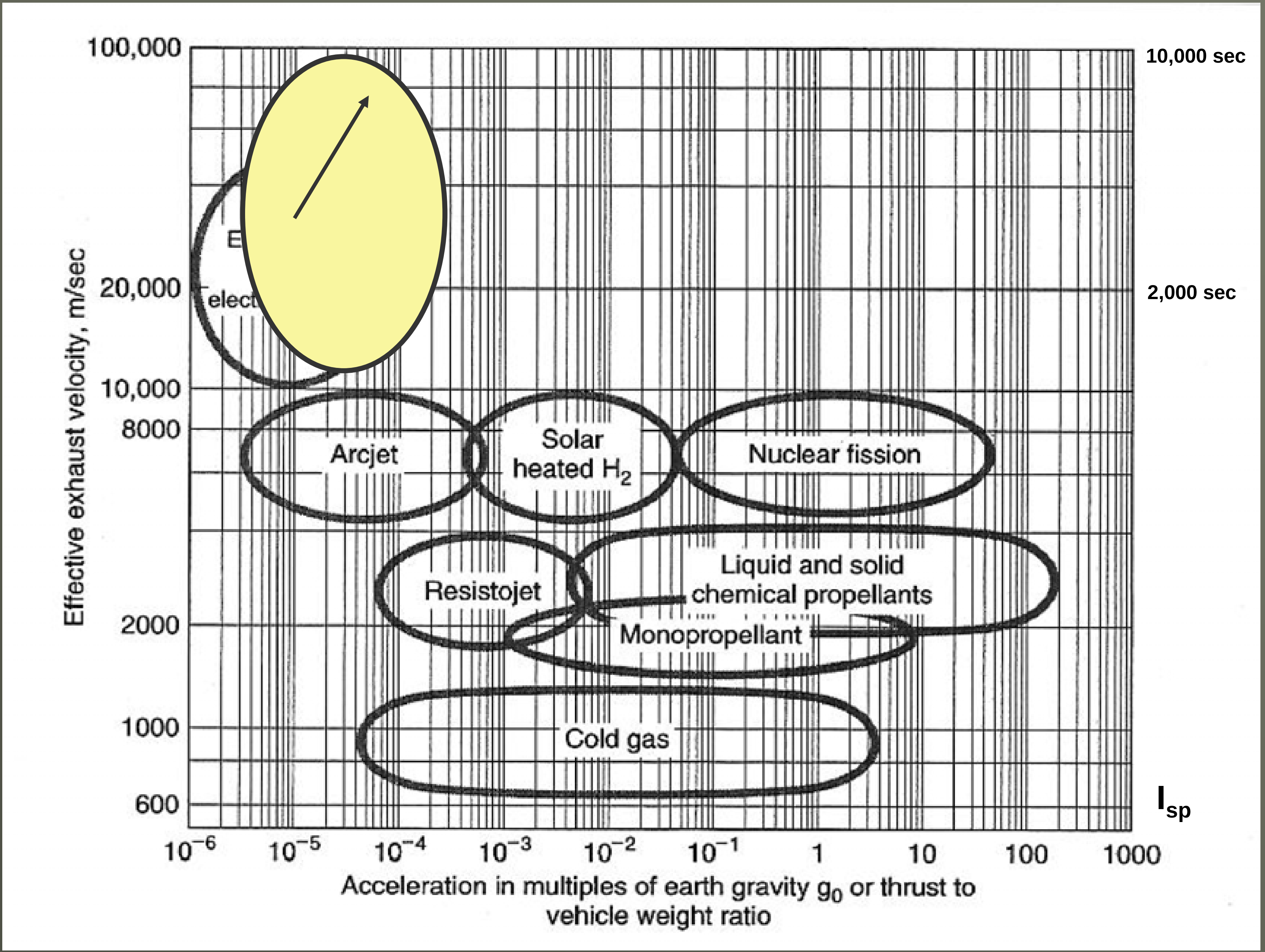
Space Propulsion Landscape



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Courtesy Gallimore, A., UMich

Electrodynamic Space Tether Propulsion

- In-space propulsion system
- PROS:
  - Converts electrical energy into thrust/orbital energy
  - Little or no consumables are required
- CONS:
  - Long (1-100km) flexible structures exhibit complex dynamics, especially in higher current/thrust cases
  - Gravity gradient tethers have constrained thrust vector
  - Relies on ambient plasma to close current loop

Given a fixed amount of power available and fixed conductor mass, thrust efficiency is independent of the length of the conductor

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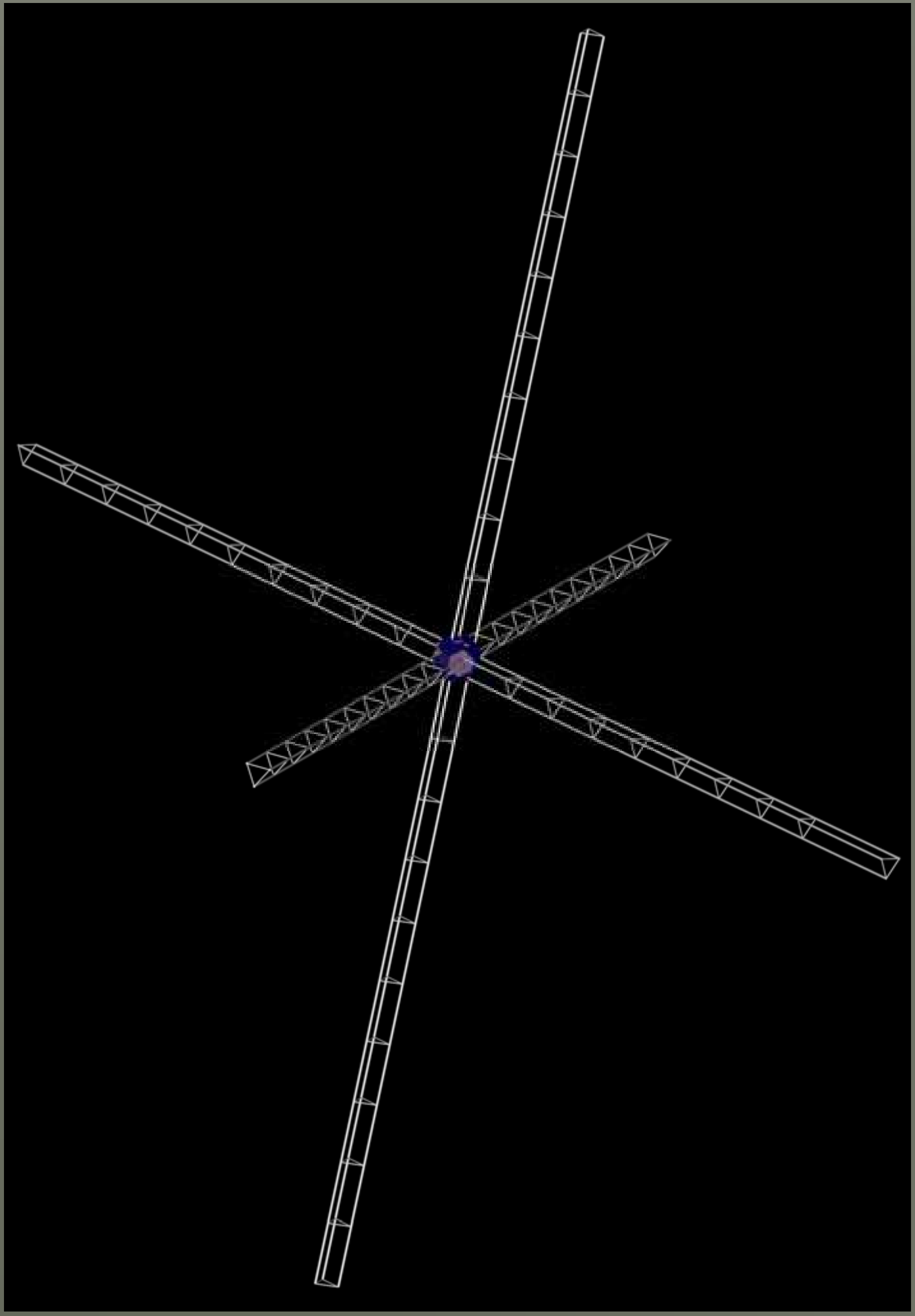
Proposed Solution



– *Multifunctional* propulsion-and-structure system that utilizes Lorentz forces ($F = iL \times B$) generated by current carrying booms to generate thrust with little or no propellant expenditure
    - Utilizes same principles as electrodynamic tether propulsion
– Utilize relatively short (≈100 meter), rigid booms with integrated conductors capable of carrying large currents, that have plasma contactors at the ends
    - Space Tether Electrodynamic Propulsion
        – Ex: 10km conductor, 1Ampere in LEO
            - Thrust $|iLxB| \approx 0.3$ Newtons
– Proposed Integrated Structural Propulsion
    - Ex: 100m conductor, 100 Ampere (!) in LEO
        – Thrust $|iLxB| \approx 0.3$ Newtons
        – Torque ≈ 750 N · m

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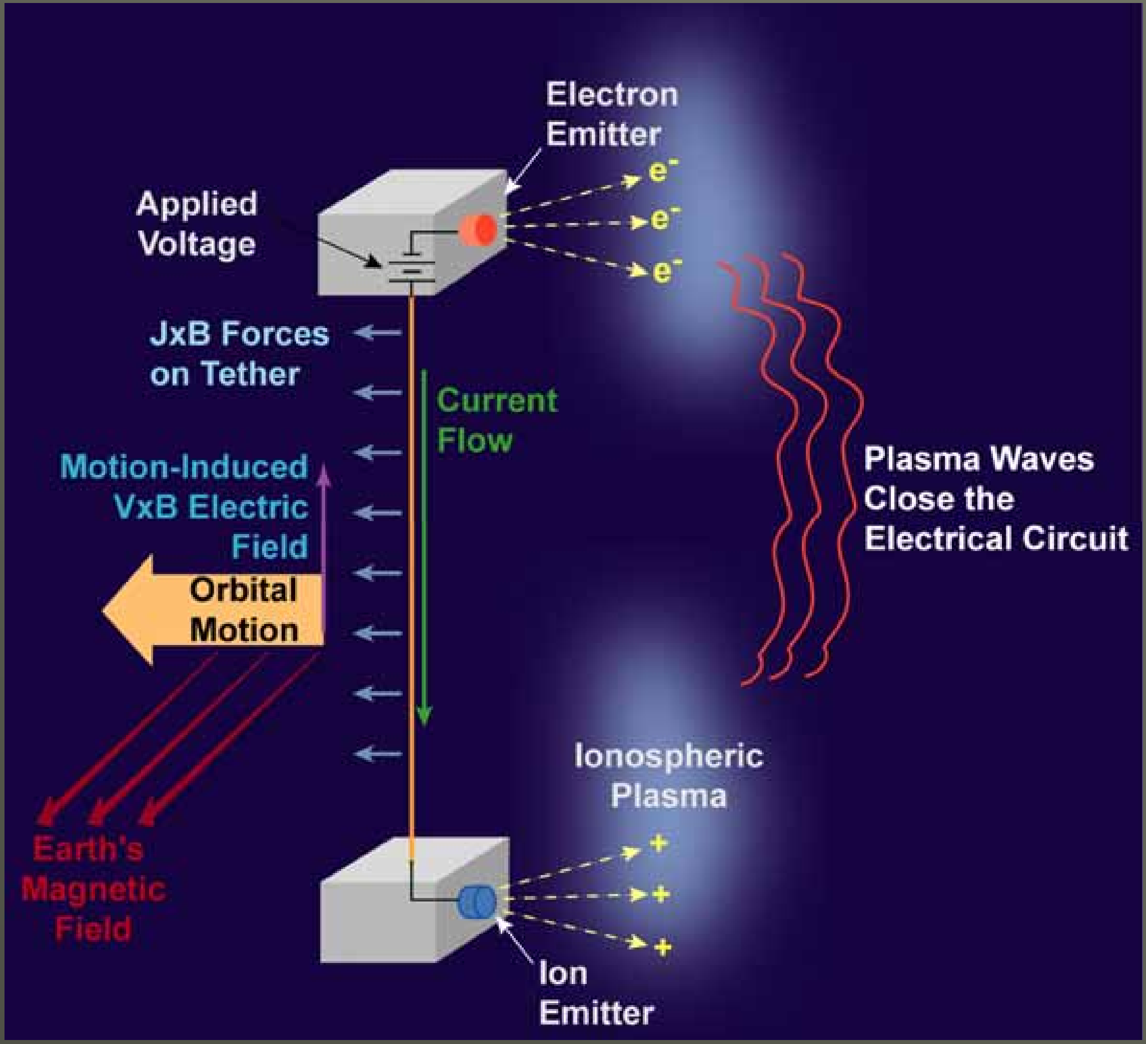
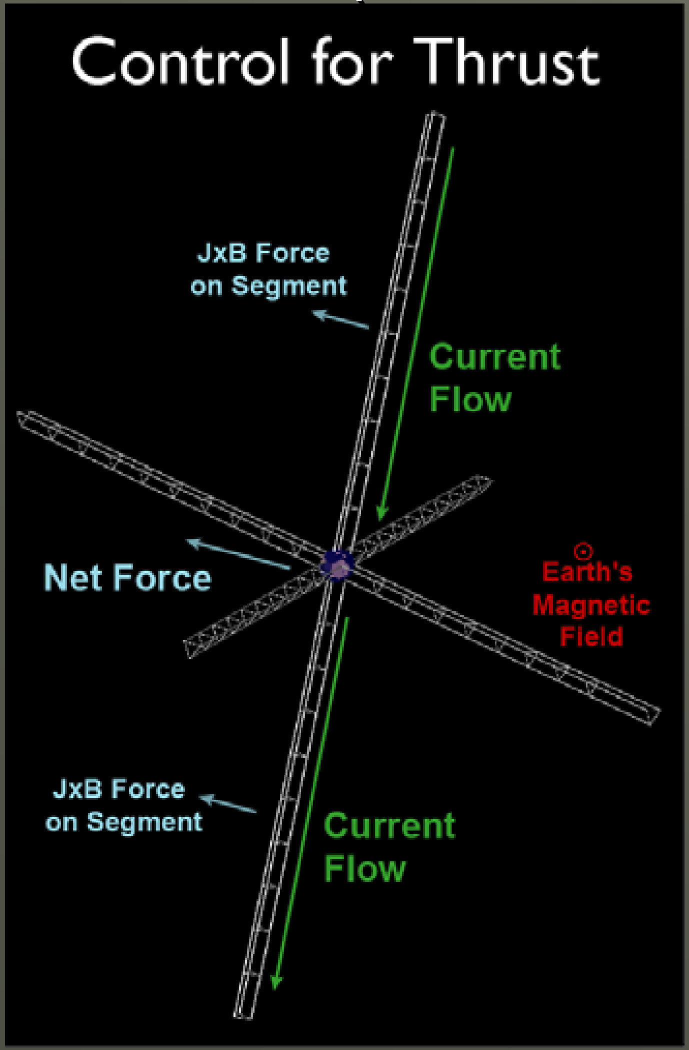
Single Boom Concept of Operation

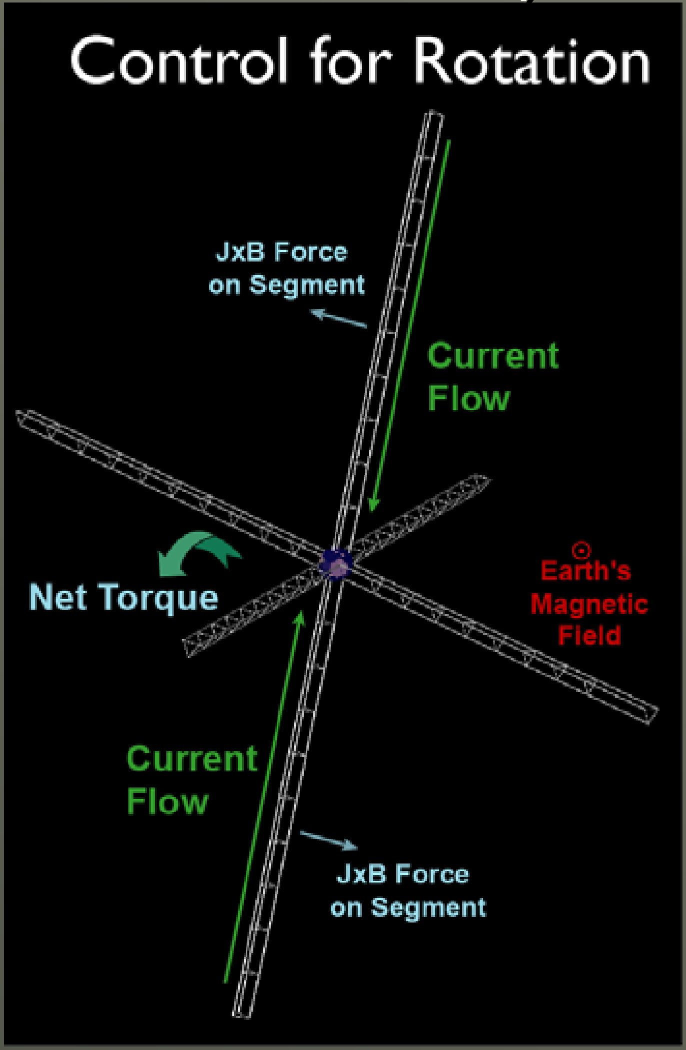
- Apply potential to overcome motion-induced electric field and drive current across magnetic field
- Current flowing down boom produces thrust force
- Plasma waves close the electrical circuit



'Structural' ED Propulsion

- By connecting six booms to a spacecraft along orthogonal axes, 4DOF of motion can be controlled (translational and rotational)





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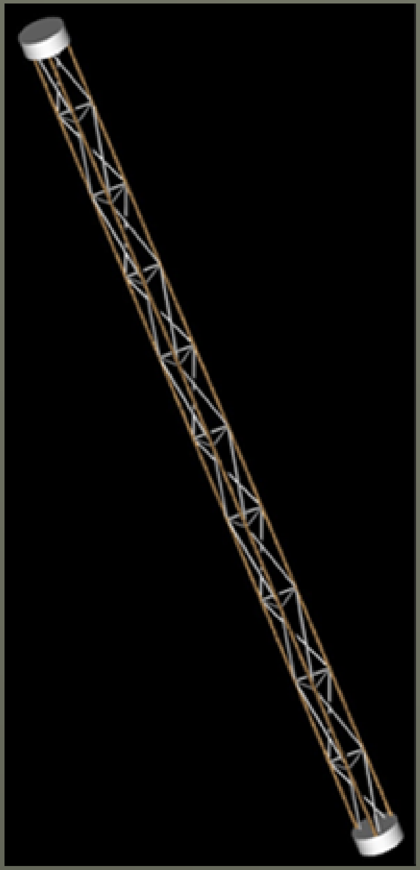
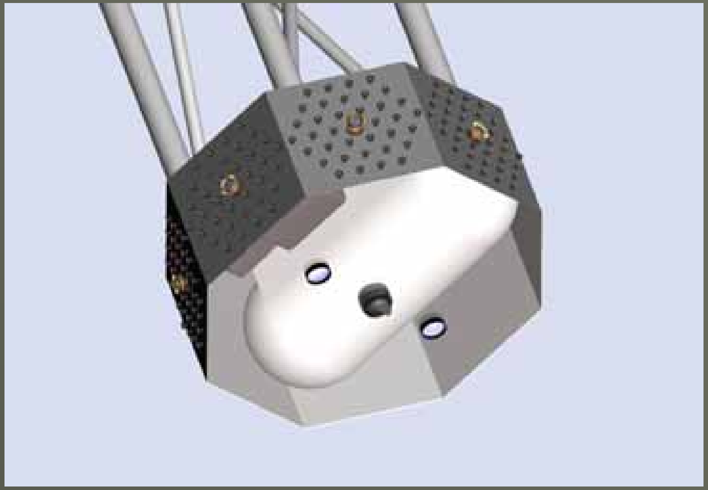
ISEP Booms

- Cold biased, low-resistance element to maximize propulsive performance
  - Copper Clad Aluminum (CCA) offers low specific resistivity, yes remains easy to work with
    - Ex. 0.01Ω/50 meter boom has a 0.44 kg/m density
- Stiffness dictated by application
- Boom ends contain plasma contactors & docking sensors
- Hemaphroditic high-current capacity docking mechanism



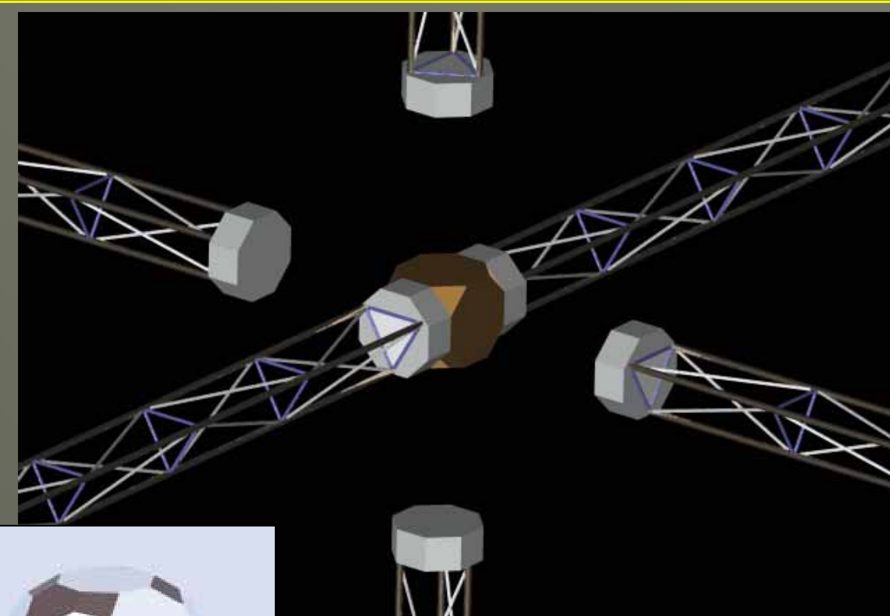


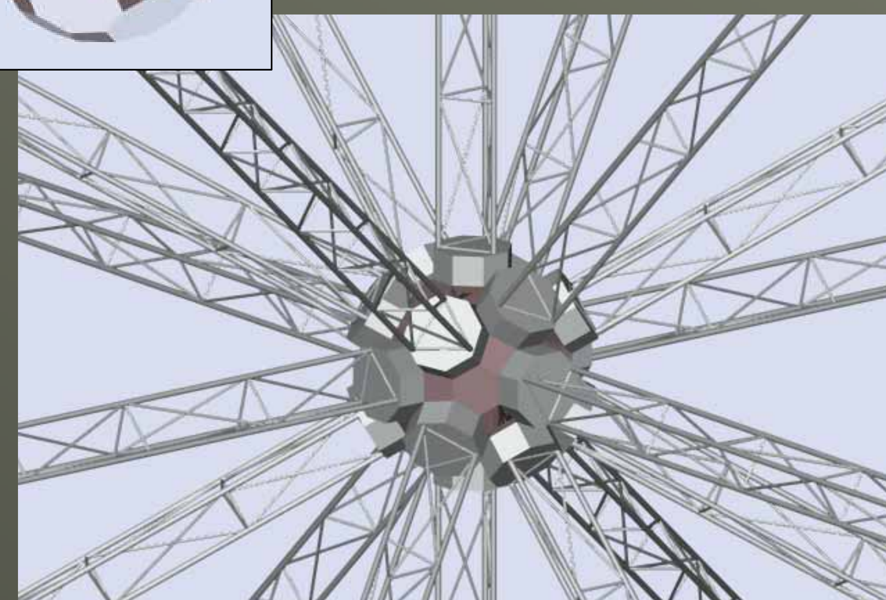
100 Ampere Contactors for ISEP

Emission	Device	Power	Notes
Electron Emission	TC + Electron Gun	2.1 MW	18 emitters, < 1.25 V for SCL
	FEA	**5860 W**	**10 emitters, < 0.4 V for SCL**
	HC	**1250 W to 10 kW**	**Flow Rates & Ion Type** **9 sccm to 40 sccm Xe**
Electron Collection	Passive Sphere a	4.7 MW	1 m radius, 6.6E-3 N Drag 90% Porous – 6.6E-4 N
	Passive Sphere b	1 MW	2.29 m radius, 3.46E-2 N Drag 90% Porous – 3.46E-3 N
	Passive Plate a	61.3 MW	5 m^2 – 5.26E-5 N Drag
	Passive Plate b	1 MW	54.52 m^2 – 5.73E-4 N Drag
	HC	6150 W + 330 W (20 A ion prod.)	280 sccm fuel 27.35 mg/s Xe^+ or 0.21 mg/s H^+
Ion Emission	Ion Emission + Ion Gun	1 MW + 1650 W (100 A ion prod.)	83,334 emitters needed
	HC	**1000 W + 1650 W** **(100 A ion prod.)**	**1400 sccm fuel** **27.35 mg/s Xe^+ or 0.21mg/s H^+**

ISEP Nodes

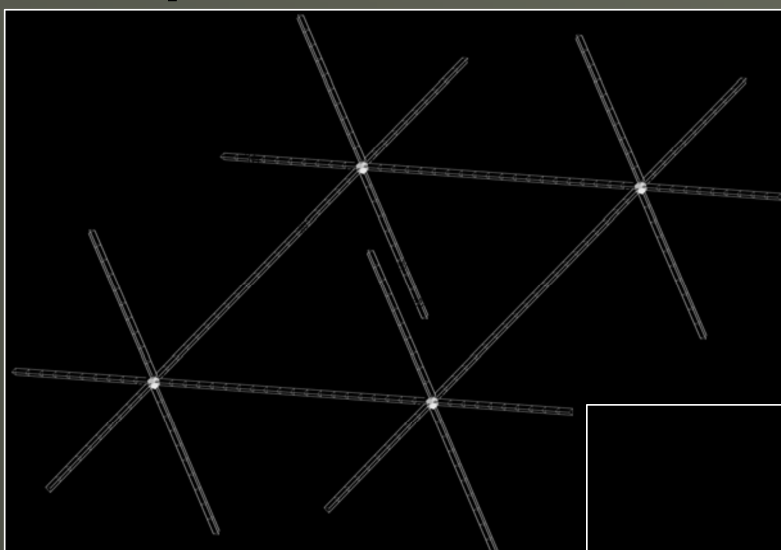
- Node geometry
  - Simplest has 6 orthogonal mating surfaces
  - Can also utilize polyhedrons with mating surfaces spaced 45° along the circumference
- Node components
  - Energy storage (flywheels @ 75 W-hr/kg)
  - System & Navigation Controllers

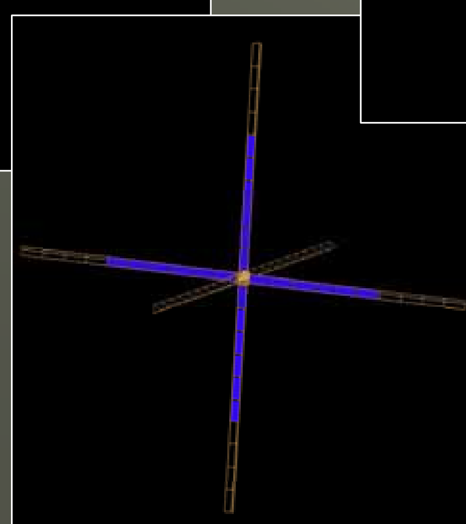


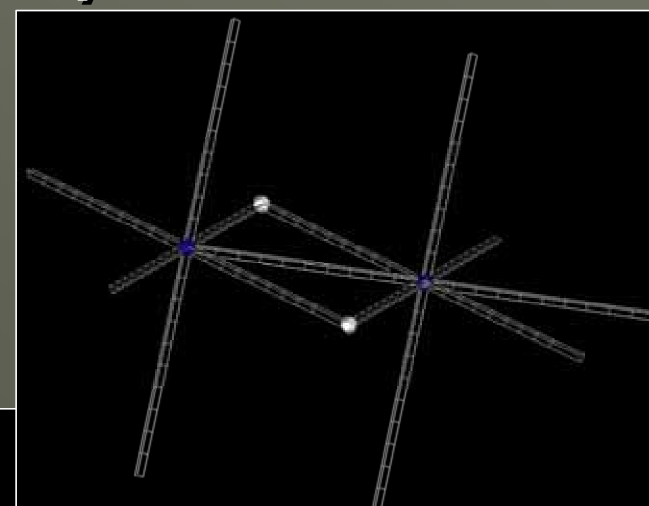


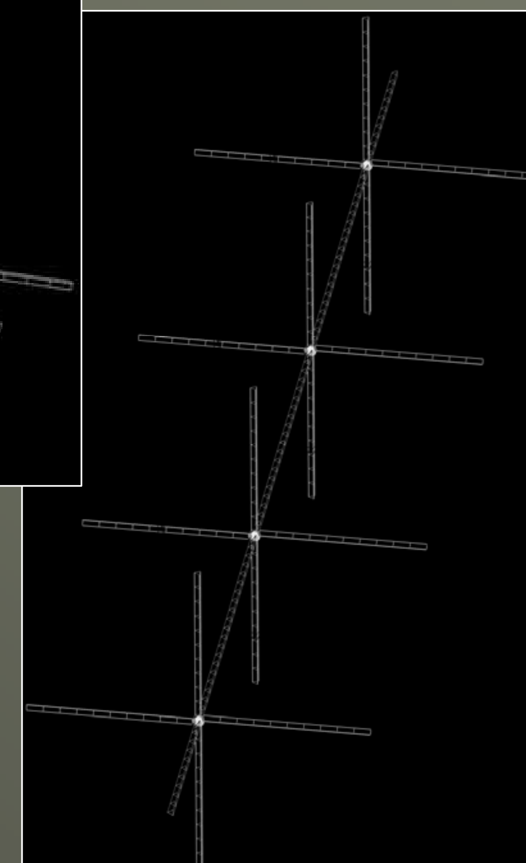
Modular Spacecraft

- By making booms and spacecraft modules modular and interconnectable, we create self-assembling Tinkertoy® like components for space structures and systems







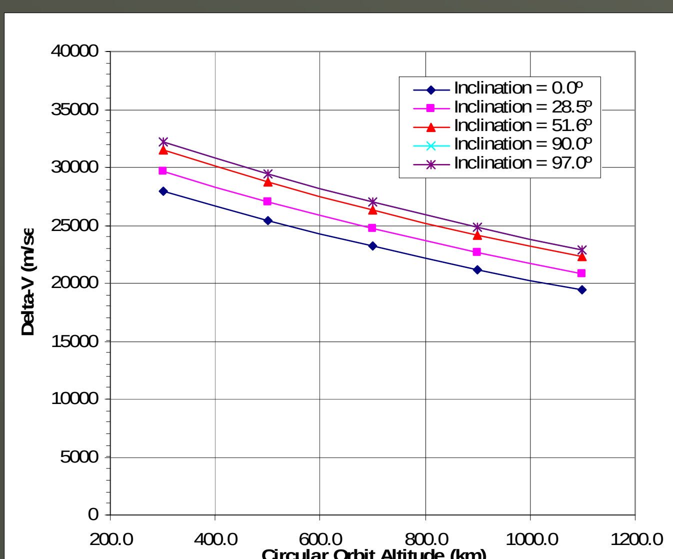


ISEP Applications

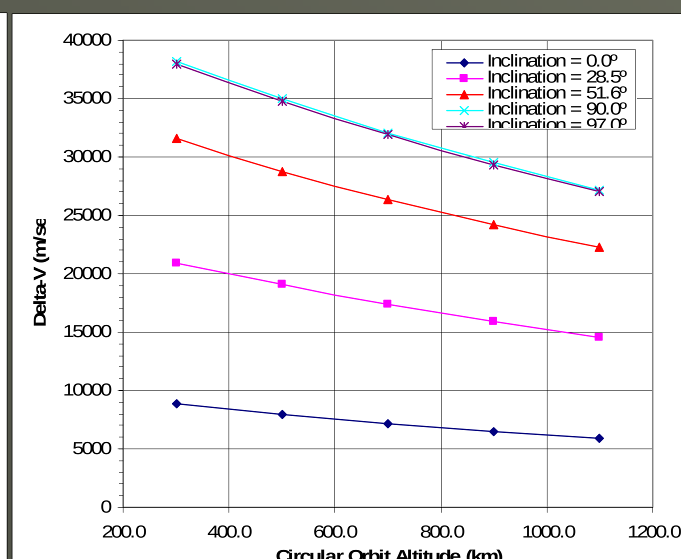
- Self-Assembling Modular Spacecraft (SAMS)
- Self-Assembling Structure for Refueling Station
  - Integral rail gun for commodity delivery
- Self-Assembling Space Tug
- Self-Assembling Structure for Large Mirror or Antenna Arrays
- Formation Flying Space Systems
  - Terrestrial Planet Finder (TPF)

ISEP Performance Analysis

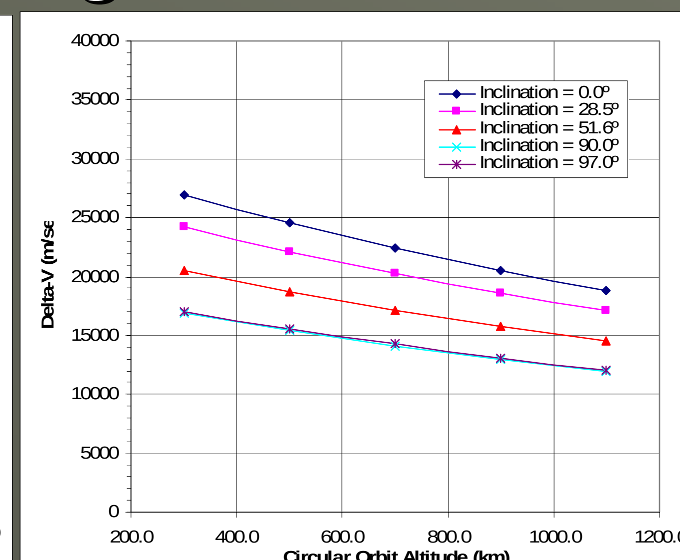
- Six 50m orthogonal booms in 300-1100km, 0-97° inclination orbits
- FEAs for electron emission, HCs for ion emission
- Total system mass – 1000kg with 20kg H consumable (approx 3 years full time operation)
- Current commanded to 100A continuous for 30 days
  - System Input power - 6500 Watts
- Performance metrics tabulated & averaged



Along-track Total ΔV



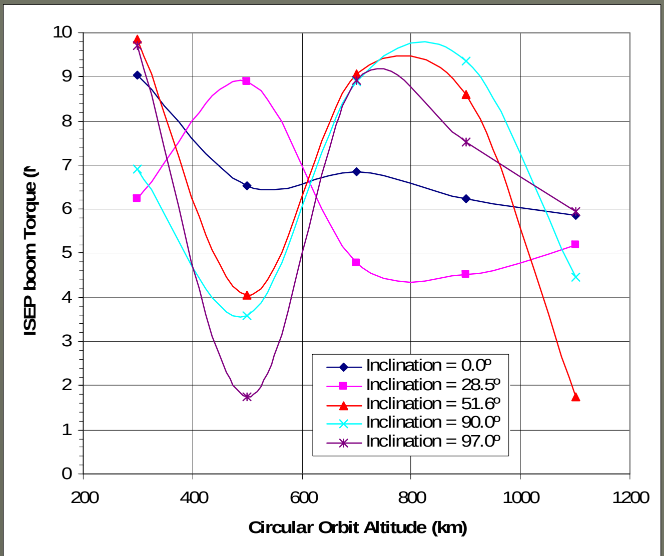
Cross-track Total ΔV



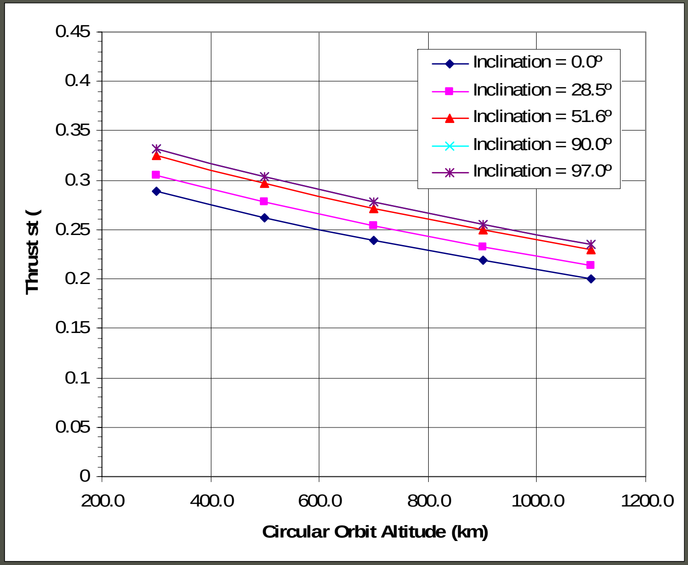
Radial TotalΔV

ISEP Performance (cont.)

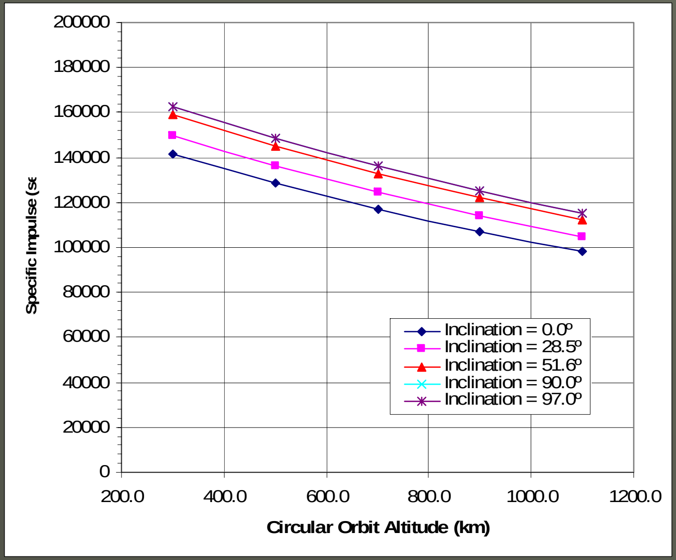
- Thrust magnitude and efficiency highly dependent on alignment of boom(s) with magnetic field
- Torques in the 1-10 N-m range as compared to disturbances in the 10^{-8} to 10^{-1} range



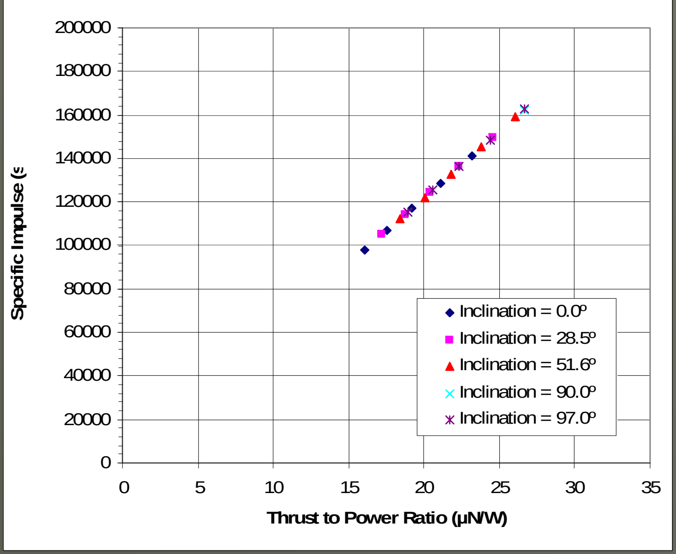
Along-track current torque (N-m)



Average Along-track Thrust (N)



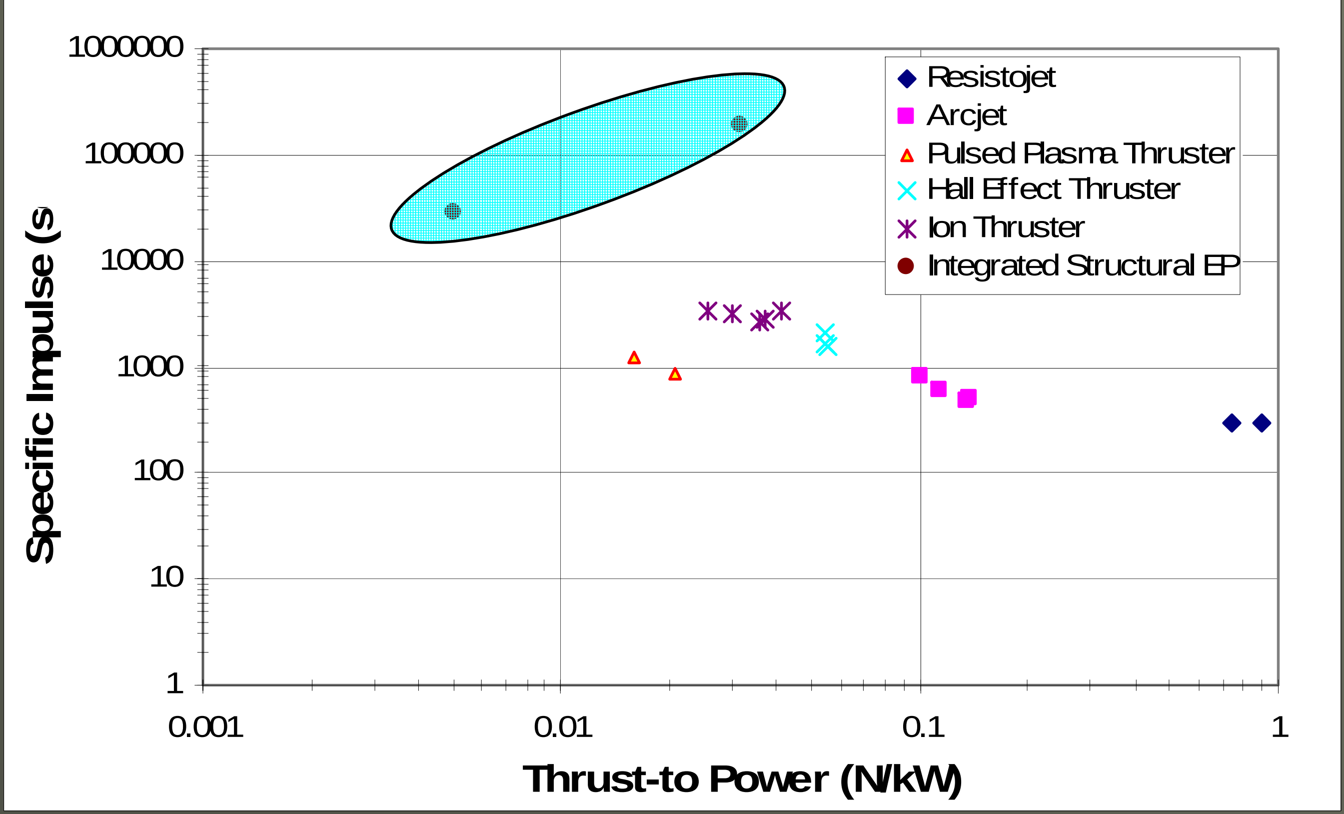
Average Specific Impulse (Isp)



Isp vs. Thrust to Power (uN/w)

ISEP Performance

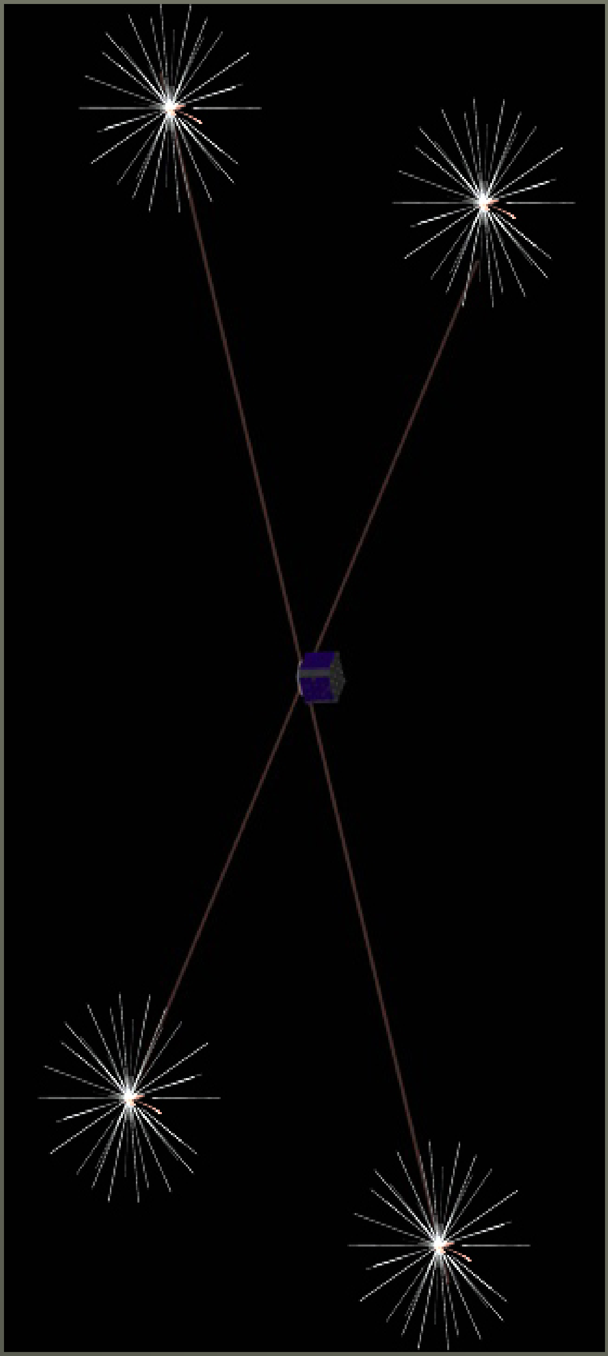
- ISEP is competitive with other EP technologies
- In systems where collinear booms are assembled, performance improves
- For missions where structural elements are required, ISEP's dual use (propulsive/structural) has significant advantages



- KEY TECHNOLOGY CHALLENGE: Power- and Mass- Efficient collection and emission of electrons from/to the ambient plasma

Technology Demonstration Experiment

- Primary Experiment Objectives
  - Generate directly detectable torque
  - Generate directly measurable thrust
- Secondary Experiment Objectives
  - Validate performance of Field Emissive Electron device(s)
  - Validate performance of lightweight electron collectors
- **GOAL**: Drive 1 Ampere of current through lightweight deployable, conductive 10-20 meter booms
  - 0.2-1.0 second impulses > 0.5 mN

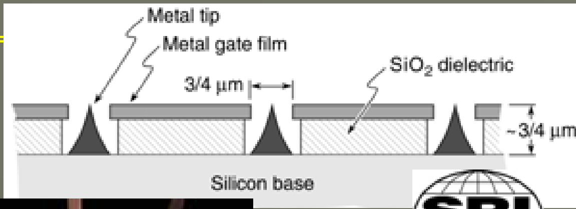


Experimental Method

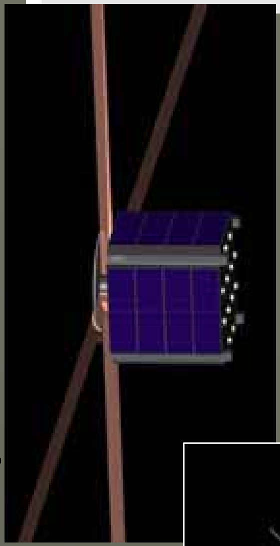
- Picosatellite launched as a secondary payload
- Target platform – CubeSat
  - 1kg – 10x10x10 cm envelope
  - Standard initially designed for University class experiments and educational purposes
  - Typically 1-2 launch opportunities a year
  - Launch costs $40-120K for a 1U CubeSat
  - Ideal for simple experiments and technology demonstrations


Poly Picosatellite Orbital Deployer (P-POD)

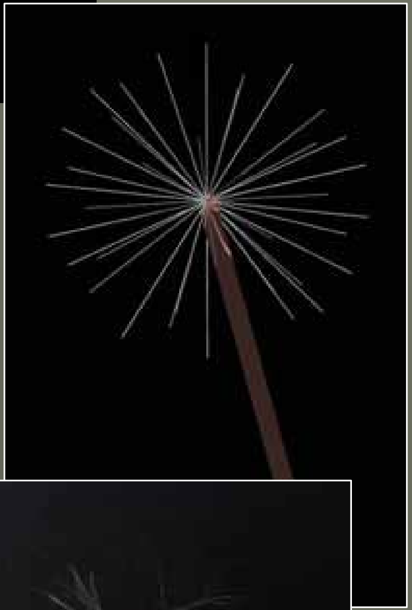
Picosat Experiment Contactors



- Field Emissive Cathodes
  - Microfabricated Emitter tips rely on sharp emitter tips, and close non-intercepting electrodes to generate high field required to enable electrons to quantum tunnel out of the material into space
  - High current densities (5000A/cm^2) have been demonstrated
  - Development undergoing to increase total current output and reduce environmental constraints

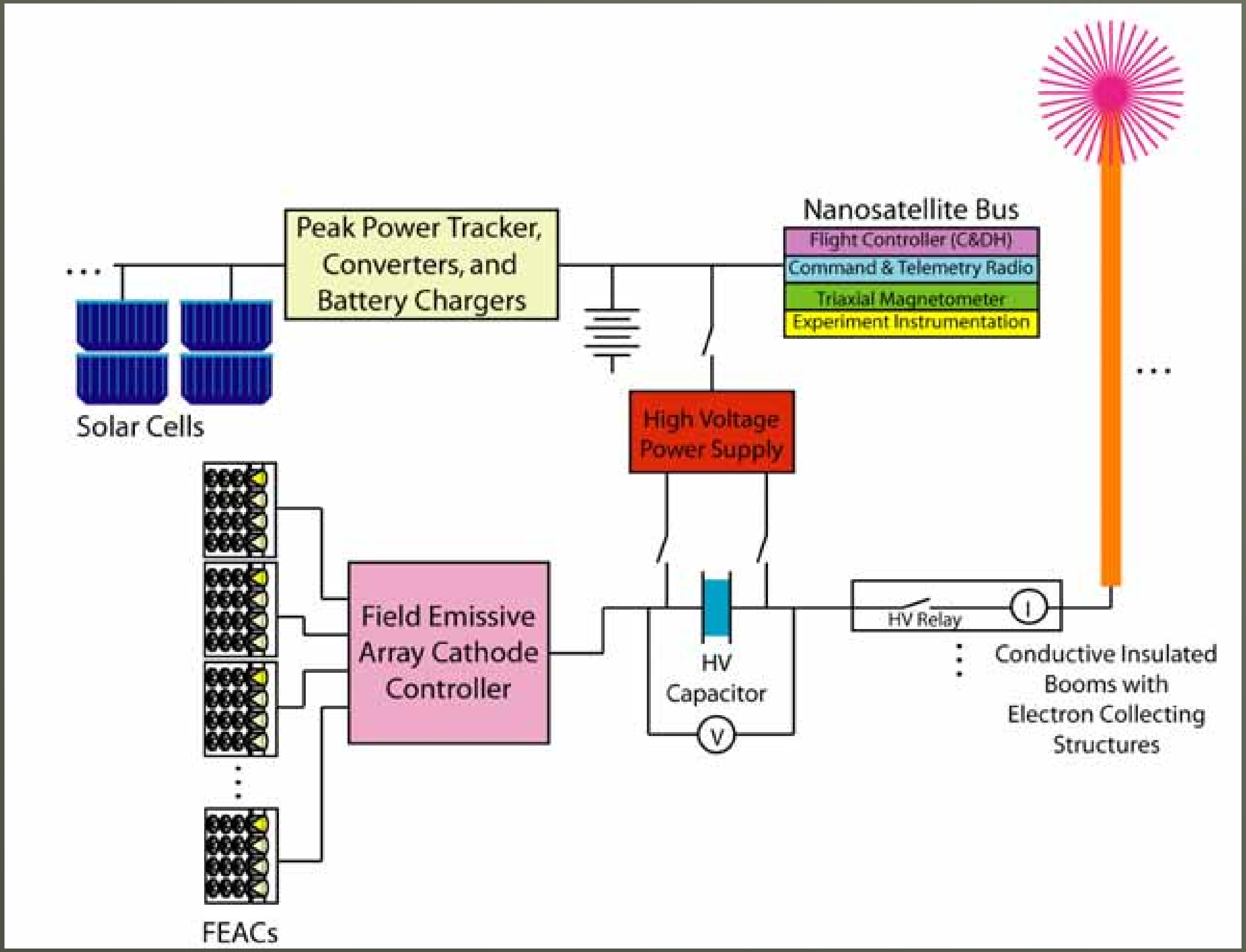


- Passive Electron Collector ('Hedgehog')
  - Bundle of conductive yarns
  - Yarns tied together at root, and when charged will form approximately a 'Koosh-ball' like spherical structure due to electrostatic repulsive forces
  - 2 meter diameter structure with yarns every 40°, and filament every 1° can weigh 10 grams(!)



Experiment Conops

- Converted Solar Energy is stored onboard in capacitor bank
  - Allow for thrust pulse every 4-6 orbits
- At desired B-field alignment, discharge capacitor to generate 1Ampere pulse
- Measure Thrust with onboard accelerometers
- Measure Torque with body attitude rate change



Summary

- Proposed Concept IS feasible
  - Requires small amount of consumables for ion source
  - 4DOF propulsion– no thrust in B-field direction
  - Competitive with tradition Electric Propulsion with added benefit of structural elements
- Technology Challenges
  - High Current Plasma Contactors
    - Devices exist – robust units with higher efficiencies needed
  - Plasma Contactor Space Charge Limiting
    - High current densities may be environmentally limited
  - Collision proof coordinated control laws for formation flight, and self-assembly
    - Additional constraints imposed on low-thrust control laws
- Experiment in Phase II will demonstrate system feasibility and validate component technologies
- Potential Applications
  - Space Tug and Commodity Depot (with integral rail gun?)
  - Structure for Beamed Power Solar Array/Antenna Fields
  - Structure for Space Habitats with Integral Drag Makeup