Electrodynamic Tethers for Spacecraft Propulsion

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Electrodynamic (Drag) Tether Thrust Principles

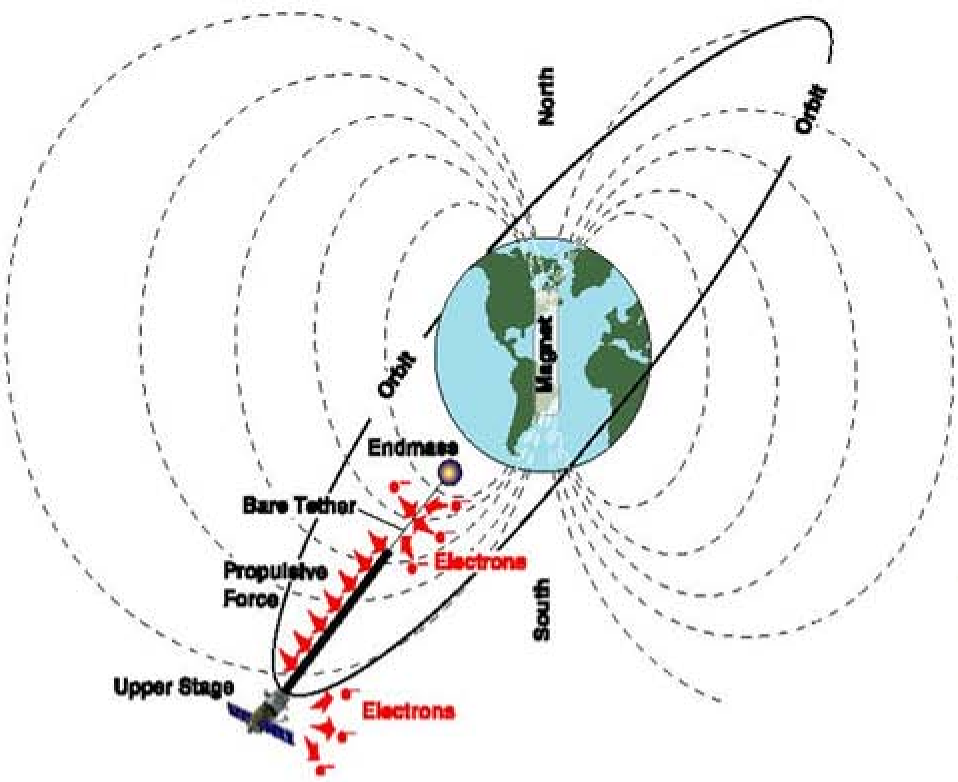
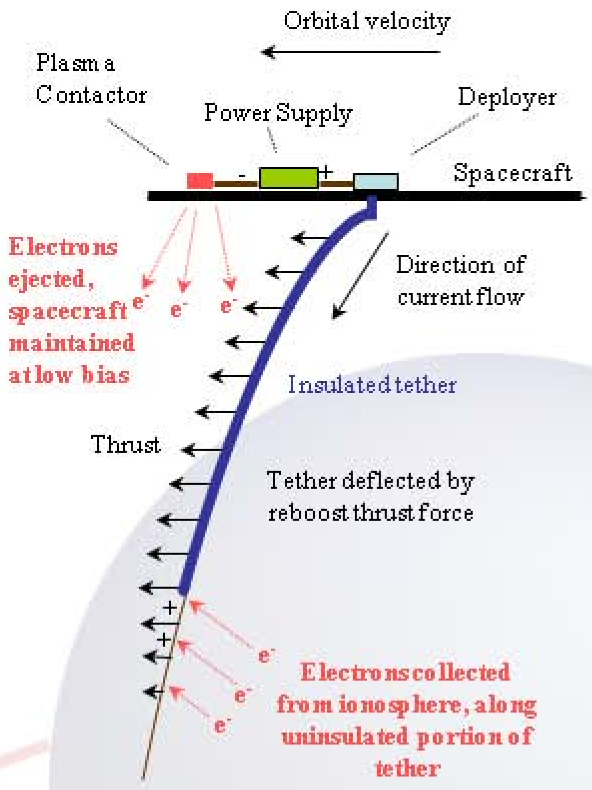


Illustration actually shows thrusting tether

- Uses both solar energy and consumes no propellant
- Tether's orbital velocity **v** (~7500 m/s) through North-pointing geomagnetic field $\mathbf{B}_{\mathbf{north}}$ (0.18 - 0.32 Gauss) induces voltage (35 - 160 V/km) in tether
- Return current is through surrounding plasma
- Current $\mathbf{I}$ produces a drag thrust force $\mathbf{F}$ on the tether
- Magnetic force $\mathbf{F}$ from current $\mathbf{I}$ through insulated tether of length l: $\mathbf{F} = l\mathbf{I} \times \mathbf{B}_{\mathrm{North}}$

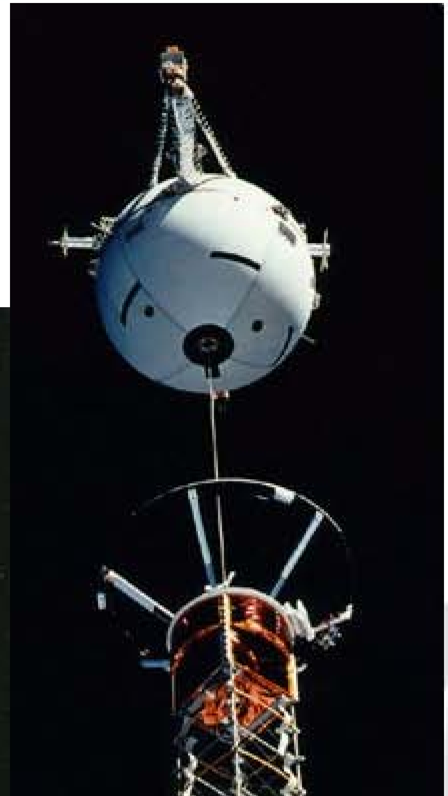
Reboost Tether Thrust Principles

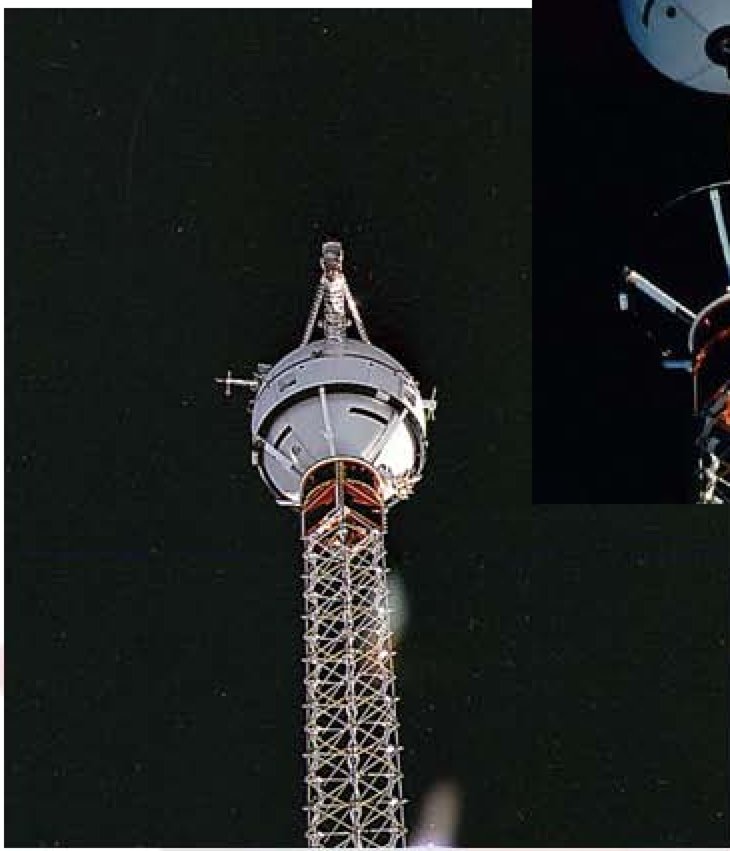


Geomagnetic field exerts thrust proportional to current at each point along tether

- Power applied at spacecraft end to force a positive tether potential and current down the tether
- Downward current **I** produces a thrust force **F** in the reboost direction along the orbit
- Actual current is determined by the ability of
  - Plasma contactor to eject electrons (completes the circuit with the plasma)
  - Bare lower tether and endmass to collect electrons
- Current maintained over a wide plasma density range
- Magnetic force **F** from current **I** through insulated tether of length l: $\mathbf{F} = l\mathbf{I} \times \mathbf{B}_{North}$

Tethered Satellite System Mission

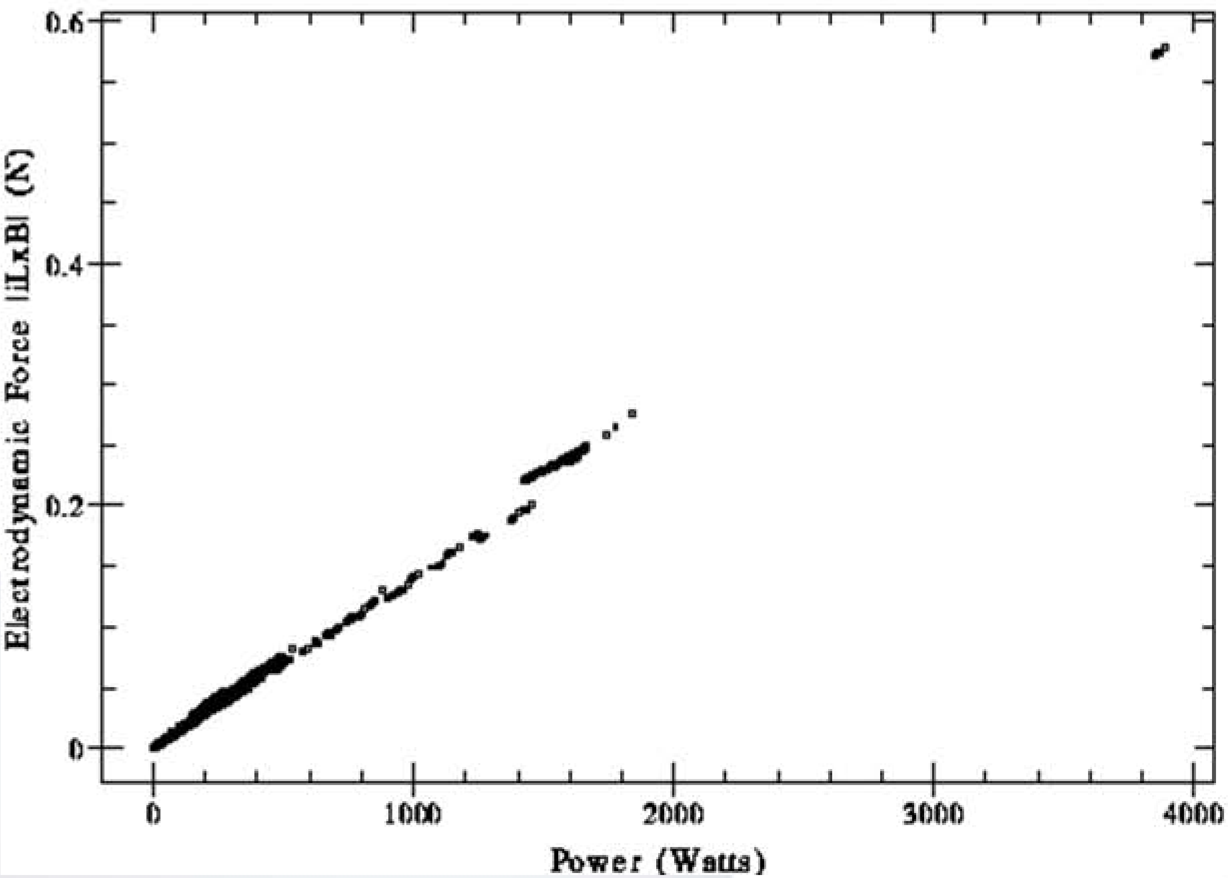




1996

- **Shown at the left is the 10-meter boom extended upward from the Space Shuttle Orbiter payload bay**
  - 500-kg satellite "end mass"
  - 20-km conducting tether runs down the mast to a deployer in the payload bay
- **The tether deployed to 19.6 km before breaking…**

The TSS Mission (TSS-1R) Produced Electrodynamic (Drag) Thrust



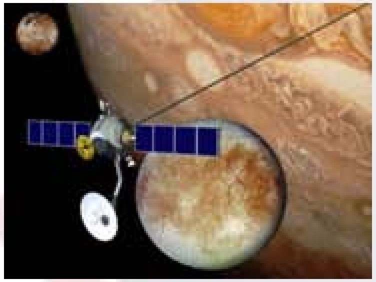
- Space Shuttle Orbiter based demonstration of electrodynamic tethers
- Prior to the break, TSS system generated ~3.5 kW power
- Electrodynamic drag on TSS tether/Orbiter system calculated to be ~0.4N
- New technology approach to current collection could significantly reduce system weight, cost and complexity

Small Expendable Deployer System (SEDS)

- SEDS-1 successfully deployed a 20-km tether from a Delta rocket in 1993
- SEDS-2 successfully deployed a 20-km tether from a Delta rocket in 1994
- Plasma Motor Generator (PMG) successfully deployed a 0.5 km tether from a Delta rocket in 1993
- Tether Physics and Survivability Experiment (TiPS) flew a 4-km tether in space for 10 years.

Diverse Interest in Tether Technology for Propulsion Applications

Propellantless Reboost of The International Space Station

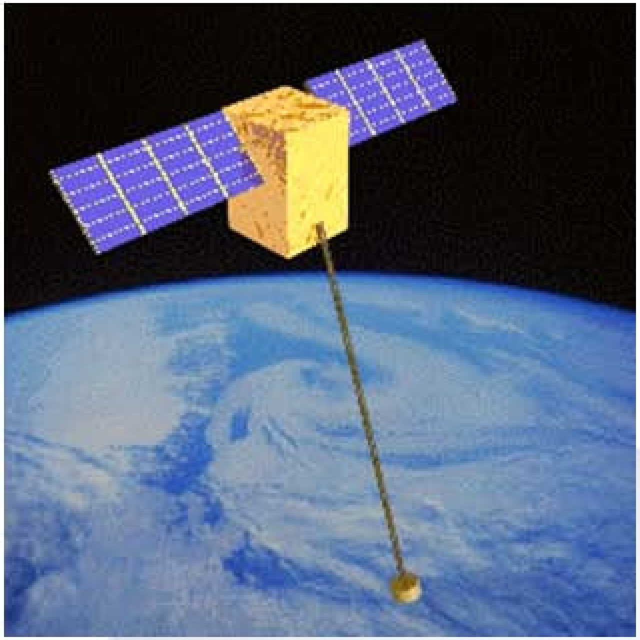


Electrodynamic Tethers for Propulsion and Power at Jupiter

Electrodynamic Tether Upper Stages

Deorbit

Electrodynamic End-of-Mission Deorbit



Terminator Tether Concept Proposed by Tethers Unlimited, Inc.

- Benefits
  - Increases efficiency of upper stages and the stationkeeping lifetime of orbiting spacecraft
  - Helps to reduce the orbital debris threat

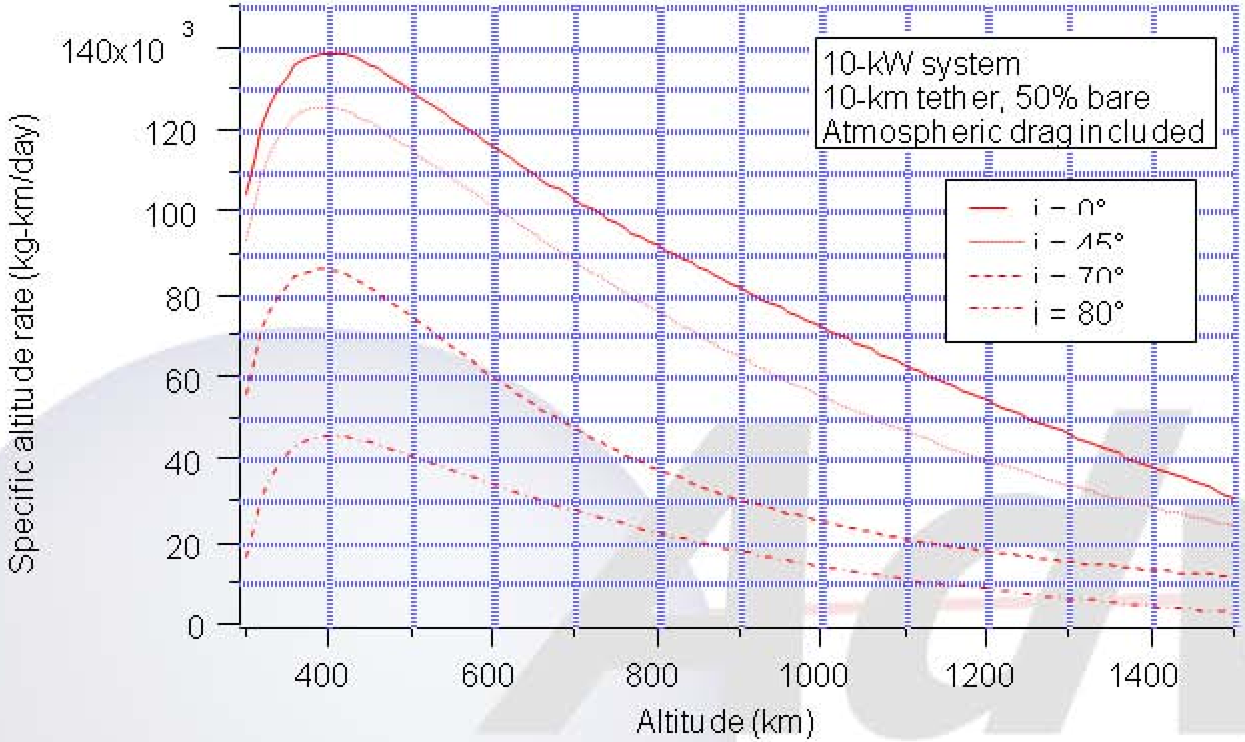
- **Simple tether and deployer on future upper stages and spacecraft for deorbit propulsion**
  - Spacecraft: No longer need to preserve onboard fuel for deorbit at end of life
  - Upper Stages: Allows all rocket fuel to be used for orbit insertion; results in higher efficiency system
- **Significant commercial interest in the technology for use on planned satellite telecommunications systems**
  - Commercial use being studied by Tethers Unlimited under the Small Business Innovative Research Program

Electrodynamic Tether Upper Stages

- Stage acquires payload from launch vehicle, delivers it to final orbit and deboosts to meet next launcher
- Can be used for altitude or inclination change
- No boost propellant is expended over many flights

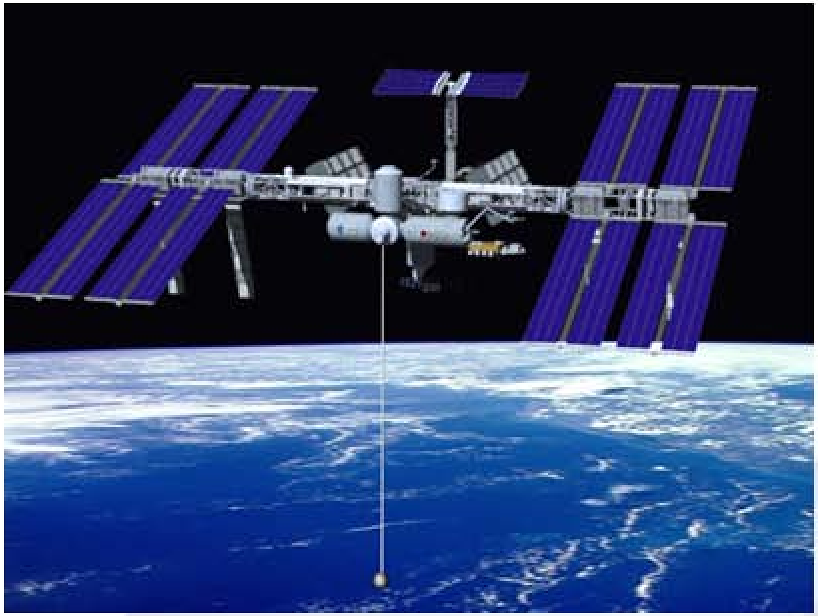
- Benefits
  – Fully *reusable* stage stationed in Low Earth Orbit
  – Requires *no propellant* and little resupply

Electrodynamic Tether Upper Stage Performance



- Divide by stage total mass (including payload) to determine rate of altitude change
- Example: A 1000 kg system could boost from 400 km to appx. 540 km in one day while in an equatorial orbit.

Electrodynamic Reboost of ISS

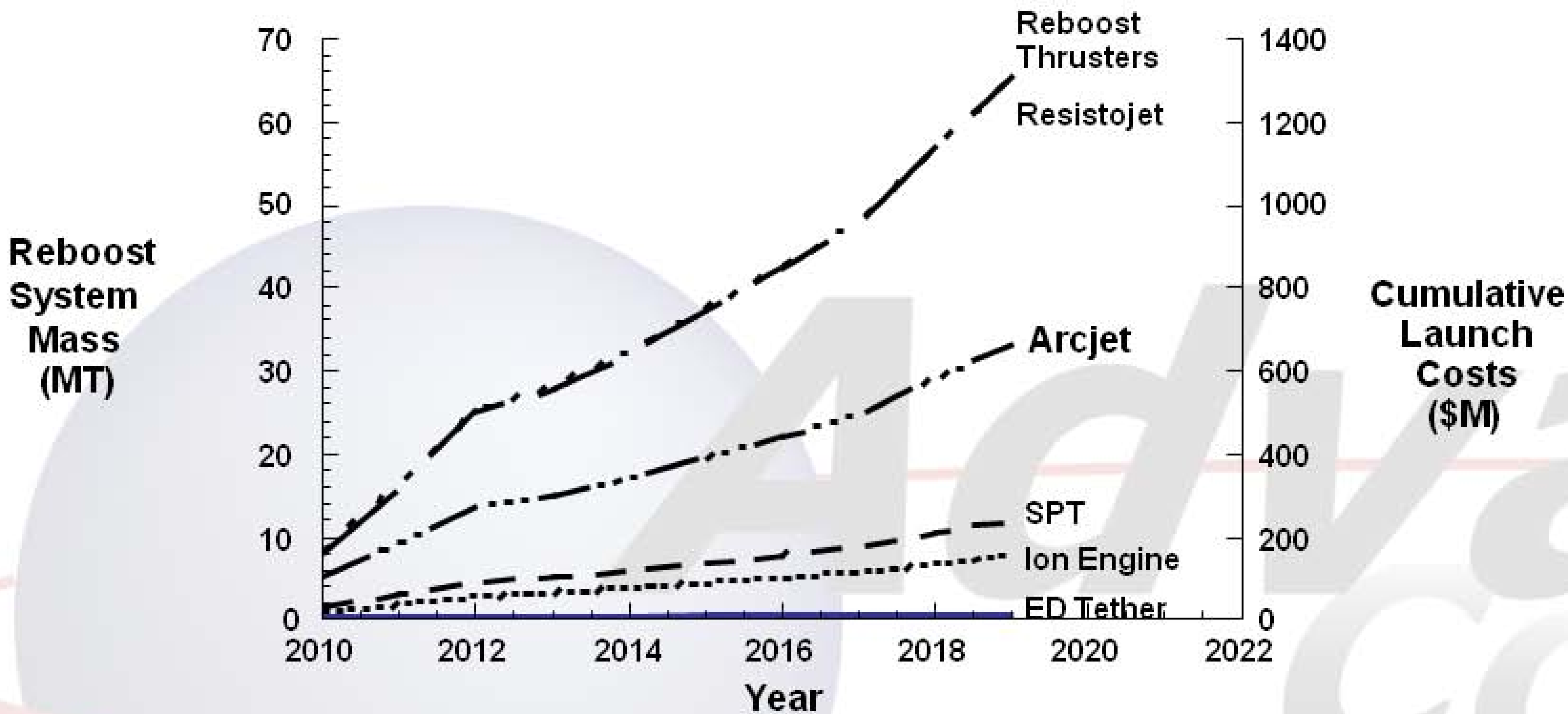


- **Tether**
  - Aluminum braided with Spectra
  - 7 kilometers length
  - 0.6 mm x 10 mm tape
- **Impacts Assessment**
  - Laboratory microgravity envelope shifted but still within prescribed guidelines
  - ISS center of mass shifted 4.5m
  - ~6 kW off-peak power required from ISS (No impact to ISS post-bus power users)
  - Some operational risk associated with tether use
- **This project is currently unfunded**

- Benefits to the ISS
  - System can potentially save 6000kg of propellant *per year*
  - Up to $2B in savings possible
  - Proposed system requires no propellant and little resupply

ED Tether Propulsion: Comparison to Competing Technologies

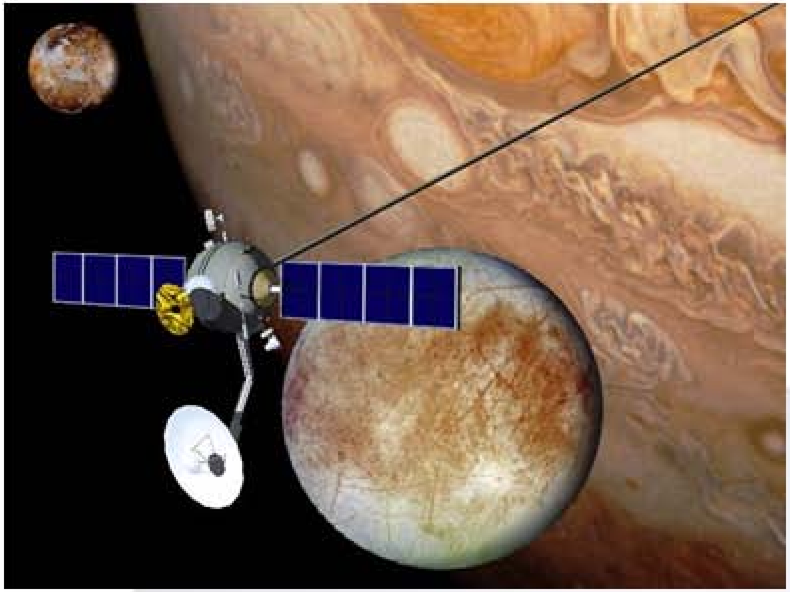
	ED Tether	Ion	SPT*	Arcjet	Resistojet	Bipropellant
Input Power, kW	5	5	5	5	1.2	0
Thrust, N	0.40	0.13	0.27	0.49	0.80	400
Isp, s	"□"	3800	1700	650	302	310
Efficiency	0.6	0.75	0.46	0.33	0.9	n/a
Lifetime, days	years	338	129	35	16	n/a
N/kW	0.08	0.03	0.05	0.10	0.66	n/a



Sources of data on EP:
Butler, GW, and Cassady, RJ, "Directions for Arcjet Technology Development," JPP, 12(6) 1996, pp. 1026-1034.
Oleson, SR, and Myers, RM, "Launch Vehicle and Power Level Impacts on Electric GEO Insertion," AIAA-96-2978, 32nd JPC, 1996.
Sources on data on ED tether:
ProSEDS Overview Presentation, 1/16/1997.

* Stationary Plasma Thruster

Jovian Electrodynamic Tether Propulsion & Power

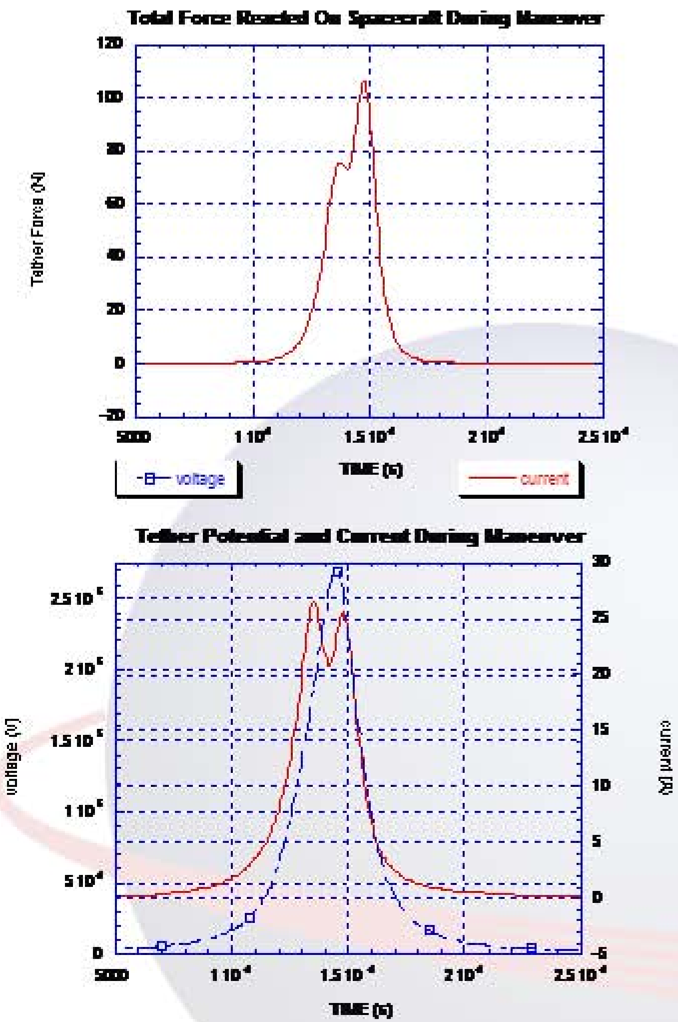


- Jupiter has a large and energetic magnetosphere ideally suited for electrodynamic tether operation
- The planet's rapid rotation produces a condition where a tether can produce power and raise orbit passively and simultaneously -- *lowering the orbit requires additional energy*!
- This project is currently unfunded

- Preliminary calculations (based on the latest data from Galileo) indicated the potential to provide ***megawatts*** of power for a tether <10 km long
- Orbit capture possible with 13-km tether

Tether Performance Parameters For Baseline Capture Maneuver

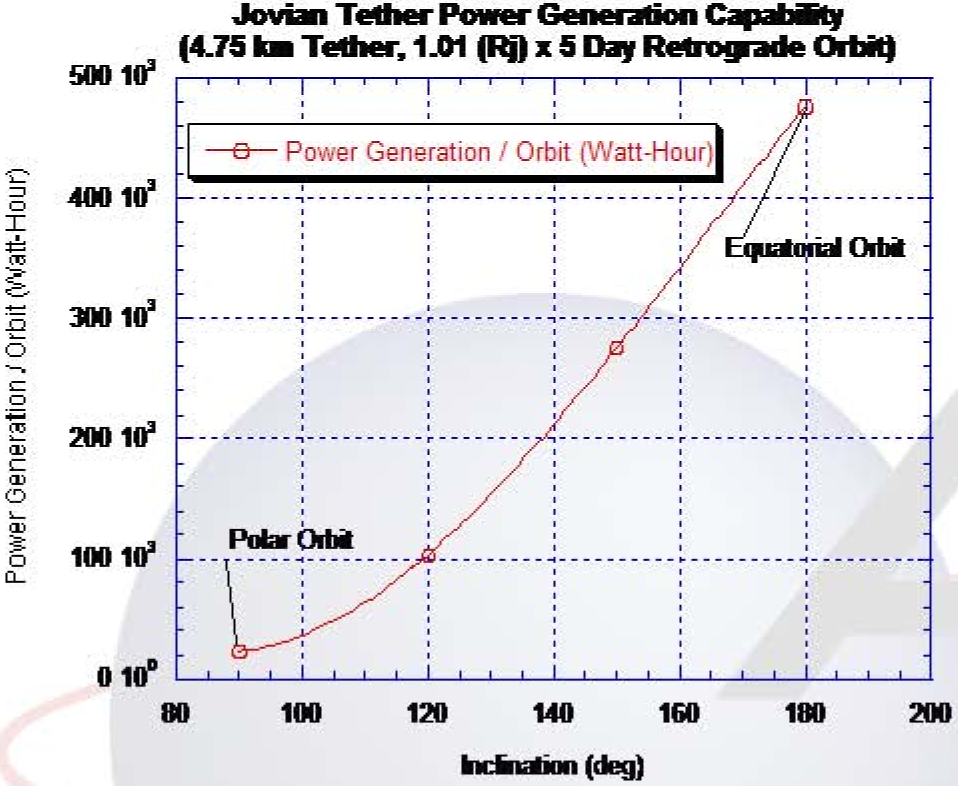
(For 1.05 Rj X 100 Days Initial Orbit)



Tether Design Characteristics

- Tether Length: 11 km
- Bare Wire Tether
- Average Power Over 100 Day Orbit 1731 (W)
- Peak Current 26.5 (A)
- Peak Power Produced 6.6 (MW)
- Peak Propulsive Drag Force 107 (N)
- Significant Reduction in Tether Length May Be Possible with Lower Perijove Radius

Jovian Tether Power Generation Performance*



- Typical Spacecraft Power Requirement
  - 180 Watts Continuous
  - 21,600 Watt-Hour/ Orbit
- 4.75 Km Tether Needed To Meet This Requirement in Polar Orbit
- Significantly Exceeds Requirement As Orbit Inclination Becomes More Equatorial
- Much Shorter Tether Length Required For Equatorial Inclination
- Rapid Charge Rate Power Storage Needed To Meet Continuous Power Requirements In Highly Elliptic Orbits.

* Applies to Radial Tether Orientation

A Japanese Test of Bare Wire Anode Tethers

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Tokyo Metropolitan Institute of Technology

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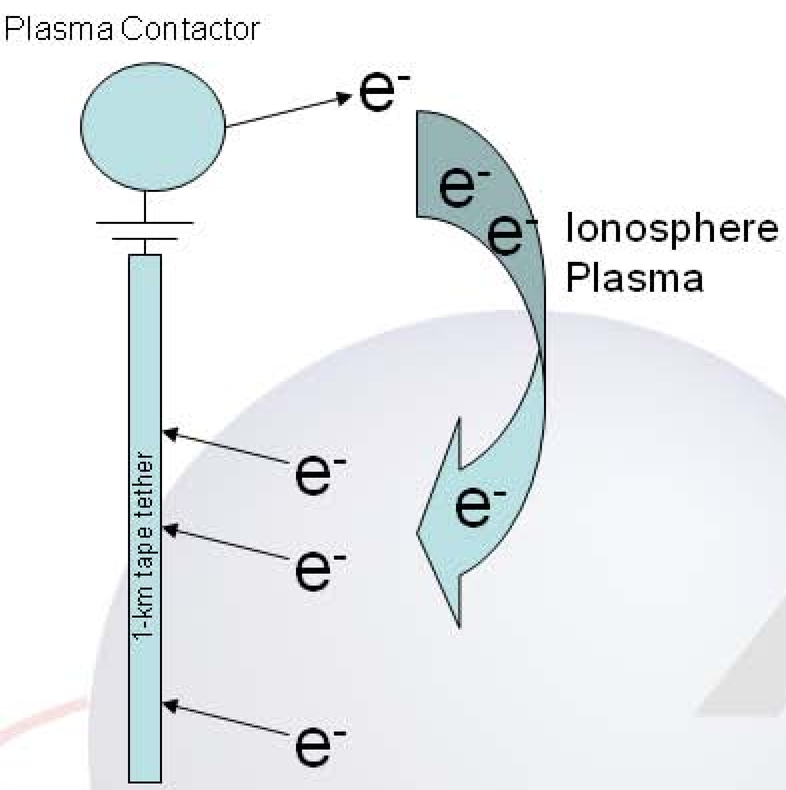
Universidad Politecnica de Madrid

Experiment Overview



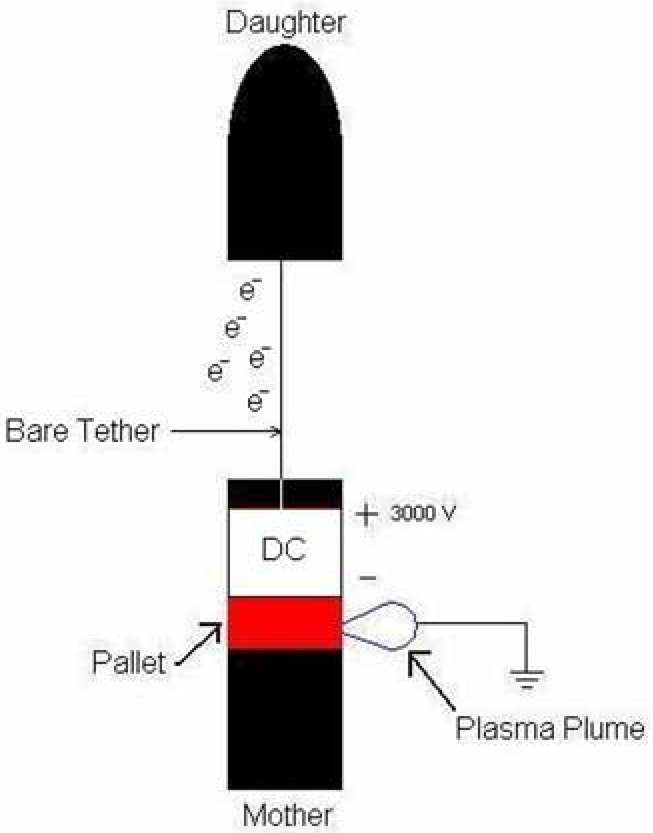
Testing OML Theory an active plasma contactor. (The tether is biased positive.)

- **What is the experiment?**
  - Primary payload on an S-520 Sounding Rocket planned for summer 2009 launch
  - 300-meter conducting tape (tether) will be deployed to collect ionospheric current along its length
- **What are the objectives?**
  - Demonstrate the deployment of a "bare" electrodynamic tape tether in space
  - Test Orbital Motion Limited (OML) theory of bare tether current collection in space
- **Status: In hardware development and scheduled for flight in the summer of 2009**

Engineering & Science Objectives

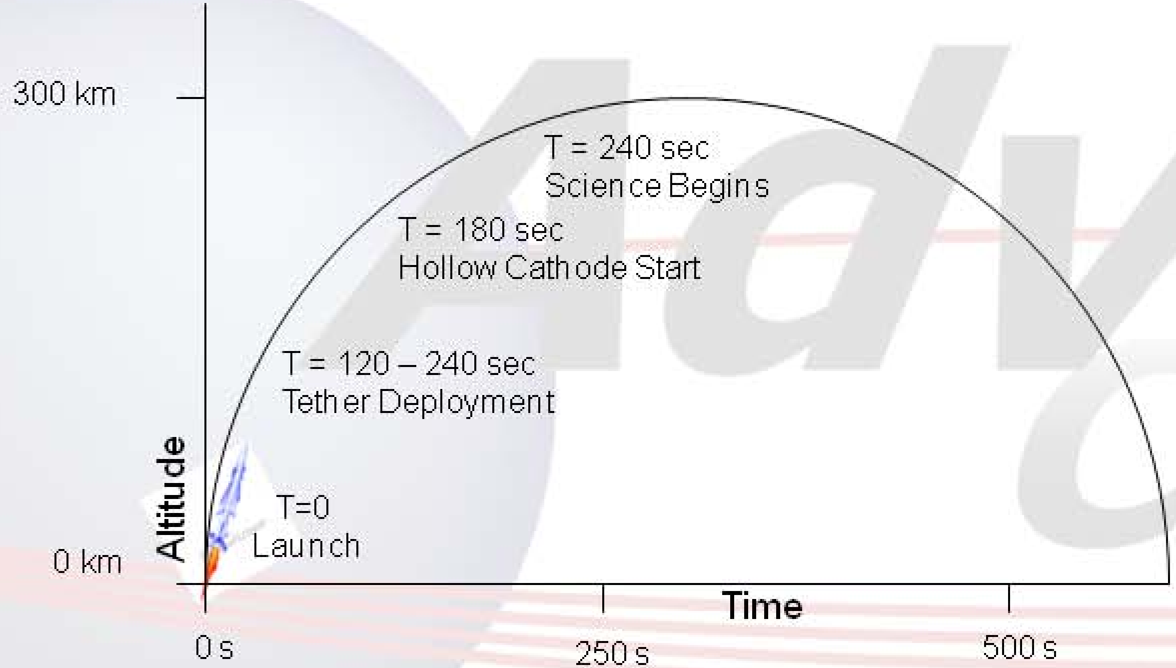
Objective	Comment
Fast deployment of a bare electrodynamic tether	Engineering: Deploy a bare, conductive tape tether in space
Fast ignition of a hollow cathode	Engineering: Ignite a hollow cathode in space for 180 seconds
Verification of electrodynamic tether operation in ionospheric plasma	Science: Eject electrons from an ignited hollow cathode and collect electrons by using a bare, electrodynamic tether
Verification of Orbit Motion Limited (OML) theory	Science: Measure electron collection by a positively-biased boom and a negatively-biased bare electrodynamic tether

Mother / Daughter Payload Configuration

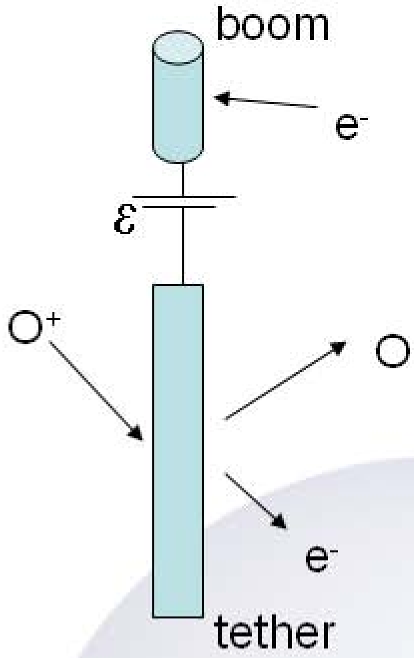


Mission Profile

- **Nominal sounding rocket profile up to separation of payloads (350-km apogee; 4 - 5 minutes in space)**
- **Deployment of conductive boom**
- **Deployment of tape tether by ejection of upper payload**
- **Begin Experiment:**
  - Negative terminal of power supply is connected to the tape. The positive terminal is connected to the boom
  - Positive terminal of the power supply is connected to the tape. The negative terminal is connected to the hollow cathode.
- **Re-entry**



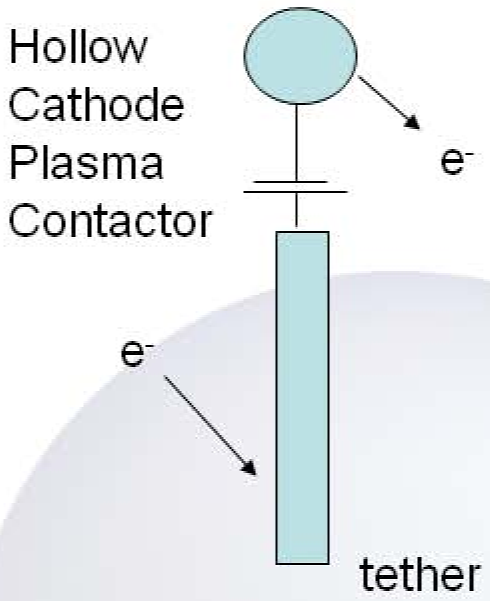
Testing OML / No Plasma Contactor



- **The positive terminal of the power supply is connected to the conductive boom with length L_b**
- **The negative terminal of the power supply is connected to the tape tether of width w_b**
- **Electrons collected by the boom cross the supply to the tape, where they leak at the rate of ion impacts plus secondary yield**
- **As the plasma density varies during the flight, six different voltages will be used every 2 seconds for a total of 12 seconds**
  - 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 kV
  - The maximum current expected is 0.1 Ampere

The boom and tether are biased positive and negative, respectively.

Testing OML With the Plasma Contactor



- The negative terminal of the power supply is connected to the hollow cathode
- The positive terminal of the power supply is connected to the tape tether
- Electrons collected by the tape tether cross the supply to be ejected by the hollow cathode
- The power supply sweeps across a range of values, from 100 V to 1500 V in 20 second intervals

Requires New Tether

- Reinforced aluminum tape tether
- 300-meters long
- 25-mm wide
- 0.05 mm thick

Developing a New Tether Was Not Easy

- **The tether experienced catastrophic arc discharge during partial vacuum testing**

Pre-test sample

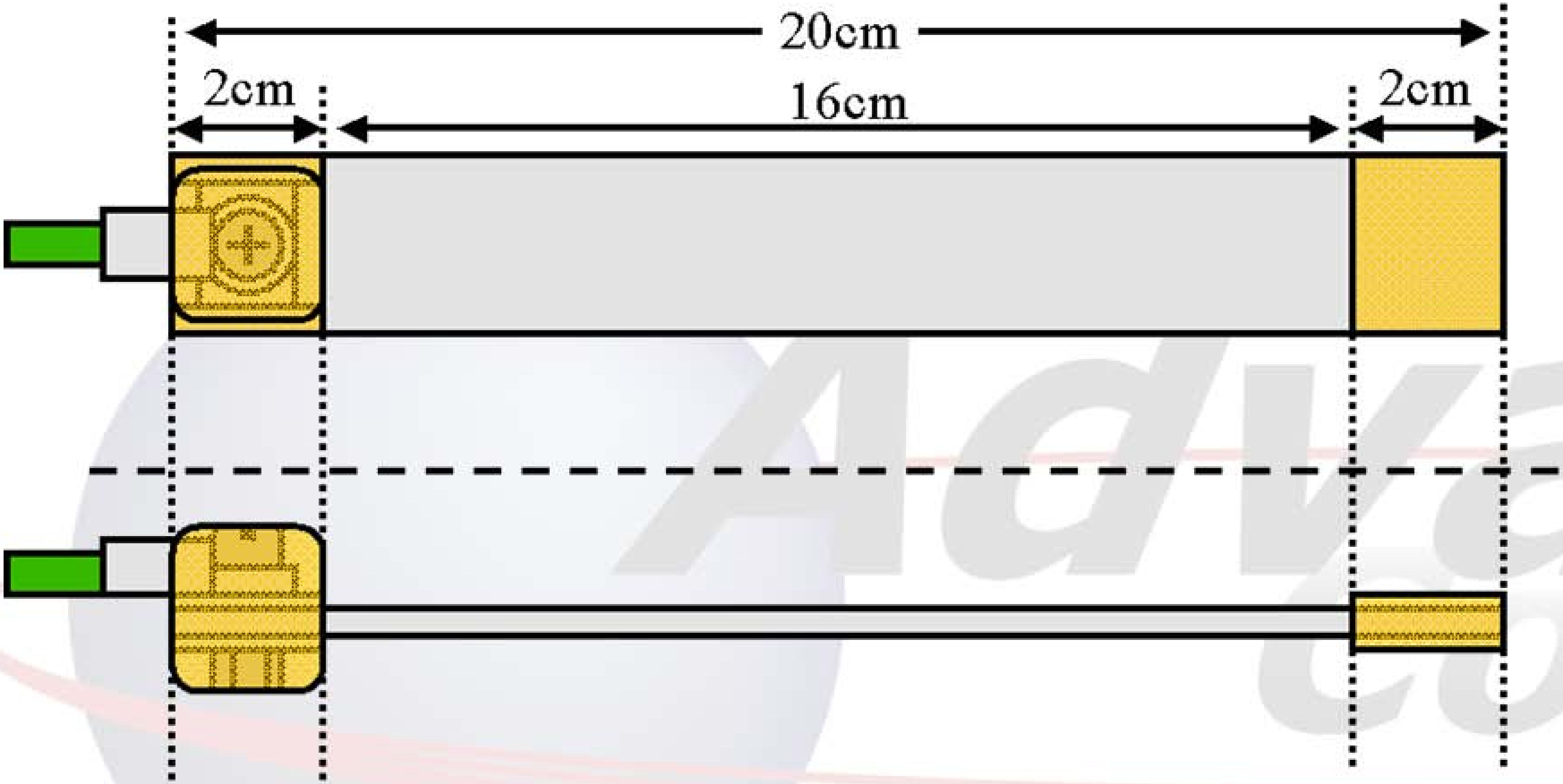
Post-test sample

Tether Test sample

- **Alpet #102510**
  - Width 25mm
  - PET resin (thickness 25μm) is sandwiched by aluminum of thickness 10μm

Tether Dimensions

Both ends of tape tether sample (length 20cm) are covered by Kapton® tape for 2cm and the part of 16mm is exposed in plasma.



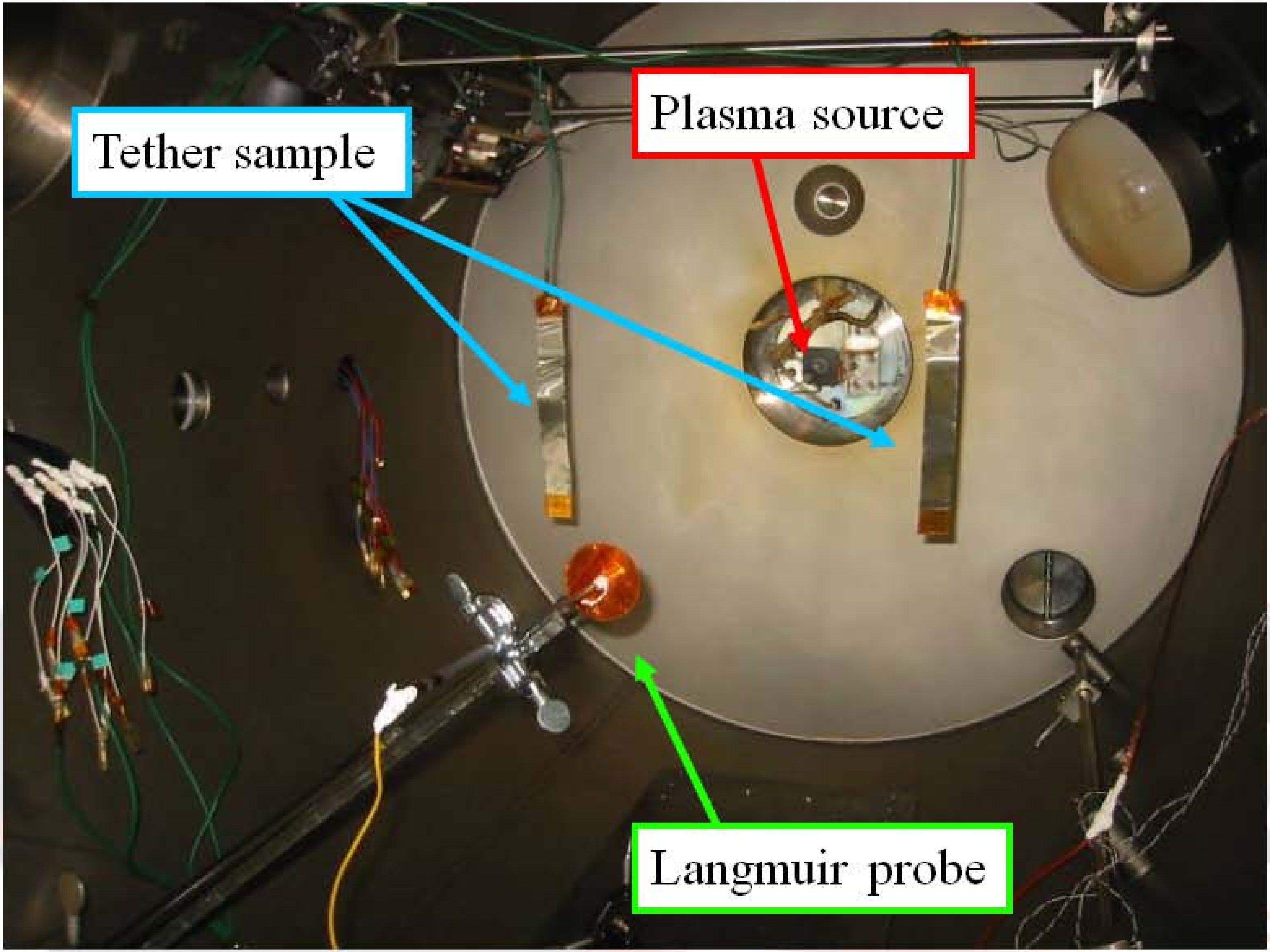
Tether Test Facility

Space Test Chamber
Kyousyu Inst. Of Tech.
Space environmental research center

Inside chamber (Plasma ignited)

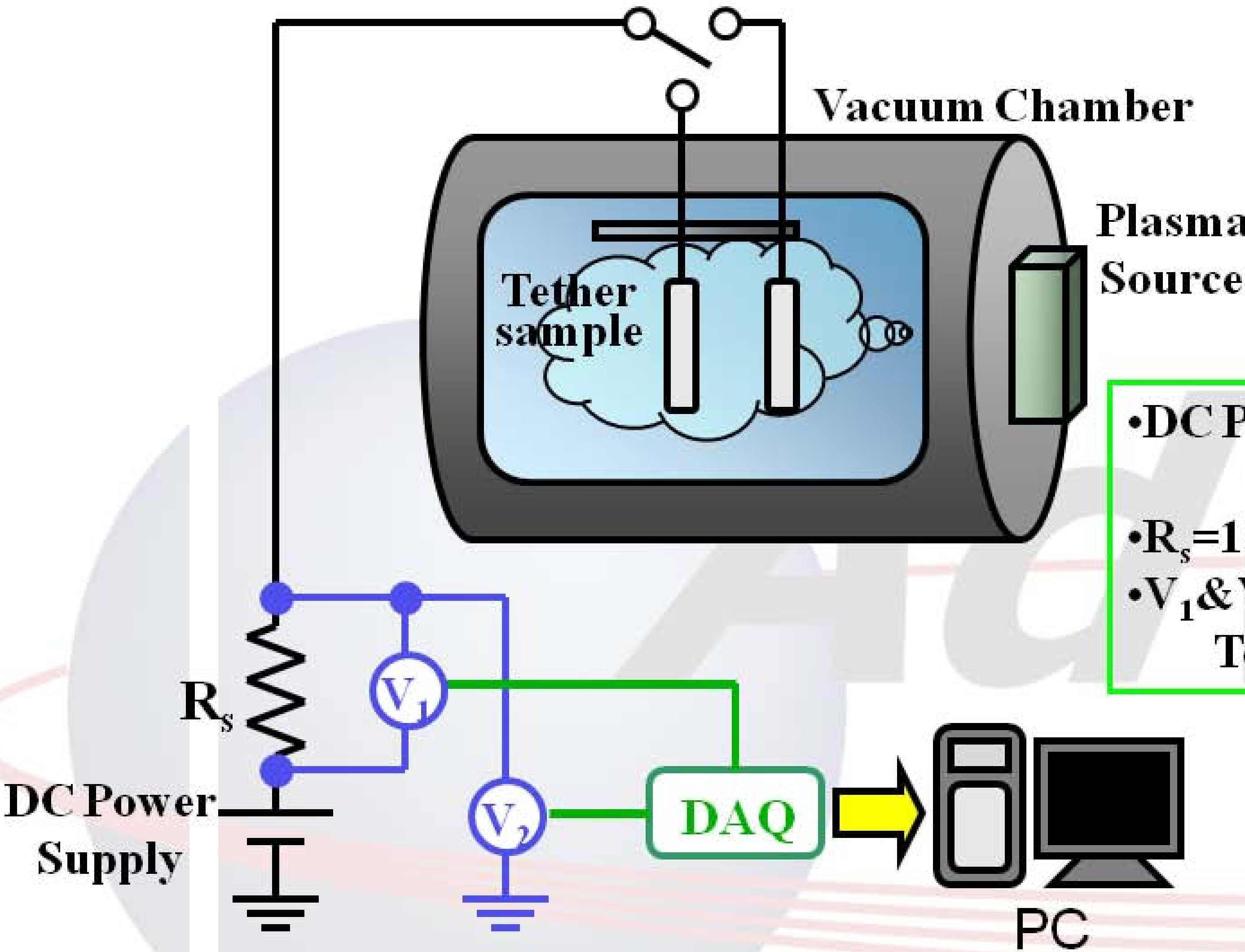
Pressure	4×10^{-3} Pa
Gas	xenon
Electron Density	$10^{11} – 10^{12}$ m^{-3}
Electron Temperature	1 – 4 eV

Inside chamber (with sample)



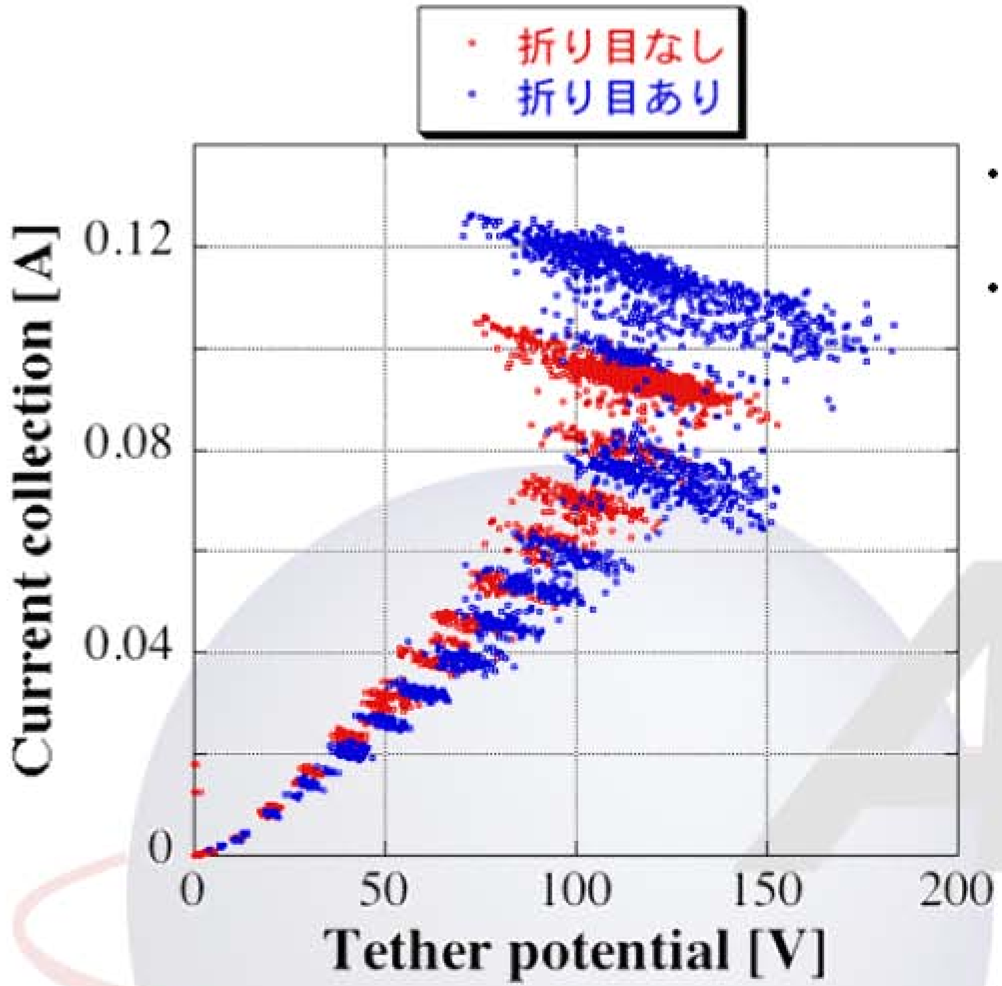
Positive bias test circuit

Positive bias test



- DC Power Supply: TMK1.0-50
- R_s=100kΩ or 23.5kΩ
- V_1&V_2: Tektronix P5200

Electron collection performance



Red: with no crease
Blue: with crease

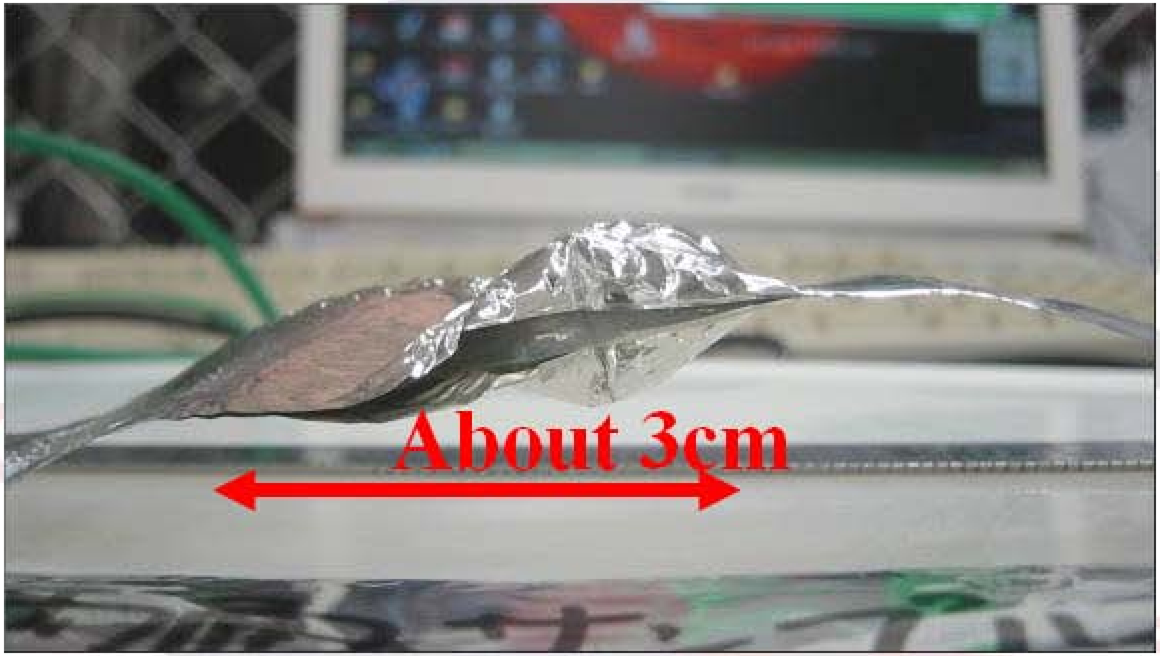
- **Tested for tether voltage in the range 0V - 120V**
- **Test sample deformed and burst at 120V input , 90mA/m in electron collection.**
  - Tested sample is shown in the next page

Deformed sample (after the positive bias test)

- **Electron collection at 120V, 90mA/m**
- **Little increase in chamber inner pressure**

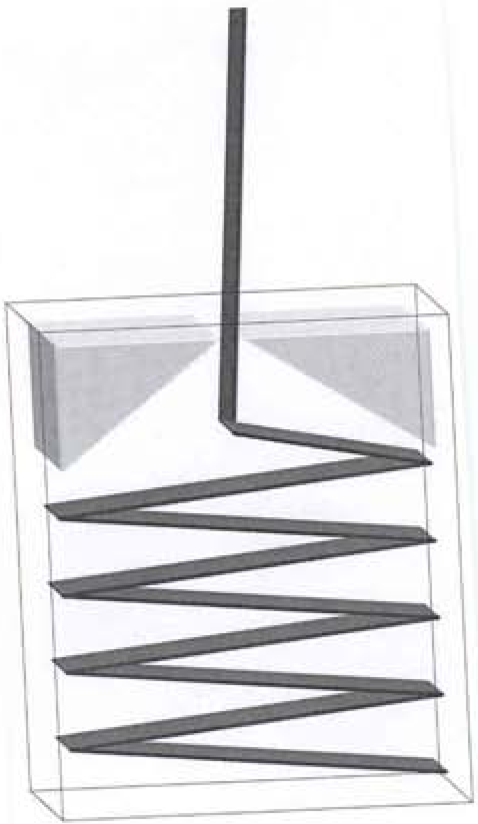
  From about 3.0x10^{-5}[Torr] to about 3.4x10^{-5}[Torr]

  - Generated gas is supposed to be air contained between the film
  - Temperature of the sample is more than 120°C



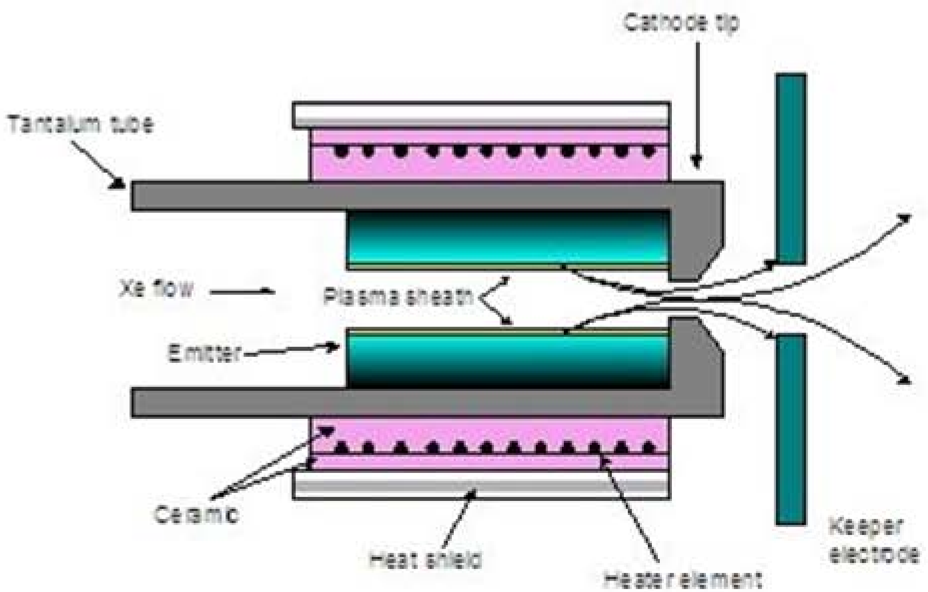
Requires New Tether Deployer

- **Spring ejects the endmass; onboard gas jet maintains deployment**
- **Tape tether is pulled from a box at 4 m/s**
- **Full deployment is expected at T = 120 seconds**
- **Braking is accomplished by applying a coating to the last several meters of the tether to increase deployment friction**

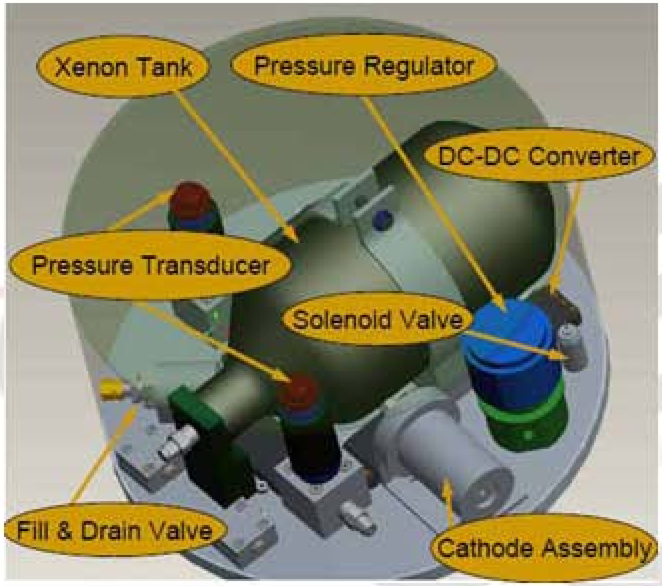


Note: NRL developed a tape tether deployer that was to be demonstrated by the ATEx experiment in 1999. The experiment was terminated before full deployment.

Requires New Plasma Contactor



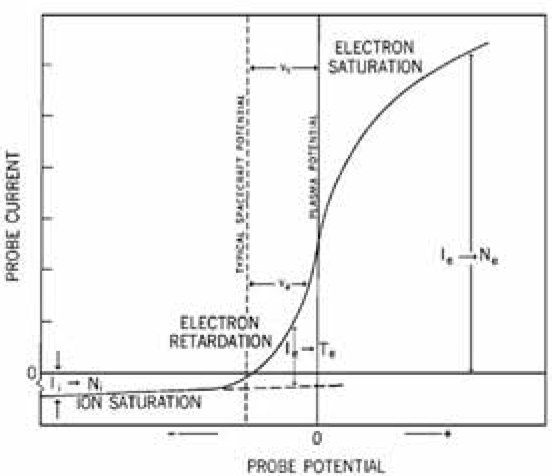
- **Colorado State University is developing a fast-starting hollow cathode plasma contactor for the experiment**



Plasma contactor subsystem layout.

Note: The hollow cathode plasma contactor developed for the ProSEDS experiment cannot be used due to its power and conditioning requirements.

Preliminary Instrument Listing



Sample Langmuir Probe data

- **Langmuir Probes: plasma diagnostics (electron temperature, density and plasma potential)**
- **3-Axis Magnetometer: measurement of local magnetic field**
- **Accelerometers: engineering data**
- **Ammeter: measures the current at the onboard power supply**

ProSEDS endmass' magnetometer

Spacecraft accelerometer

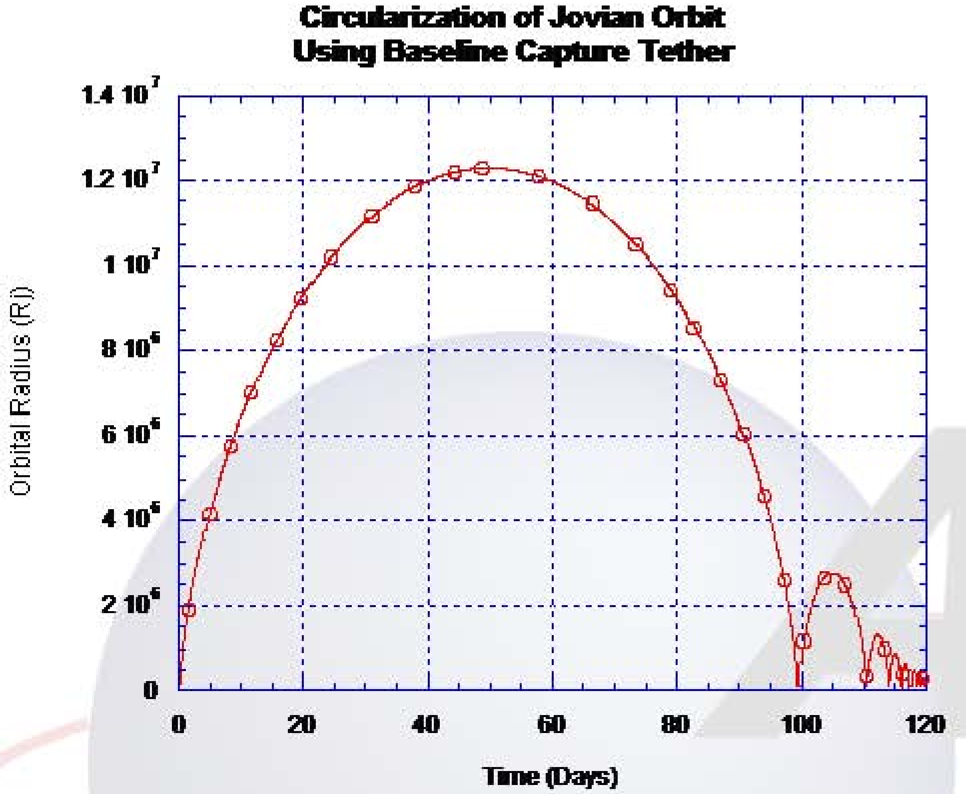
The Team

Les Johnson | Juan Sanmartin | Hiro Fujii

The full team – including students

Supplemental Information

Orbit Circularization Using Capture Tether



• Capture Tether Can Reduce Apojove to Any Desired Altitude with no Propellant or Additional Weight Penalty.

• A Projected "Radio Science Observer Mission"* Orbit (1.05Rj X 5 Days) can be Established in Approximately 110 Days From Initial Fly-By.

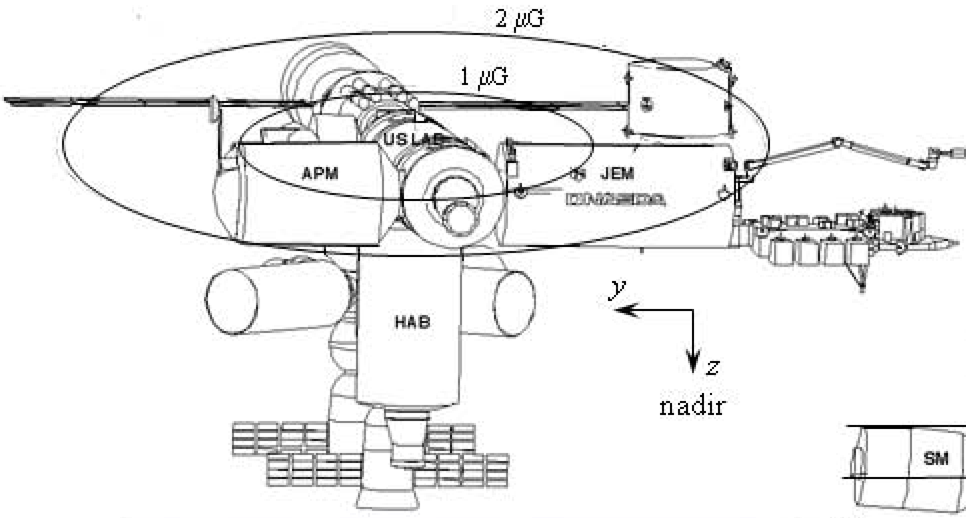
- •100 of 110 days are in first orbit (continuous thrust)
- •Continuous thrust for remaining 10 days establishes orbit

•Propellant Weight Savings of ~ 139.6 kg Assuming 340 kg Spacecraft and Isp = 330 s

*Jupiter Close Polar Orbiters: Preliminary Mission Studies, Outer Planets Science Working Group Meeting, Sept. 26, 1995

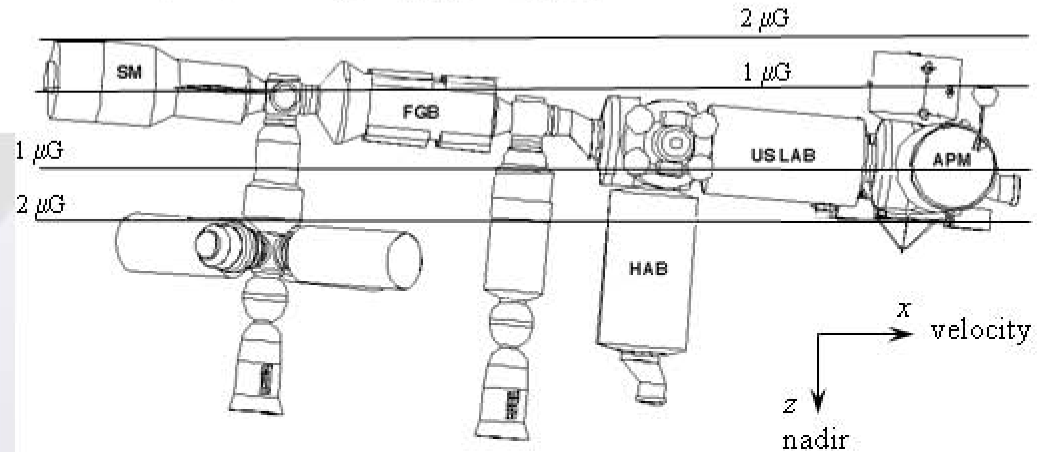
ISS Microgravity Environment Impact

Quasi-Steady Accelerations at Assembly Complete (without tether)



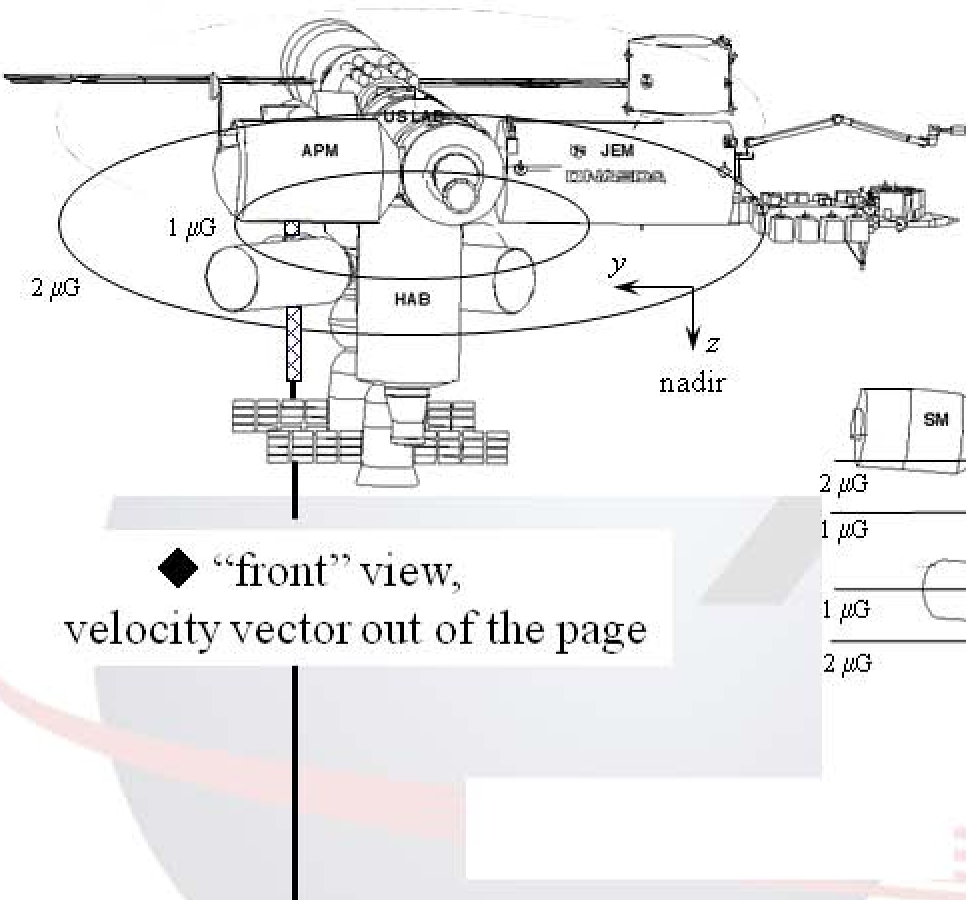
- "front" view (velocity vector out of the page)

- "side" view



ISS Microgravity Environment Lowered By Tether

Quasi-Steady Accelerations at Assembly Complete (with tether)



◆ "front" view, velocity vector out of the page

◆ "side" view