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Advanced Energy Conversion Engineering

Solar Wind and Space Environment Utilization

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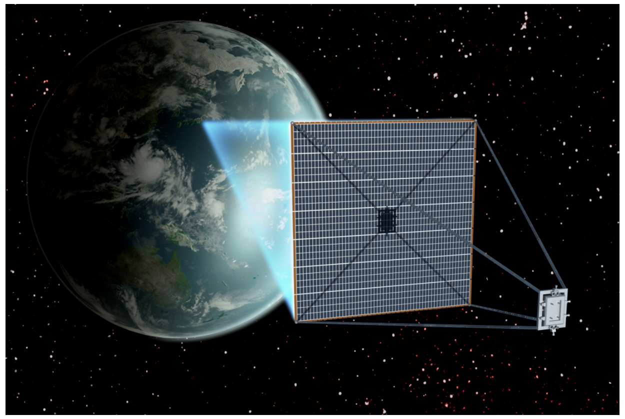
Outline

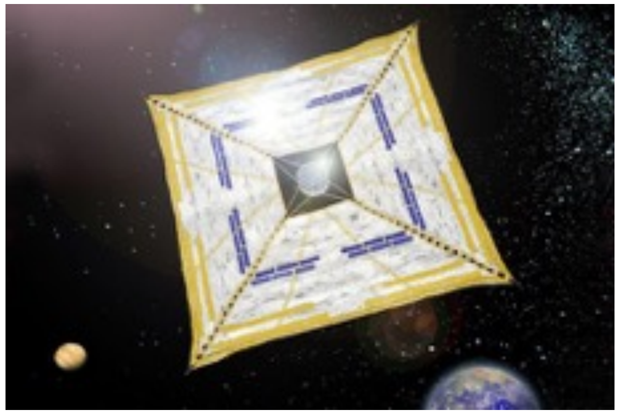
- Resources in Space
- Solar Wind Utilization
  - Magnetic Sail
  - Electric Sail
- LEO Environment Utilization
  - Magnetic Plasma Deorbit (MPD)
  - Air-breathing Electric Propulsion
- Summary of the Lecture

Resources Available in Space

- Solar Light Power

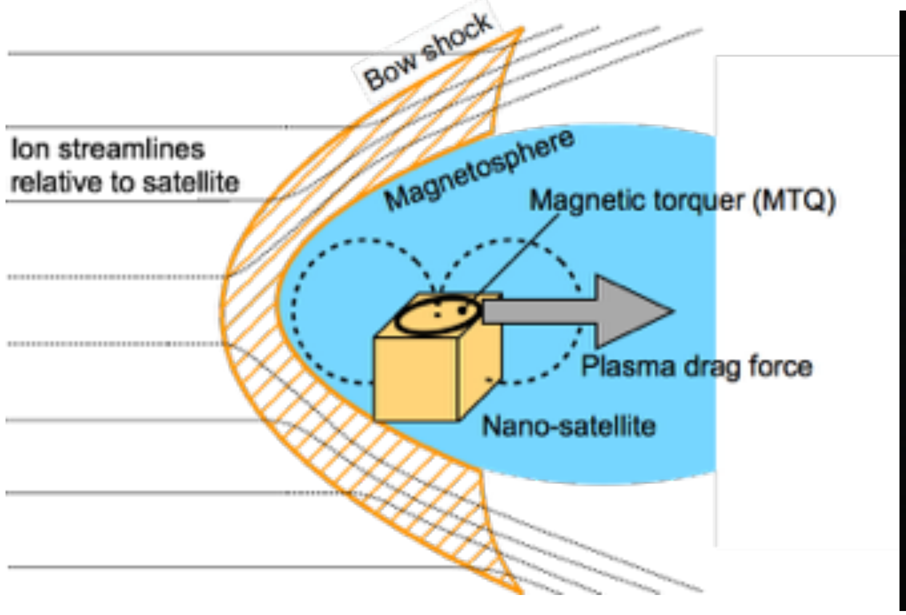


Solar power satellite

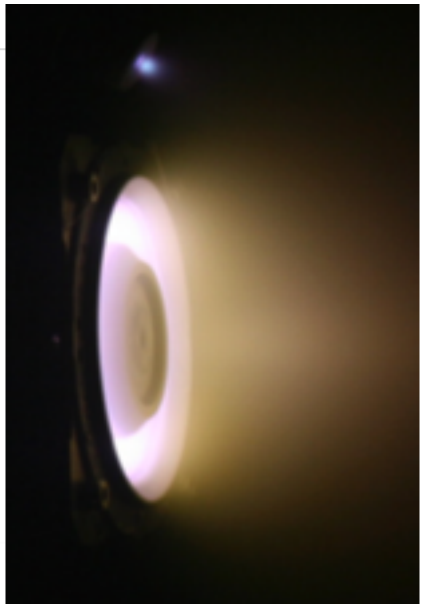


Solar sail propulsion

- LEO Environment



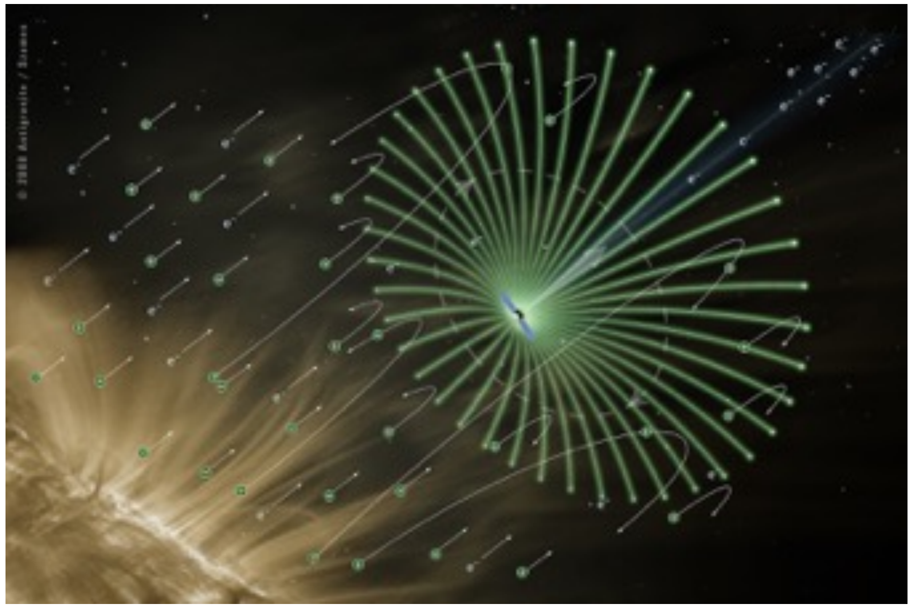
Magnetic plasma deorbit



Air-breathing EP

- Solar Wind

Magnetic sail propulsion



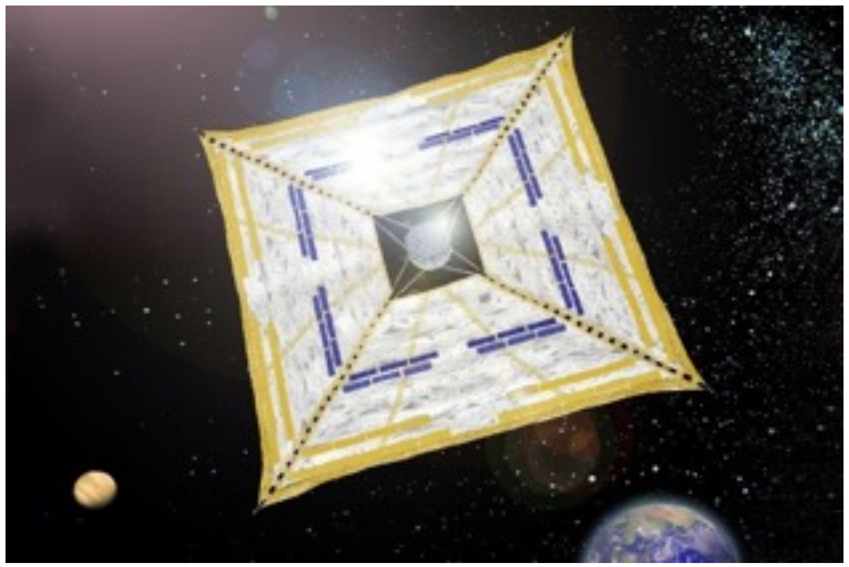
Electric sail propulsion

Solar Wind Utilization

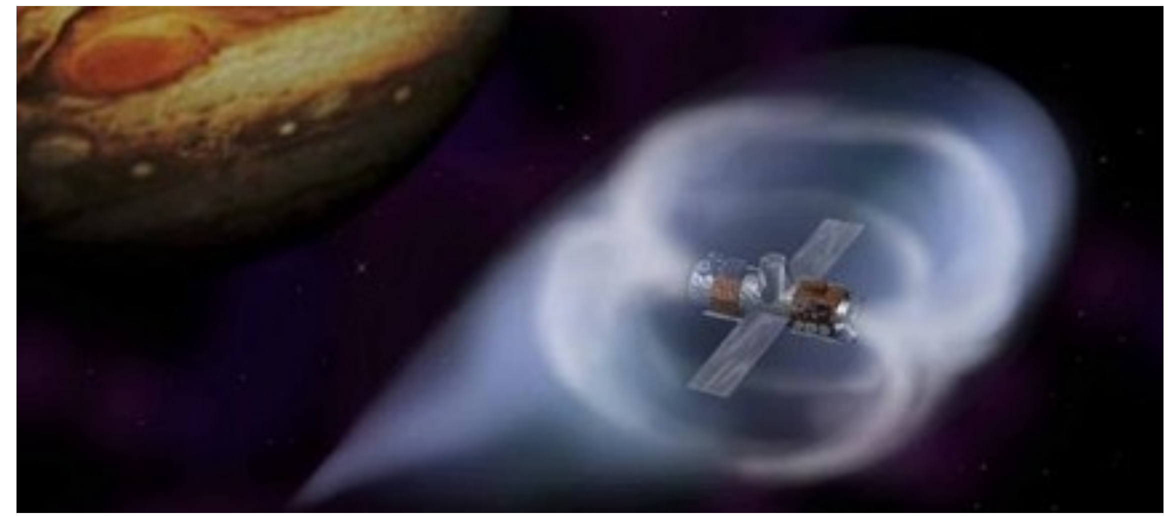
- Magnetic Sail (Magsail)
- Electric Sail

Types of Sail Propulsion

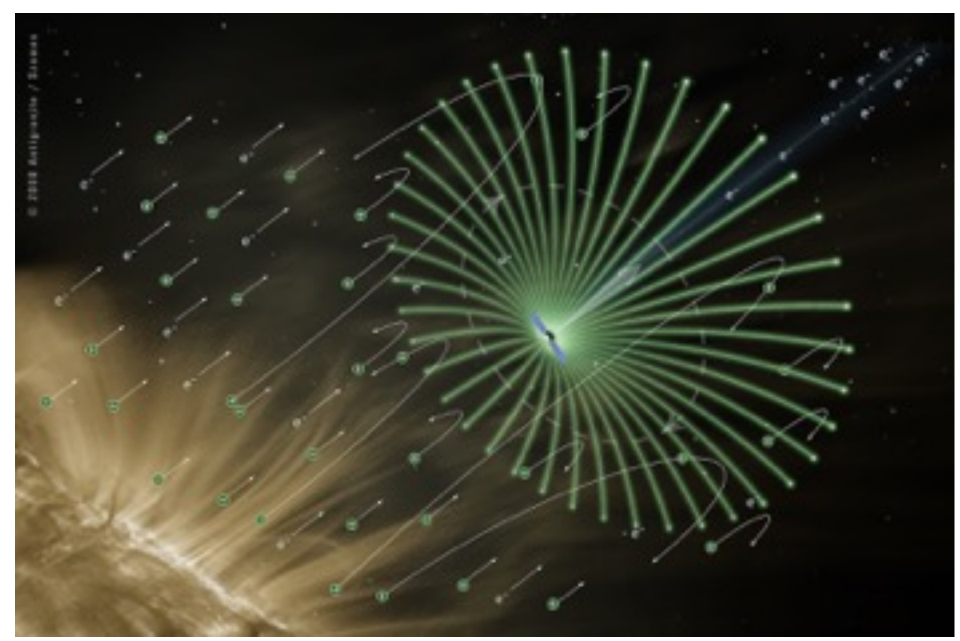
- Solar Light Sail
  - Reflection of **solar light**



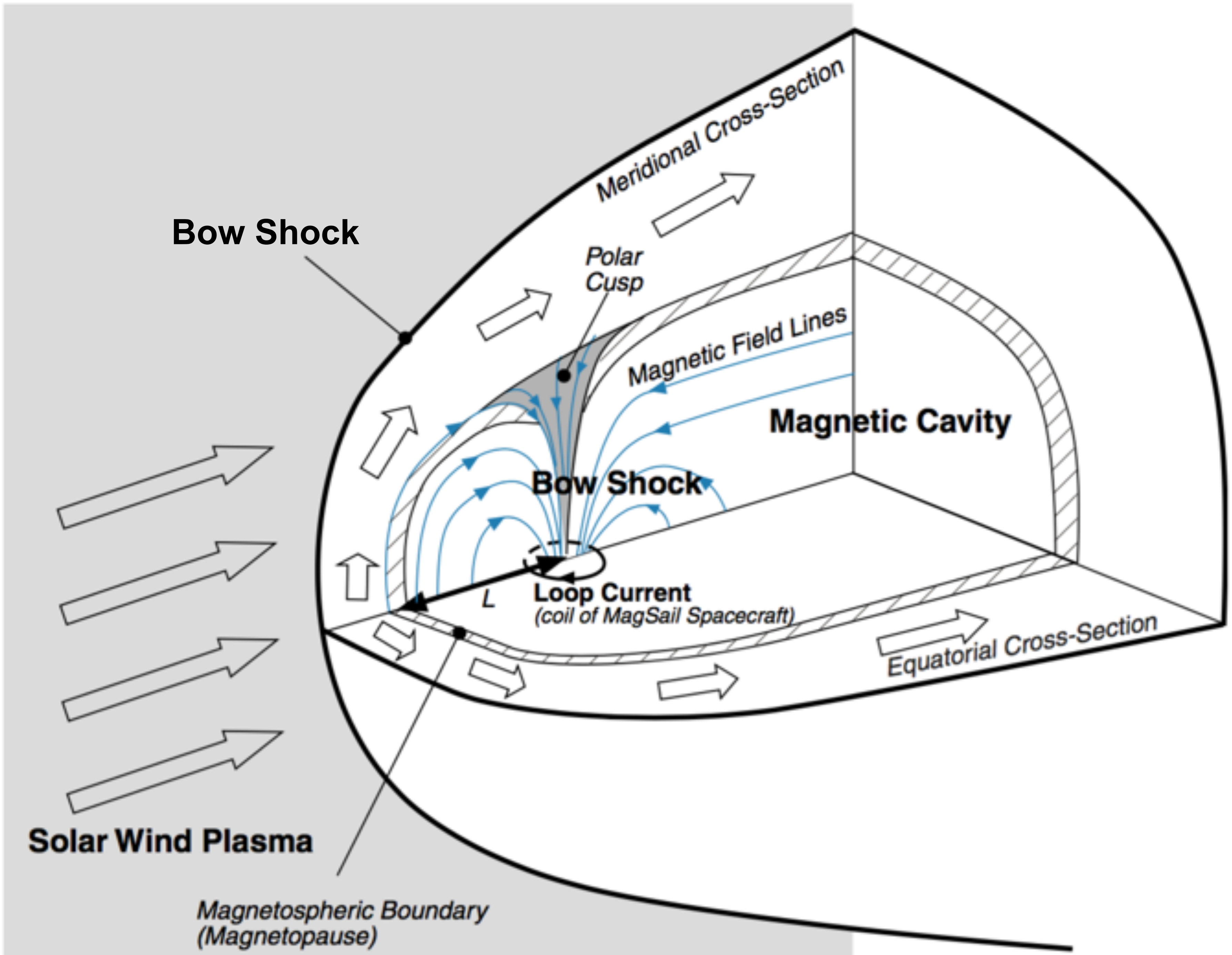
- Magnetic Sail
  - Reflection/deflection of **solar wind** (plasma flow) by using magnetic field



- Electric Sail
  - Reflection/deflection of **solar wind** by using high voltage tethers



Magnetic Sail Principle



Solar wind plasma flow around the satellite magnetic field[1]

[1]Funaki et al., Astrophys. Space Sci. 307 (2007).

Solar Wind Properties

Average solar wind parameters at 1 AU[1]

	Slow wind	Fast wind
Flow speed	250 - 400 km/s	400 - 800 km/s
Proton (H^+) density	10.7×10^6 m^{-3}	3.0×10^6 m^{-3}
Proton temperature	3.4×10^4 K	2.3×10^5 K
Electron temperature	1.3×10^5 K	1.0×10^5 K

- Dynamic pressure of a solar wind (H^+ ion flow) at 1 AU

$$P_{\mathrm{sw}} = \frac{1}{2} m_{\mathrm{i}} n_{\mathrm{i}} u_{\mathrm{i}}^2 = \frac{1}{2}\left(1.67 \times 10^{-27} \cdot 5.0 \times 10^6\right) \cdot \left(5.0 \times 10^5\right)^2$$

$$\sim 1 \ \mathrm{nN/m^2}$$

- Pressure of solar sail on a flat perfect reflector

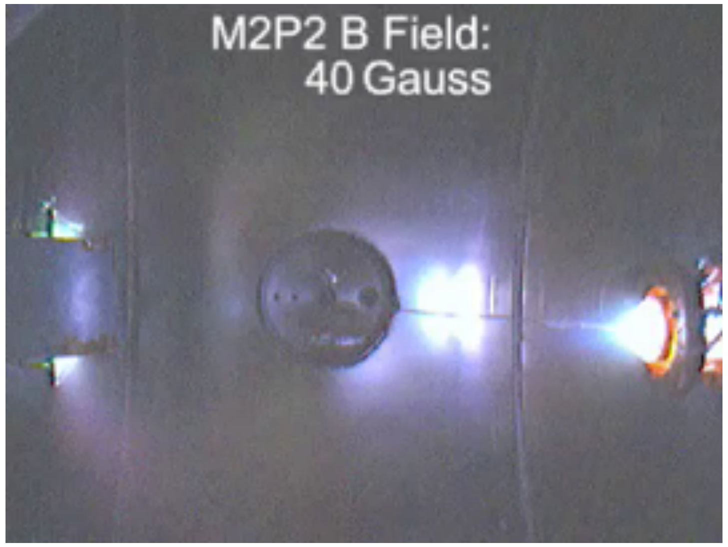
$$P_{\mathrm{sl}} = 9.12 \ \mu\mathrm{N/m^2}$$

Magnetic sail must deflect much larger area than solar sail

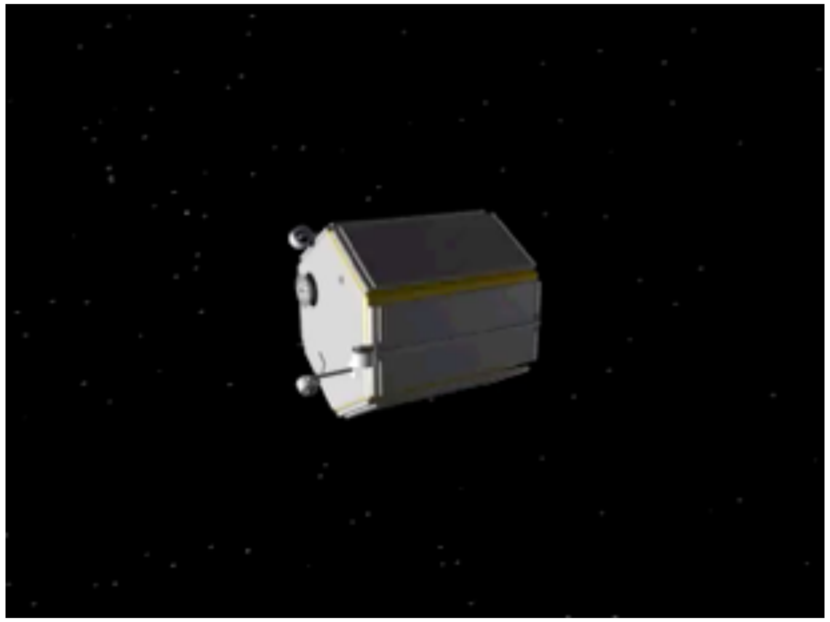
[1]Solar Wind: Global Properties, Encyclopedia of Astronomy and Astrophysics.

History and Status of Magsail Research

- Zubrin and Andrew proposed the Magnetic sail (Magsail) for earth escape and interplanetary travel in 1991
- Due to technical issues, Magsail has never flown in space
- In 2001, Winglee started Mini-magnetospheric plasma propulsion (M2P2)
- From 2006, JAXA and Japanese universities continue theoretical and experimental investigations on Magsail



Experiment of magnetosphere inflation[2]



Artist animation of M2P2 deployment[2]

[1]Zubrin and Andrews, J. of Spacecraft and Rockets 28 (1991).

[2]University of Washington, Winglee's Lab. Webpage.

Theory of Magnetic Sail

Plasma drag force:

$$F = C_\mathrm{d} \frac{1}{2} \rho u_\mathrm{sw}^2 S$$

Characteristic area:

$$S = \pi L^2$$

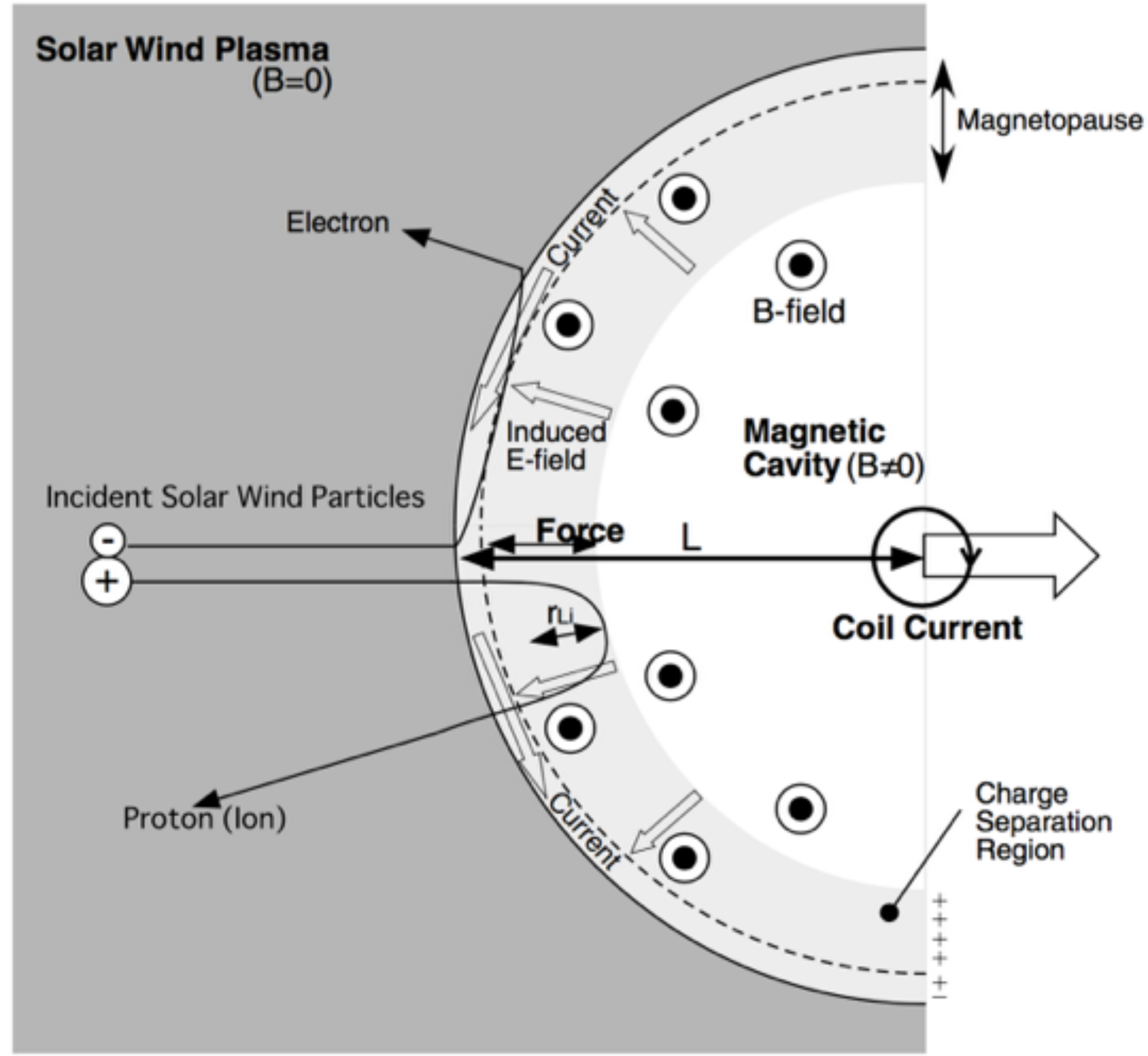
Balance of plasma pressure and magnetic pressure:

$$n_\mathrm{i} m_\mathrm{i} u_\mathrm{sw}^2 = \frac{(2B_\mathrm{mp})^2}{2\mu_0}$$

$$B_\mathrm{mp} = \frac{M_\mathrm{d}}{4\pi L^3}$$

Characteristic length:

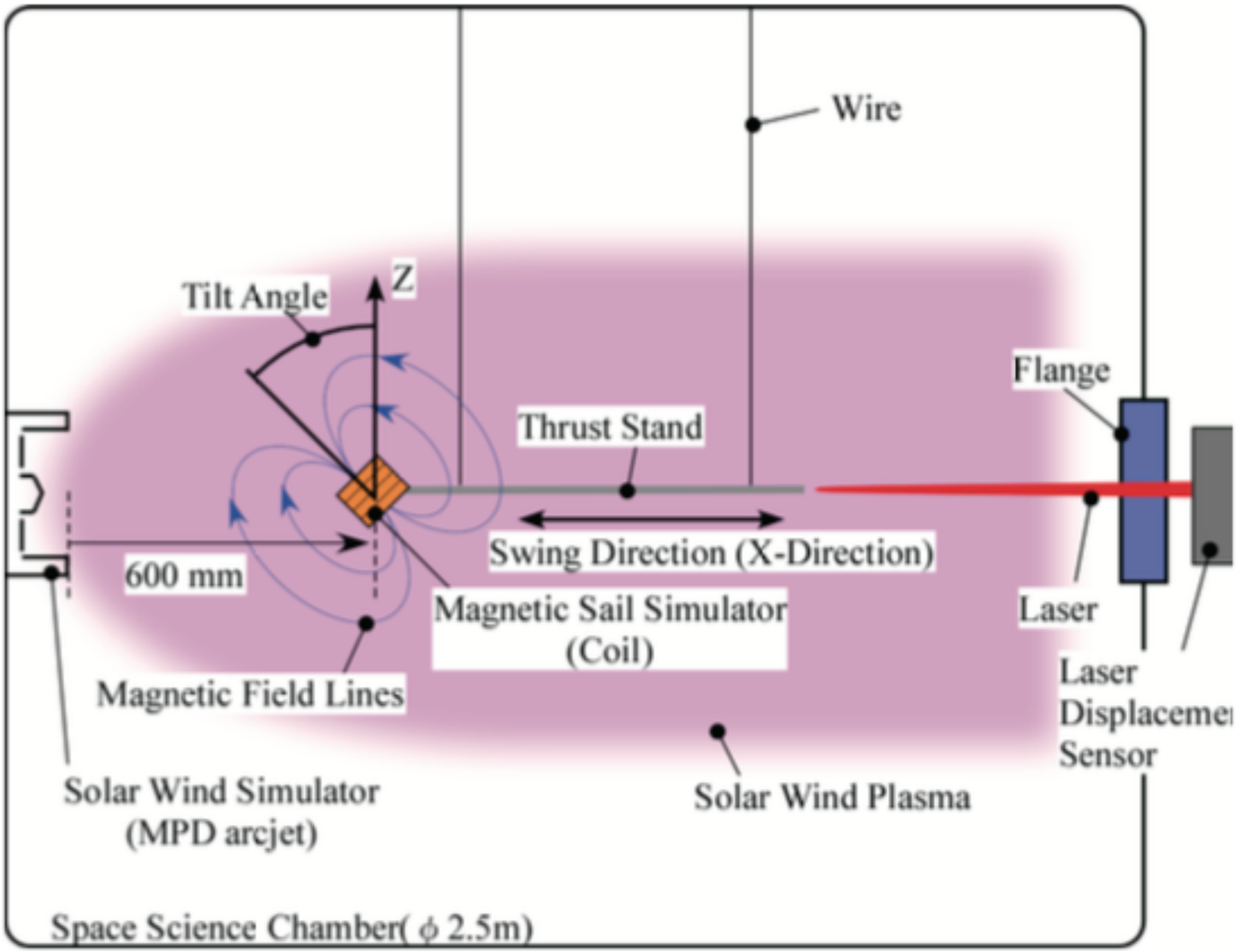
$$L = \left(\frac{M_\mathrm{d}^2}{8\mu_0 \pi^2 n_\mathrm{i} m_\mathrm{i} u_\mathrm{sw}^2} \right)^{1/6}$$



Structure of magnetosphere[2]

[1]Funaki et al., Astrophys. Space Sci. 307 (2007).

Experiment of Magnetic Sail



Setup of Magnetic Sail Experiment[1]

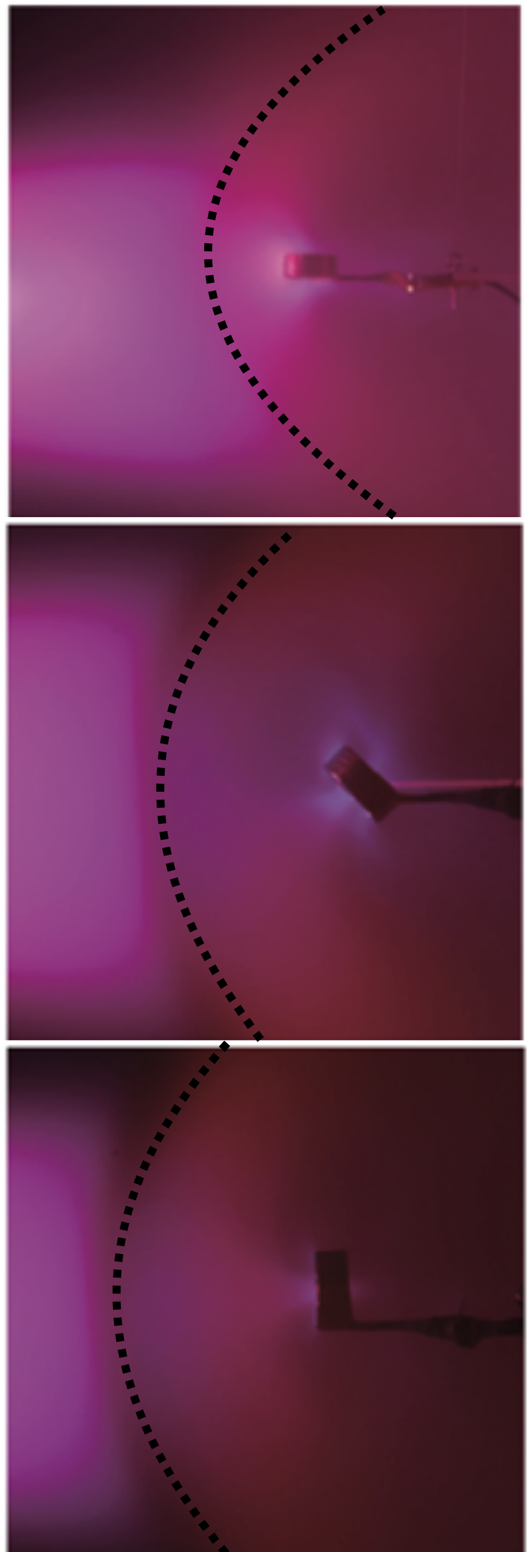
[1]Ueno et al., Trans. JSASS Aerospace Tech. Japan 10 (2012)

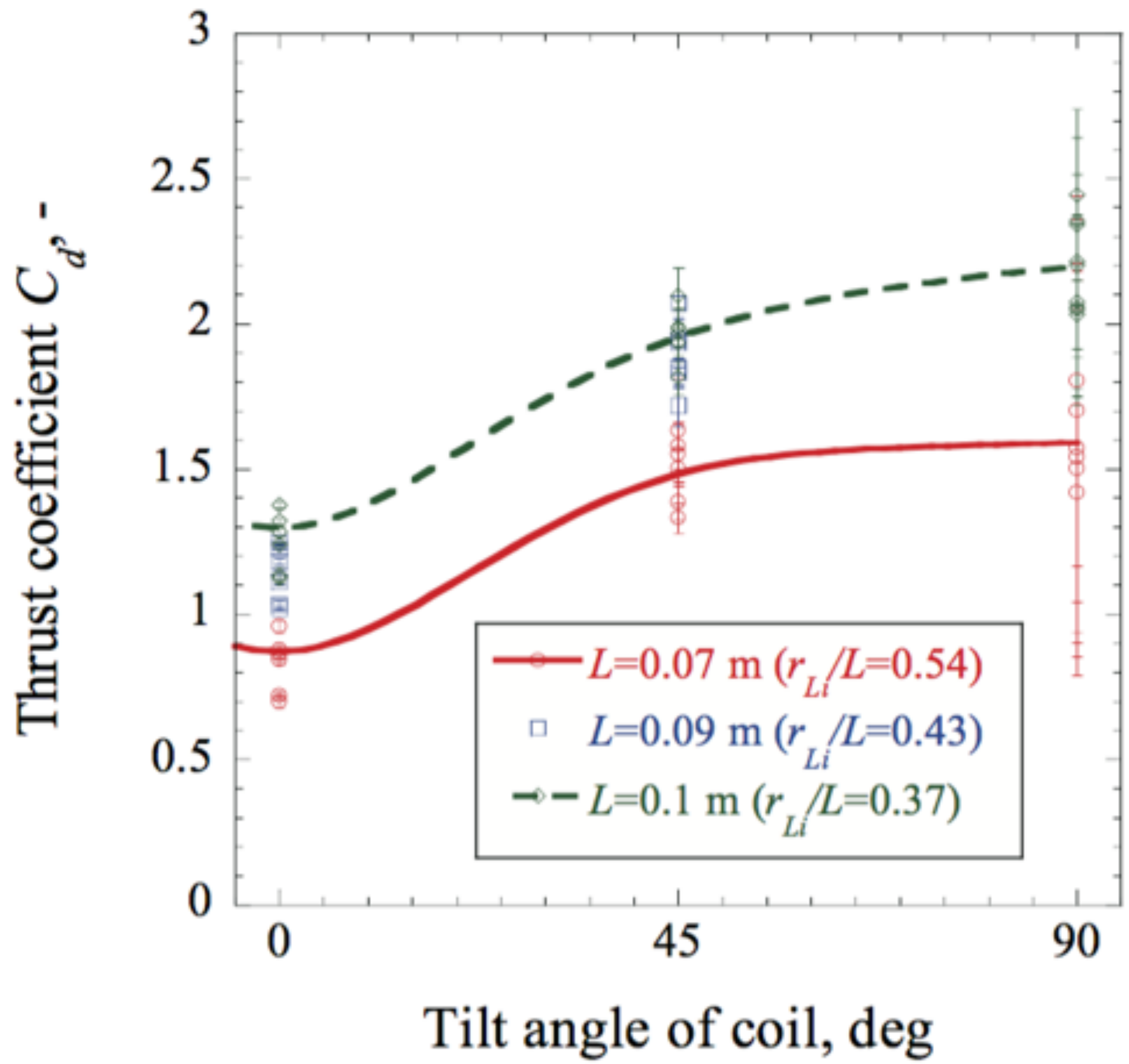
Thrust Measurement for Various Coil Angles

Tilt angle
0 deg

Tilt angle
45 deg

Tilt angle
90 deg





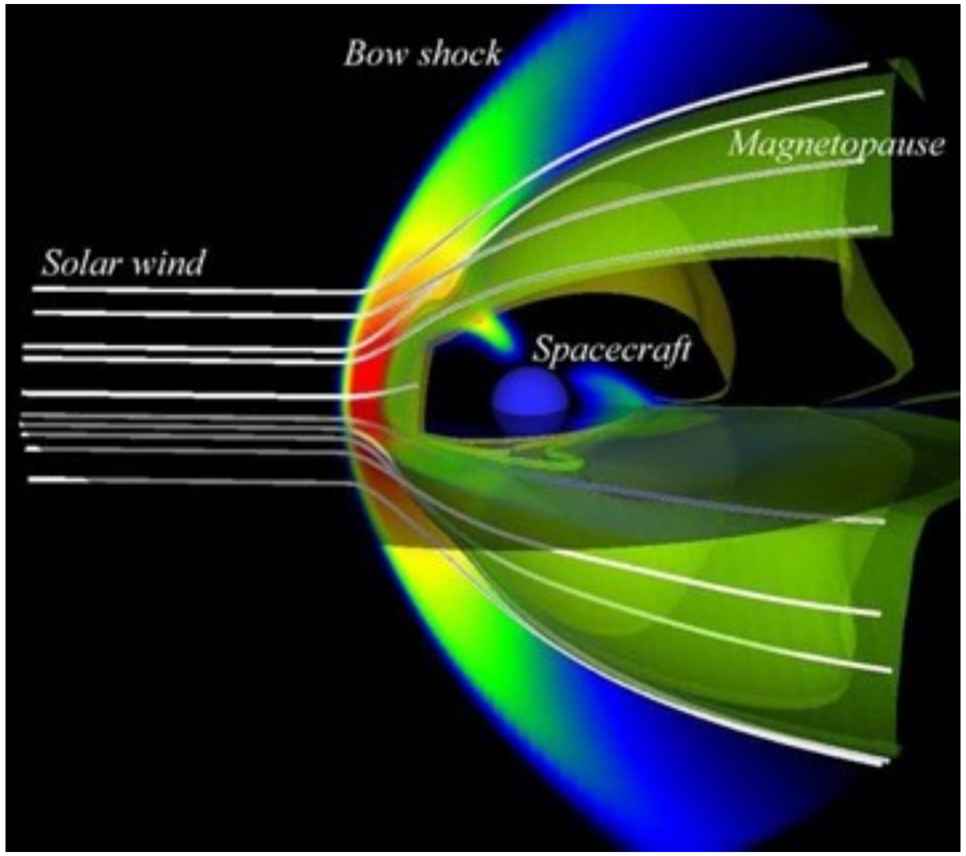
Thrust coefficient dependency on coil tilt angle

Same trend is confirmed by numerical simulations[1]

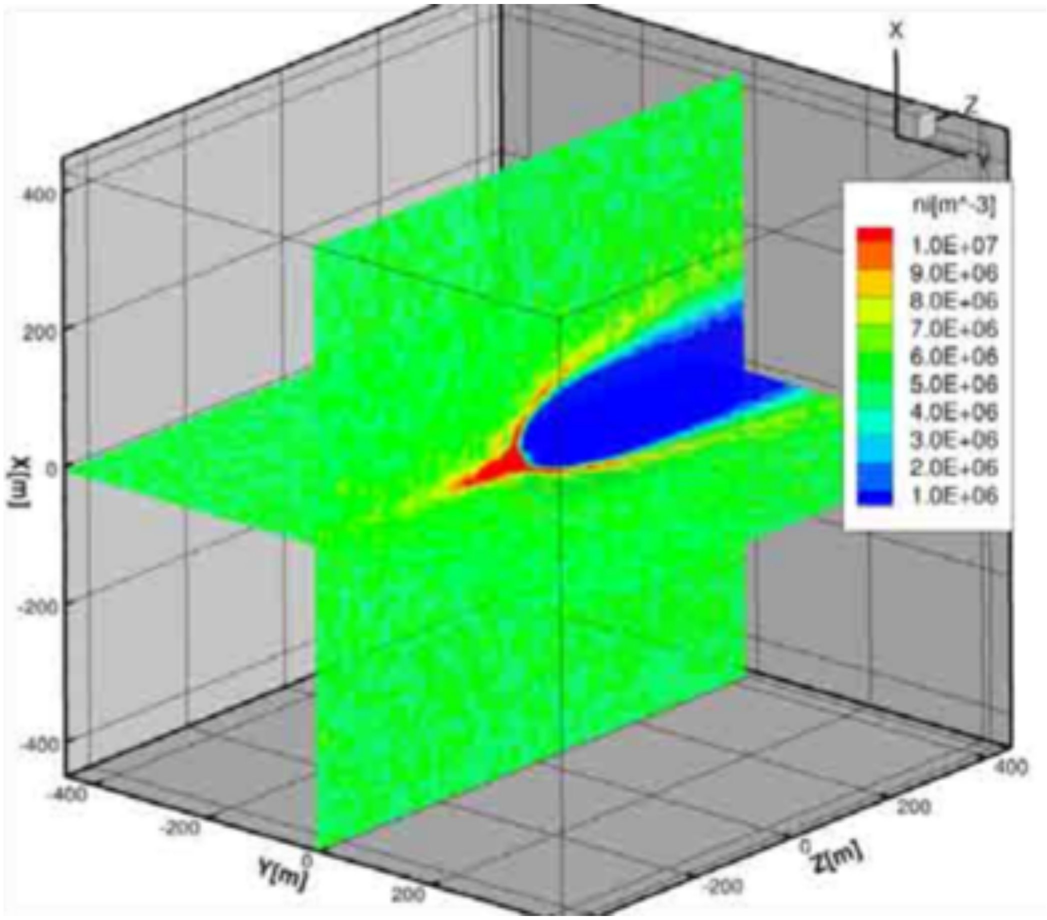
[1]Nishida et al., J. of Spacecraft and Rockets 43 (2006)

Numerical Simulation of Magnetic Sail

- Numerical simulations using MHD, particle-fluid hybrid, and full particle models have been conducted
  - Physics, parametric study, interplanetary magnetic field effect, etc…



3D MHD Simulation of a Magsail[1]



3D Full Particle Simulation of a Magsail[2]

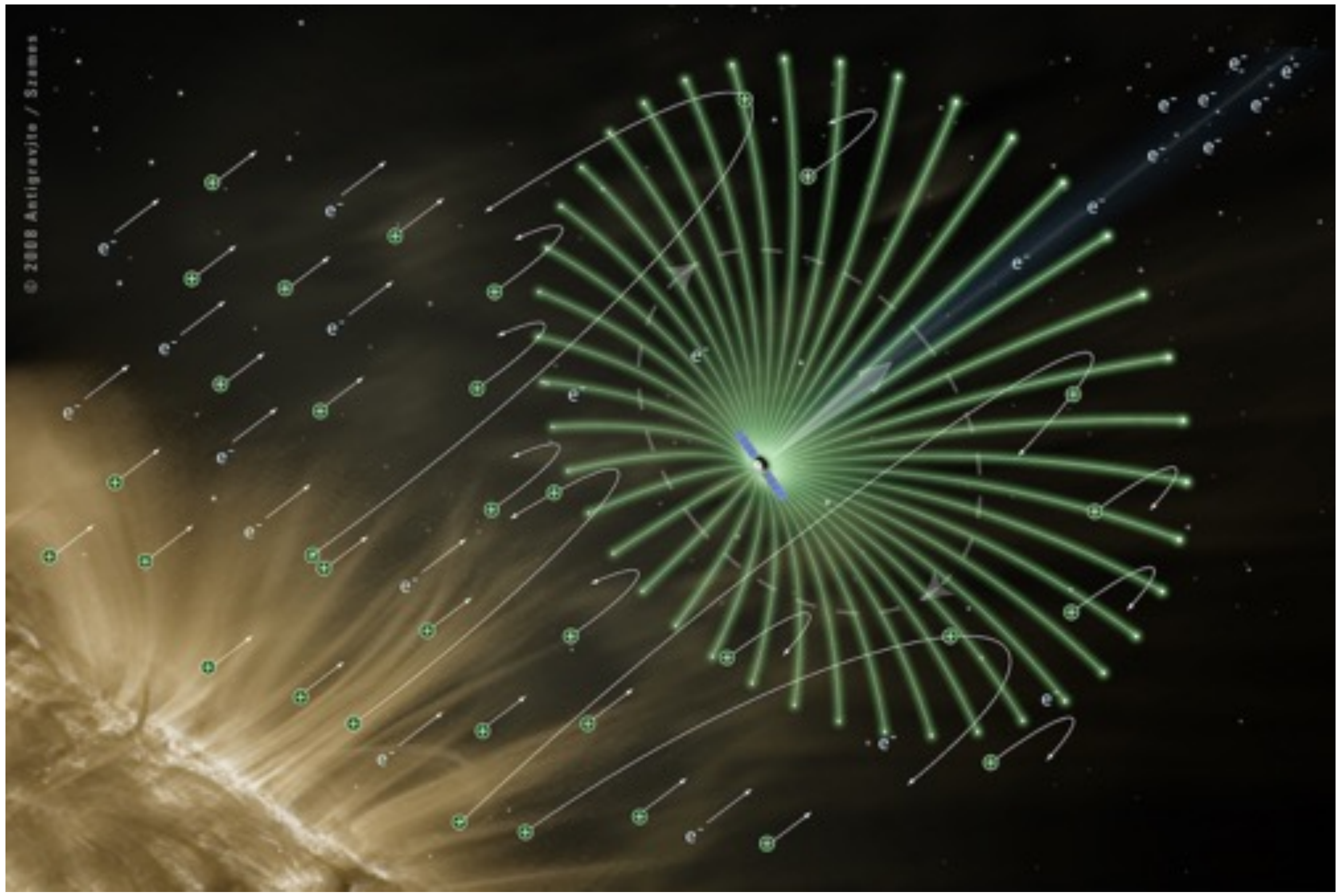
[1]TUAT Nishida Lab. Webpage.

[2]Ashida, Ph.D. Dissertation, 2014.

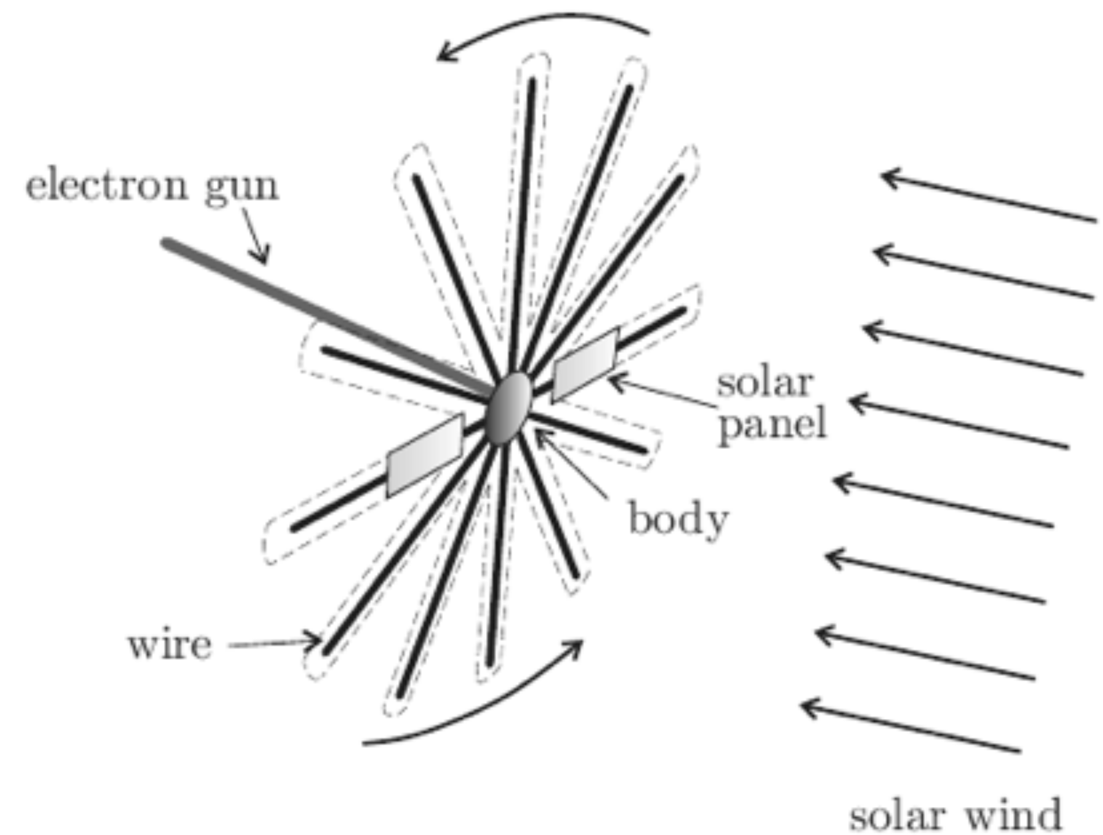
Summary: Magnetic Sail

- Dynamic pressure of solar wind: 1 nN/m^2 (Solar radiation pressure:9 μN/m^2)
    - Magnetic sail must deflect much larger area
    - Expansion of the magnetosphere is important
- Various experiments and numerical simulations are being conducted in JAXA
    - Good agreements between experiment and simulation have been confirmed
    - More advanced concept (**Magnetoplasma sail**) is being researched

Electric Sail: Concept



Artist's image of electric sail

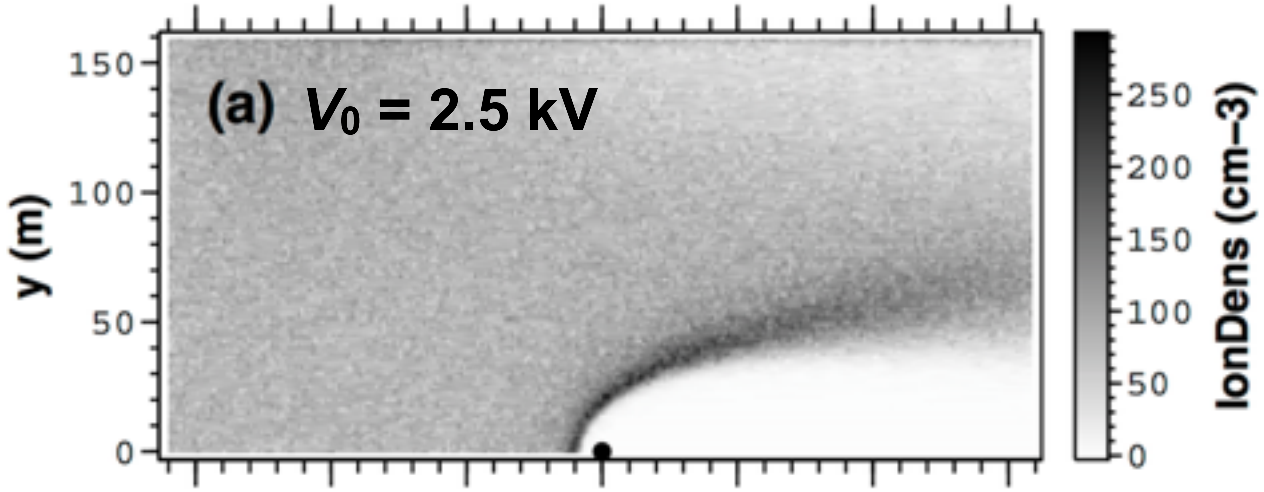


Structure of electric sail

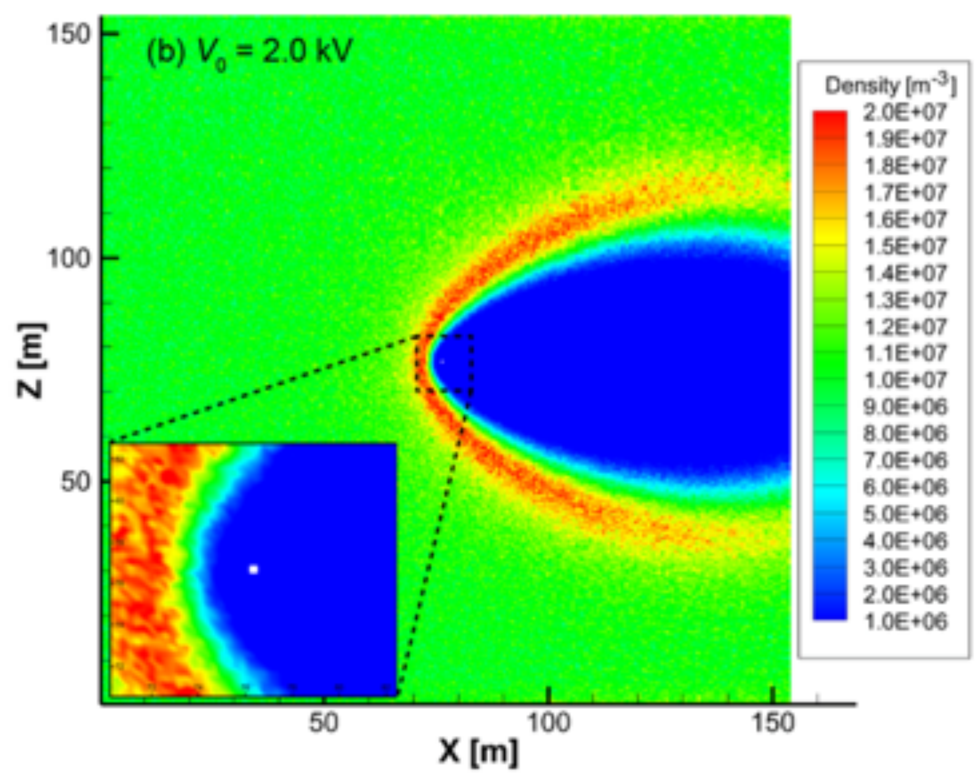
- "A full-scale electric sail consists of a number (50-100) of long (e.g., 20 km), thin (e.g., 25 microns) conducting tethers"
- Electron gun keeps the tethers in a high (typically 20 kV) potential

images from Janhunen's webpage (https://www.electric-sailing.fi)

Numerical Simulation Works of E-Sail

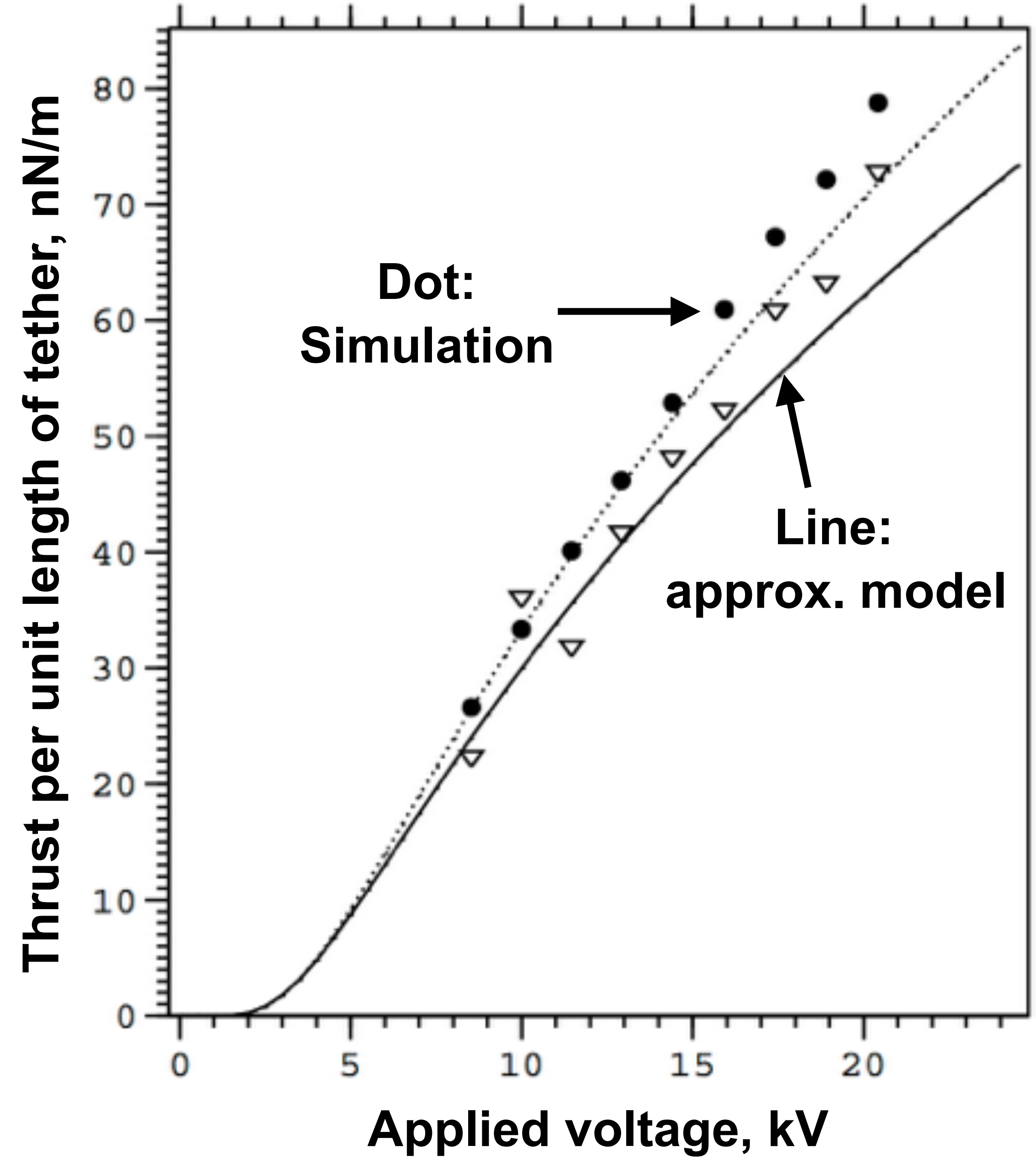


2D PIC simulation by Janhunen and Sandroos[1]



3D PIC simulation at Kyoto University[2]

[1]Janhunen and Sandroos, Ann. Geophys. 25 (2007)
[2]Hoshi et al. Ann. Geophys. 34, 2016.



Thrust per unit length vs. Tether voltage[1]

Development Status of Electric Sail

- Janhunen (Kumpula Space Center, Finland) proposed the concept in 2004.
- Until recently, theoretical model and spacecraft design were studied by Janhunen's group
- E-sail is to be demonstrated by the ESTCube-1 Satellite
  - Launched on May 2013
  - Deploy a 10 m long tether

ESTCube-1 (1 kg nano-sat): the first satellite to test electric sail[1]

[1]Janhunen, J. of Propulsion and Power 20 (2004)
[2]ESTCube-1 Webpage (www.estcube.eu/en/home)

LEO Environment Utilization

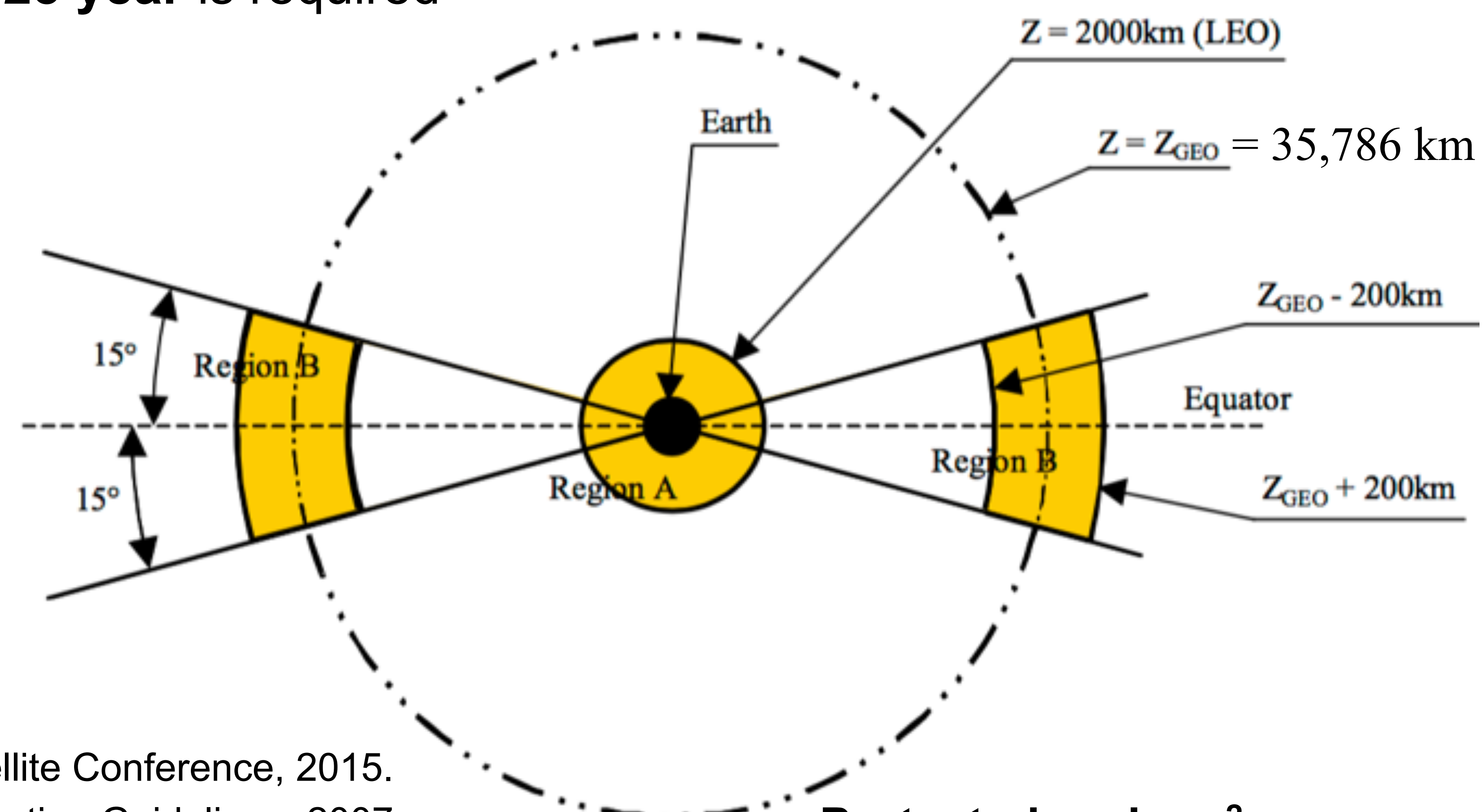
- Magnetic Plasma De-orbit (MPD)
- Air-breathing Electric Propulsion (ABEP)

De-orbit Method for Nano/Microsatellite is Necessary

- The number of satellites of 1 - 50 kg-class nano/microsatellite is increasing

  2011: 20 satellites → 2014: 158 satellites[1]

- Not to generate space debris by nano/microsatellites, de-orbit is necessary
  - Deorbit within **25 year** is required[2]

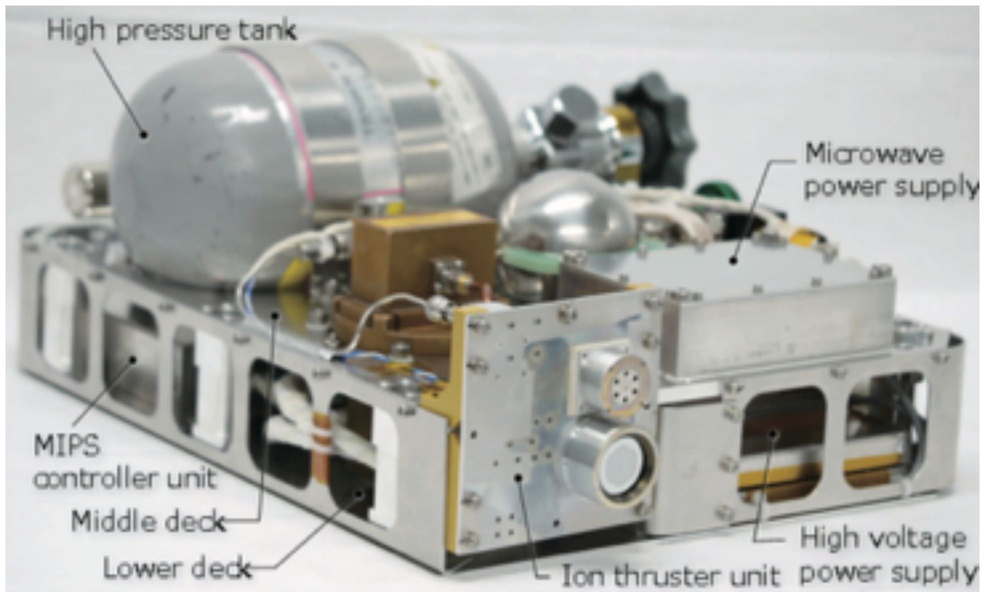


Protected regions[2]

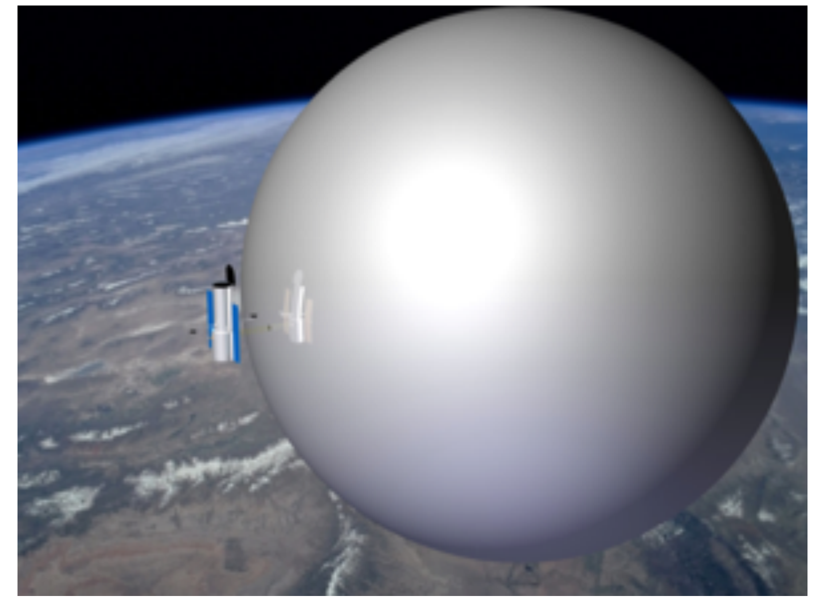
[1]Buchen, 29th Small Satellite Conference, 2015.
[2]IADC Space Debris Mitigation Guidelines, 2007.

De-orbit Method for Nano/Microsatellite is Necessary

- However, the weight and space available in nano satellite are strictly limited
  - Miniaturization of conventional method is not satisfactory

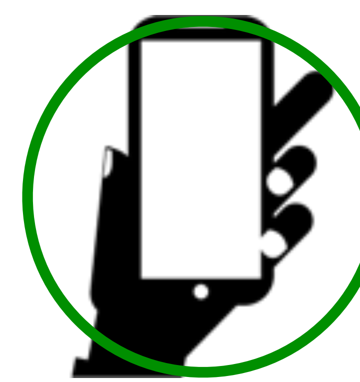


Miniature Ion Propulsion System (MIPA) for 67 kg Satellite[3]



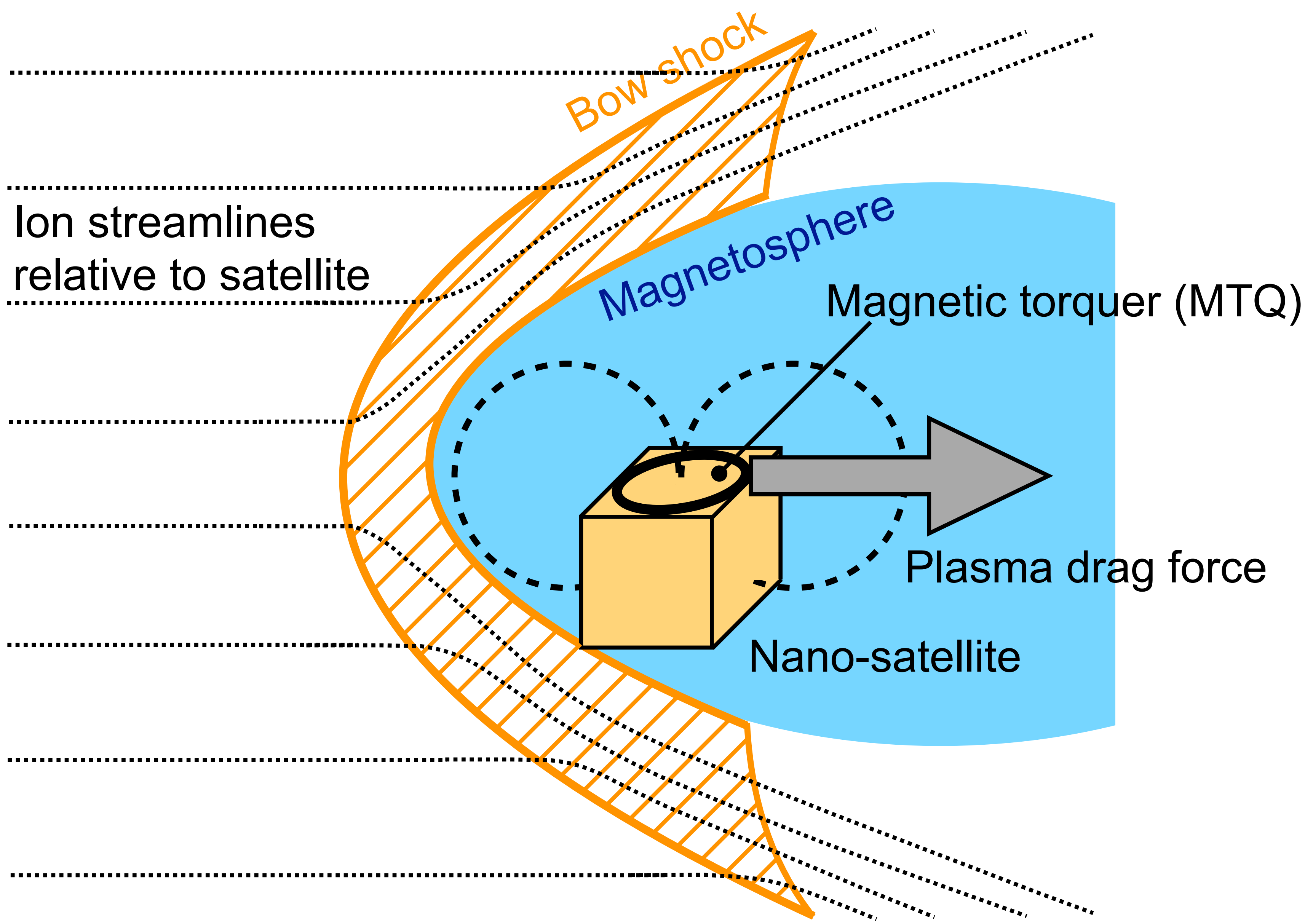
Gossamer Orbit Lowering Device (GOLD) for 700 kg Satellite[4]

- **New deorbit method for nano/ microsatellite is needed**
  - What is the “smartphone” of satellite deorbit?



[3]Koizumi et al., Trans. JSASS Aerospace Tech. Japan 12, 2015.
[4]Nock et al., AIAA 2010-7824, 2010.

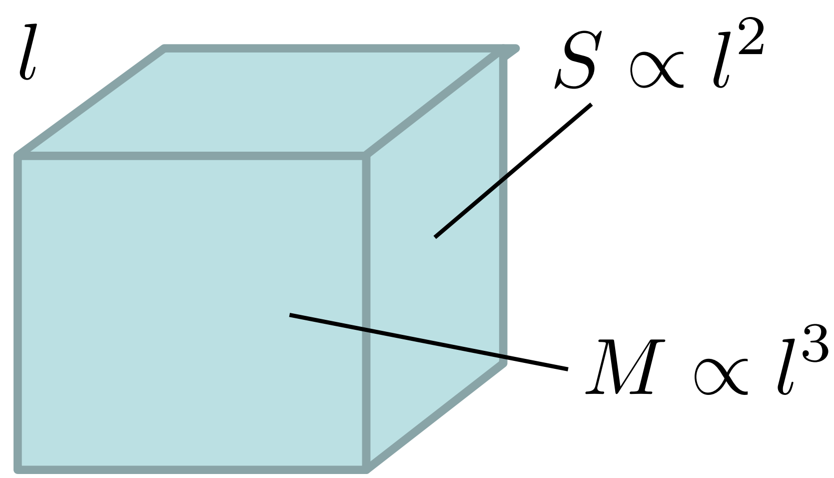
Magnetic Plasma De-orbit (MPD): Concept



- Basic principle of drag force generation is similar to that of magnetic sail
- Magnetic field is generated by the Magnetic Torquer (MTQ)

No additional component is required for the deorbit

MPD is Suitable for Nano/Small Satellite



- Drag force scaling
  - Strength of MTQ is assumed to be proportional to S
  - Stronger force generation in larger satellites

$$F \propto M_{\mathrm{d}}^{\frac{2}{3}} \propto S^{\frac{2}{3}} \propto l^{\frac{4}{3}}$$

$$F = C_{\mathrm{d}} \frac{1}{2} \rho u_{\mathrm{sw}}^2 S$$

$$S = \pi L^2$$

$$L = \left(\frac{M_{\mathrm{d}}^2}{8 \mu_0 \pi^2 n_{\mathrm{i}} m_{\mathrm{i}} u_{\mathrm{sw}}^2} \right)^{1/6}$$

- Acceleration scaling
  - **Larger acceleration for orbit control in smaller size satellites**

$$a = \frac{F}{m} \propto \frac{l^{\frac{4}{3}}}{l^3} \propto \underline{l^{-\frac{5}{3}}}$$

Magnetic Plasma Deorbit (MPD) is more effective in nano/small satellites

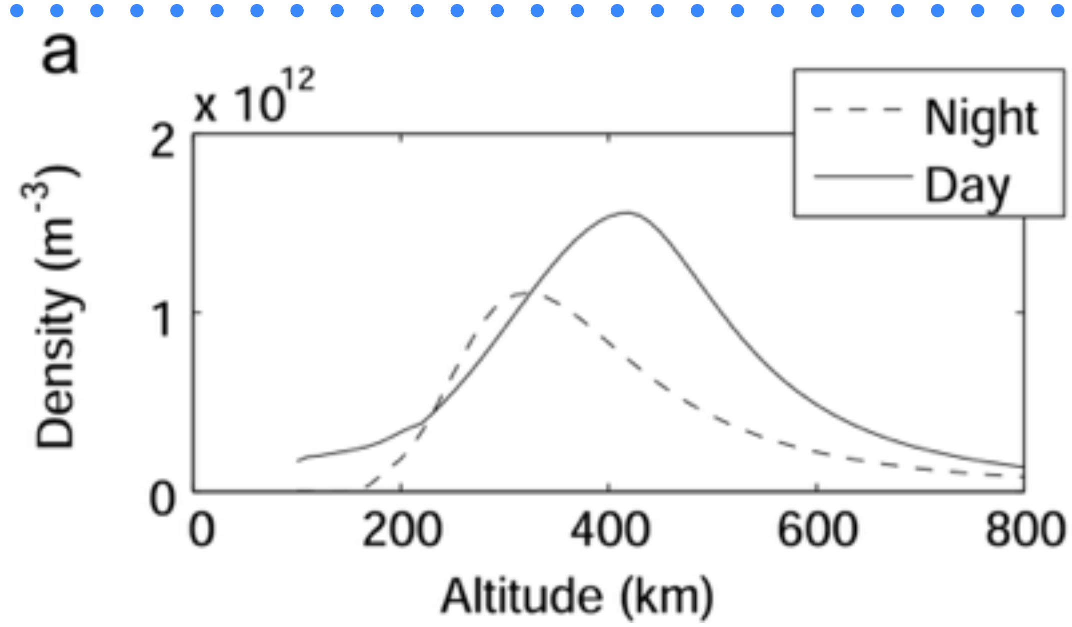
LEO Environment: Plasma Properties

- Plasma properties in the low-earth orbit (LEO) can be calculated by the International Reference Ionosphere (IRI) model[2]
- Density is ~ 10^{12} m^{-3}, main composition of plasma is O^+, and satellite speed is 8000 m/s

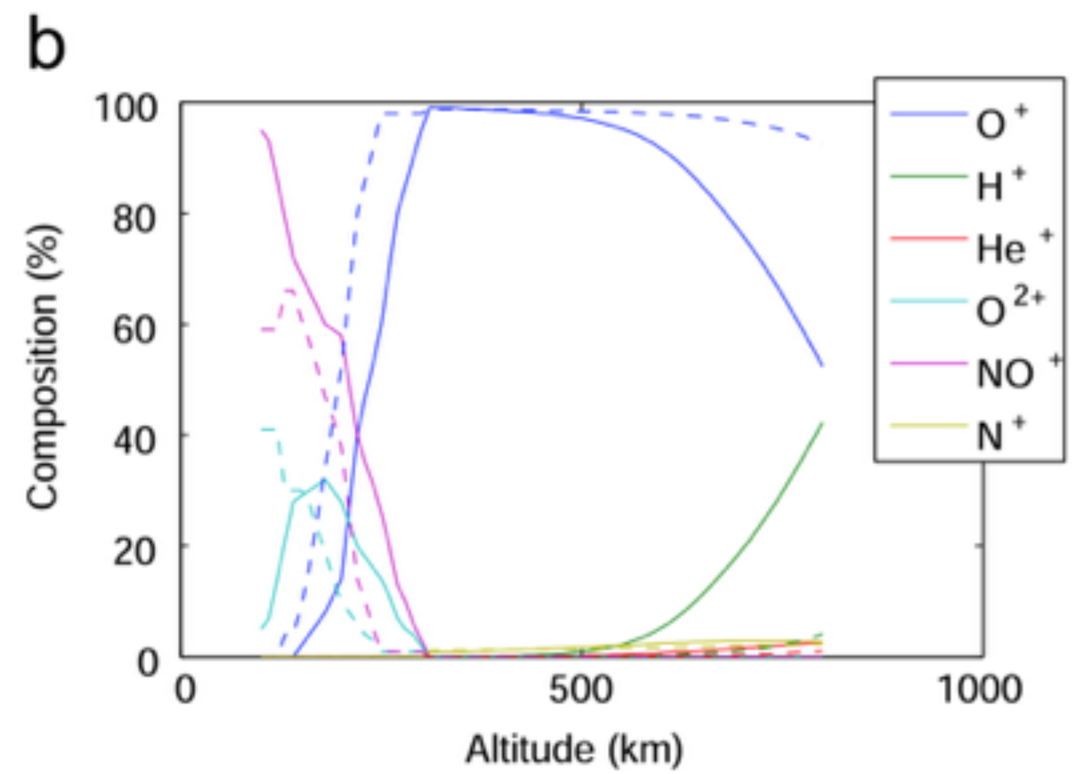
$$\frac{1}{2} m_\mathrm{i} n_\mathrm{i} u_\mathrm{sat}^2 = 850 \ \mathrm{nN\ m^{-2}}$$

Dynamic pressure of solar wind:

$$\sim 1 \ \mathrm{nN/m^2}$$



Altitude dependency of plasma density[1]



Composition of in-orbit space plasma[1]

[1]Inamori et al., Acta Astronautica 112 (2015).

[2]Biliza, International Reference Ionosphere (1990).

Deorbit Simulation

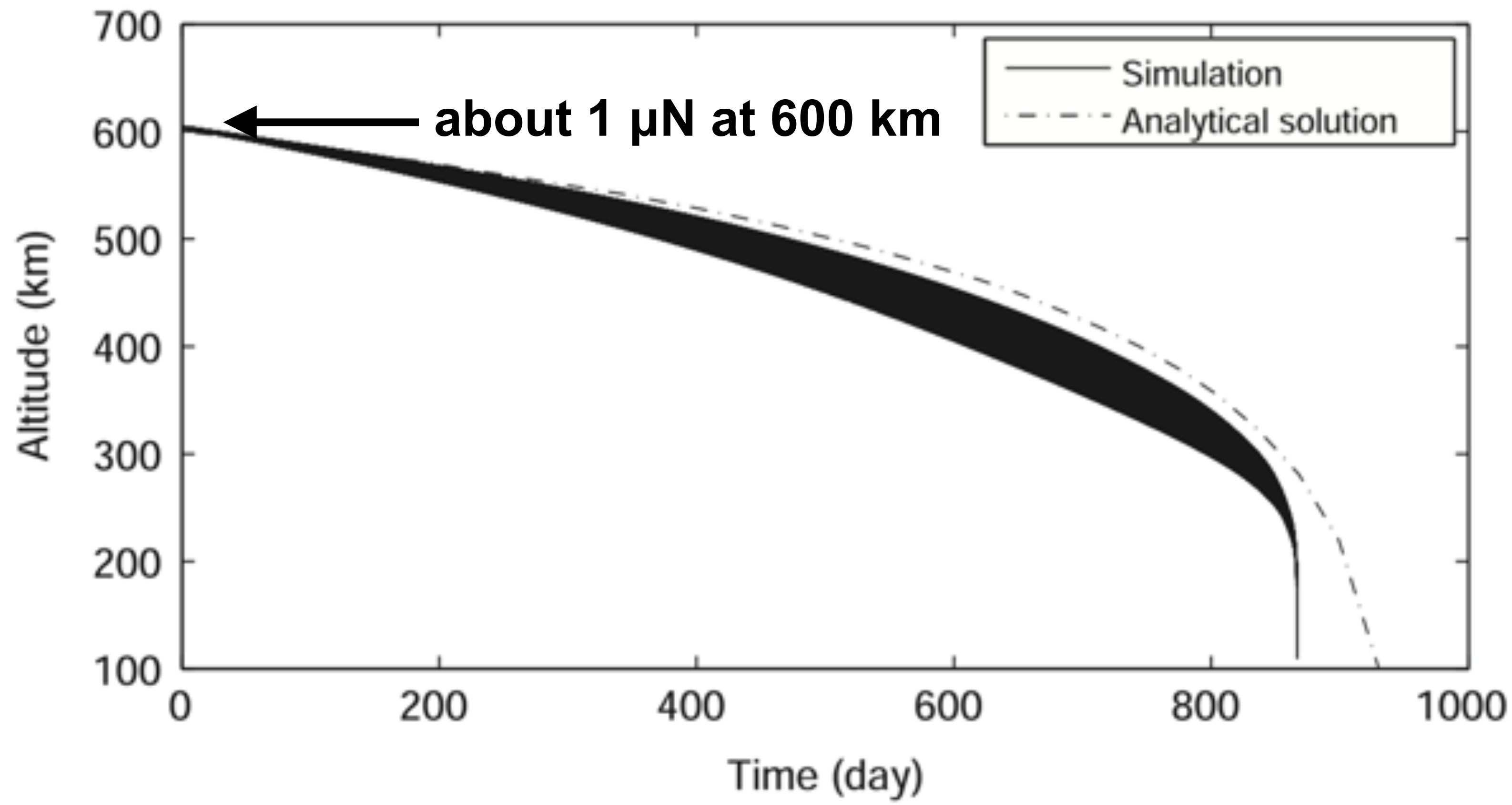
- Deorbit simulation for 10 kg, 20 cm^3 satellite
  - MTQ magnetic moment: 100 Am^2
  - MTQ mass: 2kg
  - MTQ Power: 4W

Simulated deorbit period: 900 days (~ 2.5 years)

Deorbit duration without any deorbit system: ~ 40 years

However, 100 Am^2 is too large for normal MTQ

→ **1 μN with 10 Am^2 is targeted**

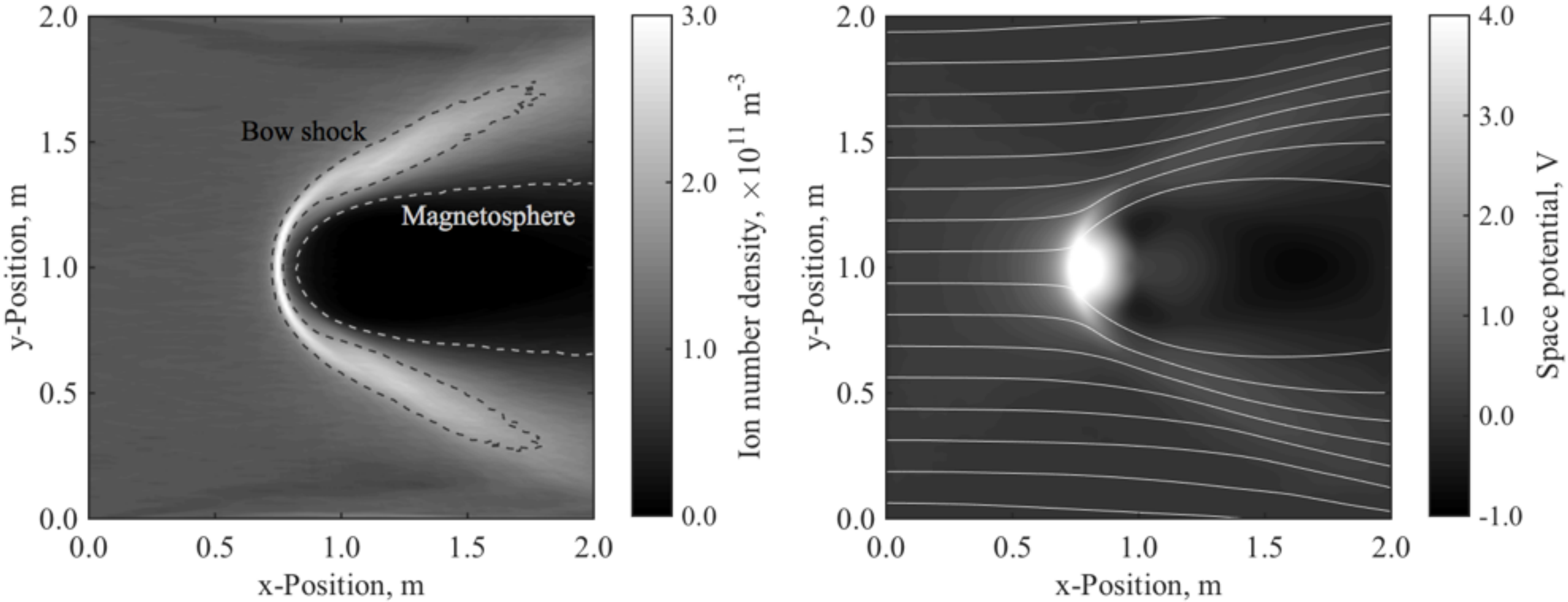


Time history of satellite altitude with the operation of MPD[1]
Satellite mass: 10 kg, MTQ: 100 Am^2

[1]Inamori et al., Acta Astronautica 112 (2015).

Numerical Simulation: Distribution

- Formation of magnetosphere and steady-state drag force generation were confirmed

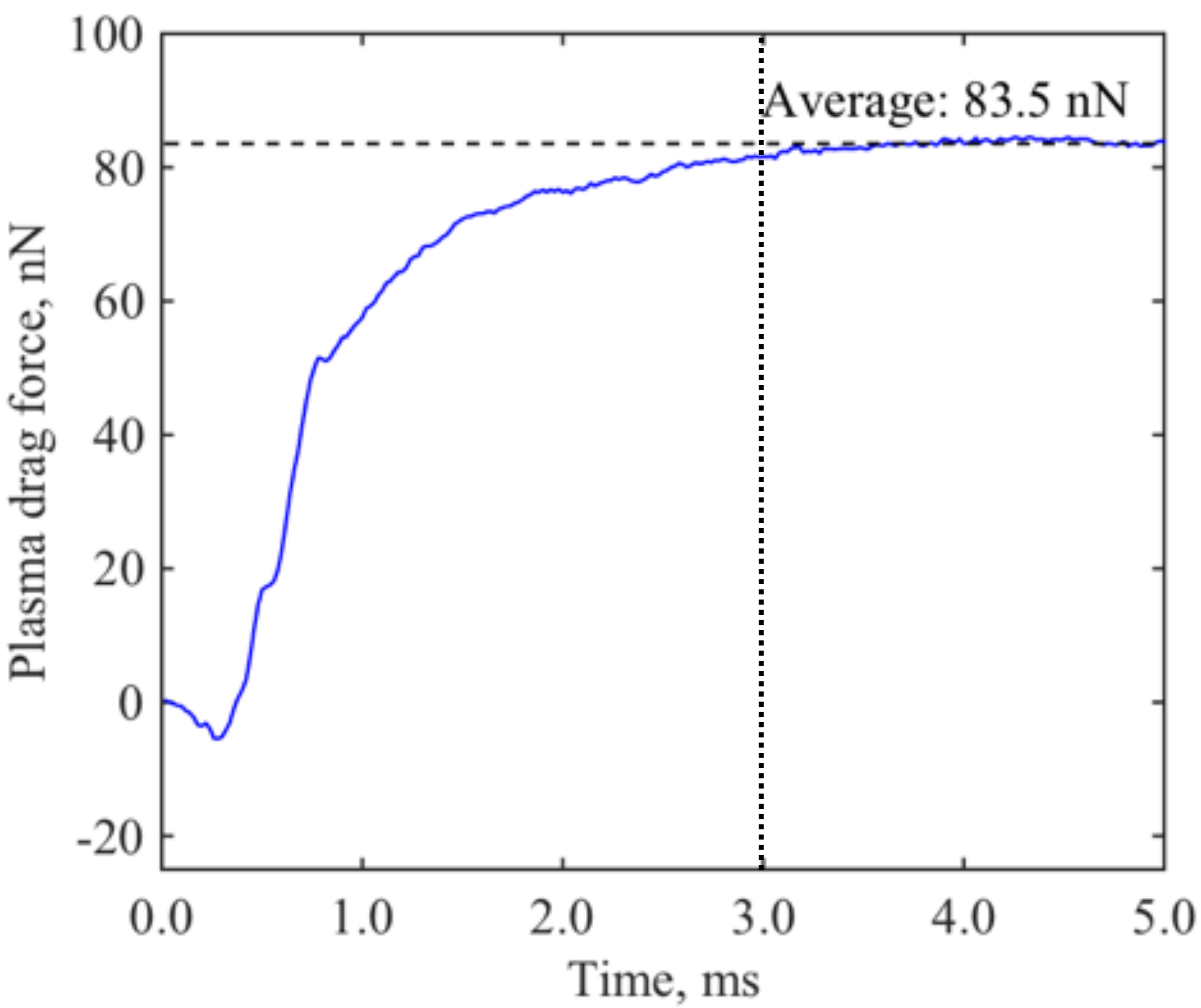


2D full particle simulation at Univ. of Tokyo

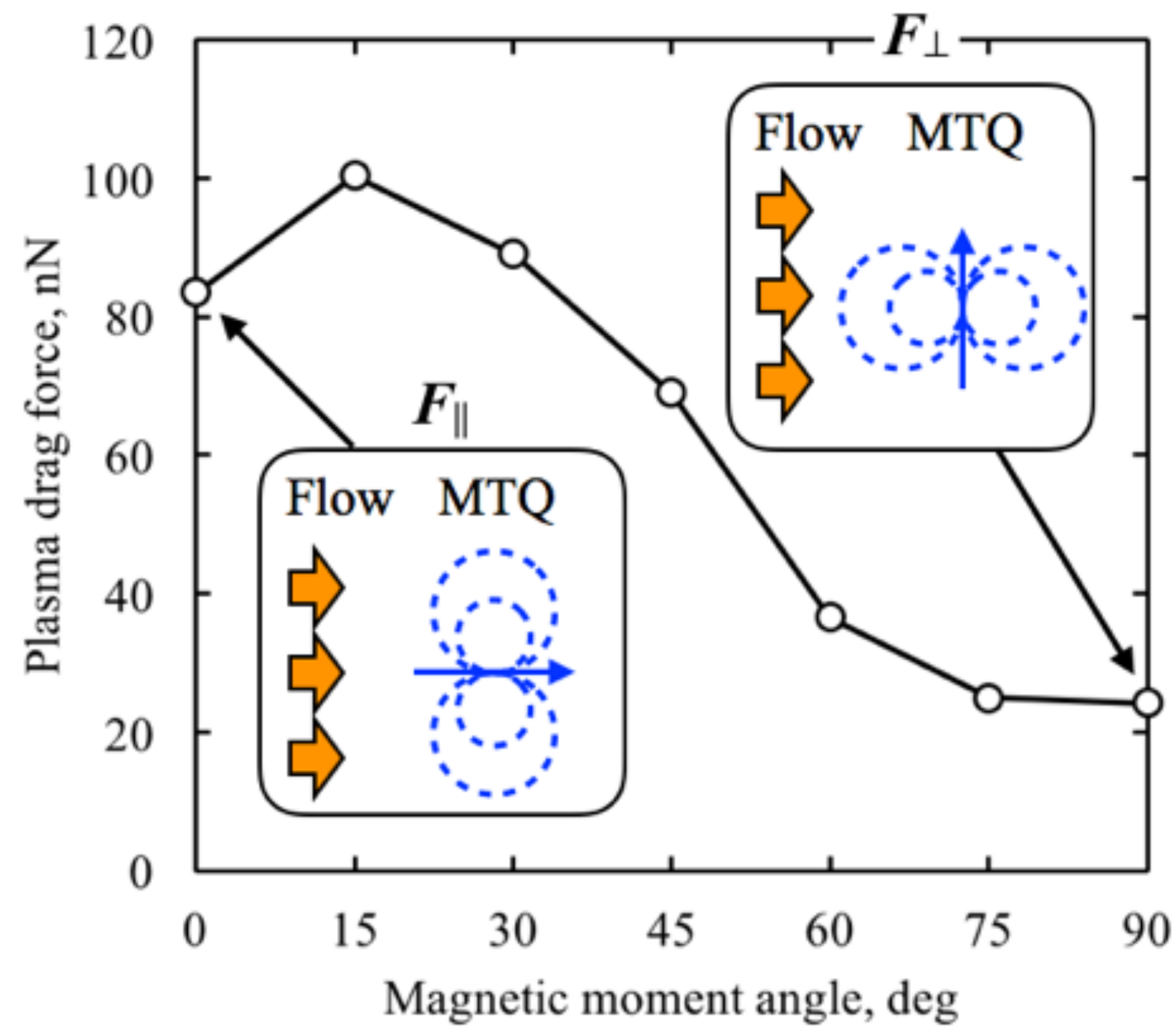
Expected plasma drag force at altitude of 600 km: ~ 80 nN

(M_d = 10 Am^2, n_0 = 10^{11} m^{-3}, Moderate solar activity)

Numerical Simulation: Plasma Drag Force



Time history of plasma drag force



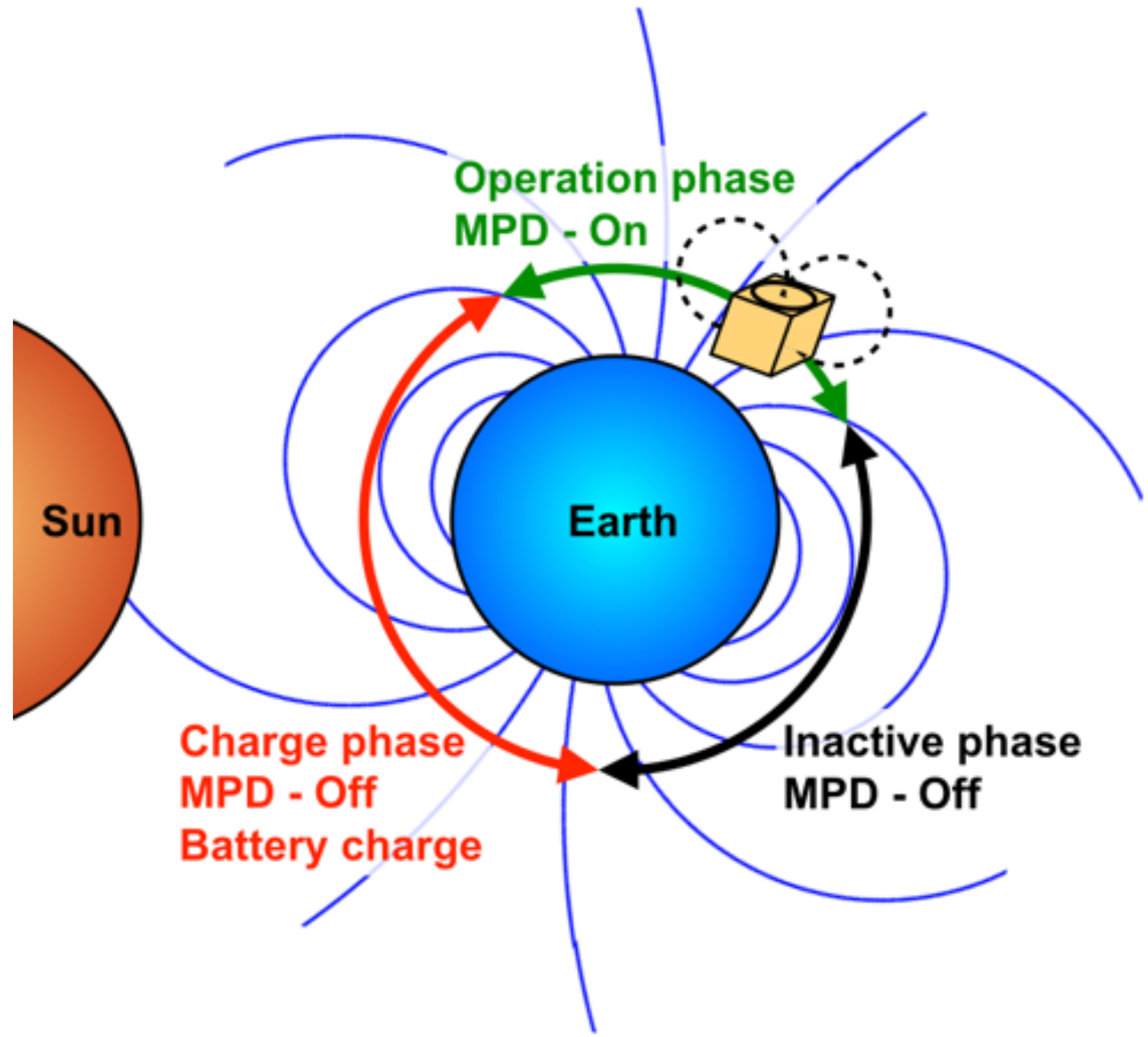
Drag force dependency on MTQ magnetic moment angle

- Response time: ~ 3.0 ms
- Steady drag force is generated

- $F_{\parallel} > F_{\perp}$
- Same trend as magnetic sail

What is the optimal operation method of MPD?

- The polar orbit is assumed
  - Orbit period: ~100 min
  - Angle between the plasma flow and MTQ magnetic moment: 0 - 360 deg
  - Angle of geomagnetic field: 0 - 720 deg
- High plasma density at daytime and high solar activity
- At the timing of large drag force generation (optimal operation condition), the power stored in the battery should be used



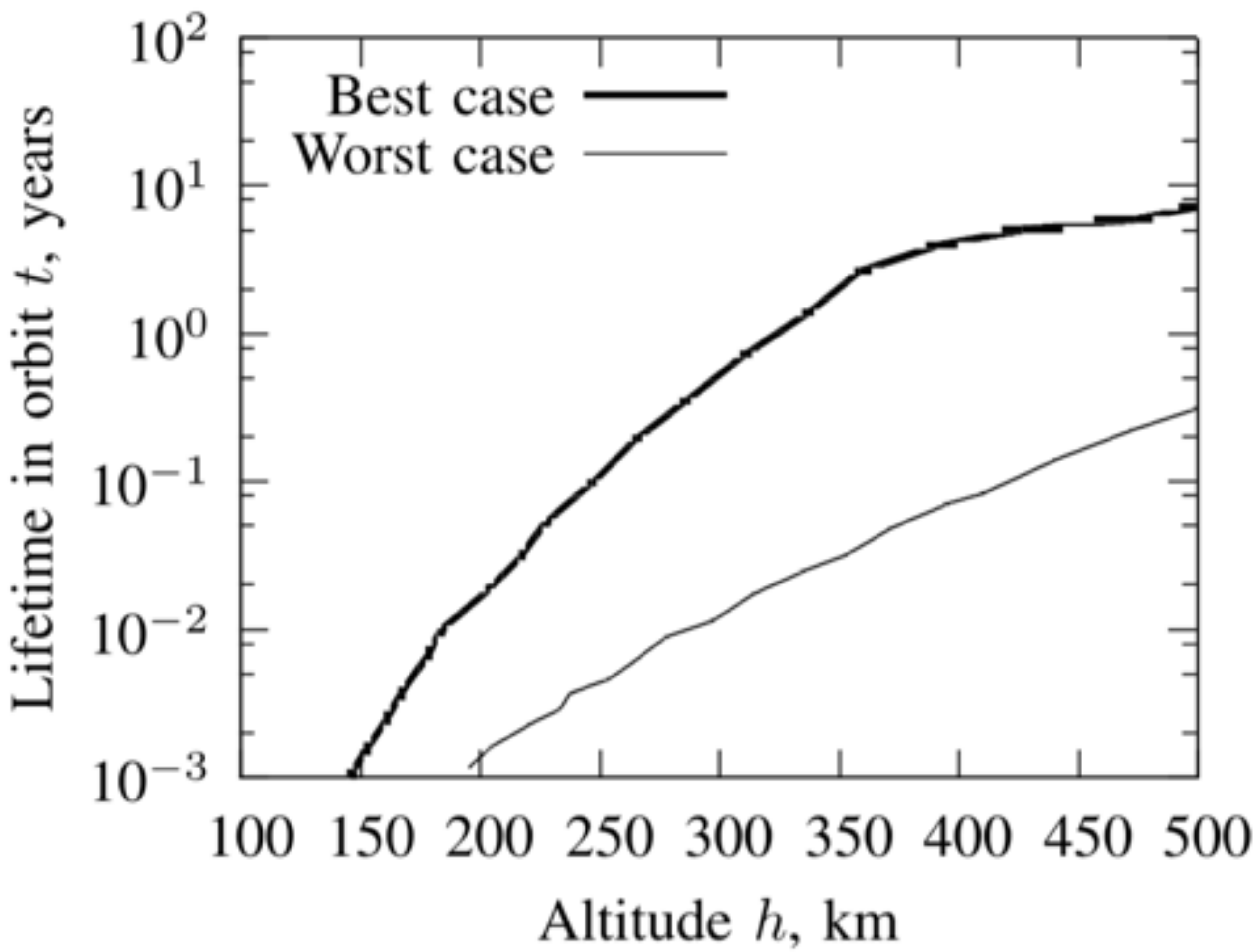
Operation of Magnetic Plasma Dheorbit (MPD)

Summary: Magnetic Plasma Deorbit

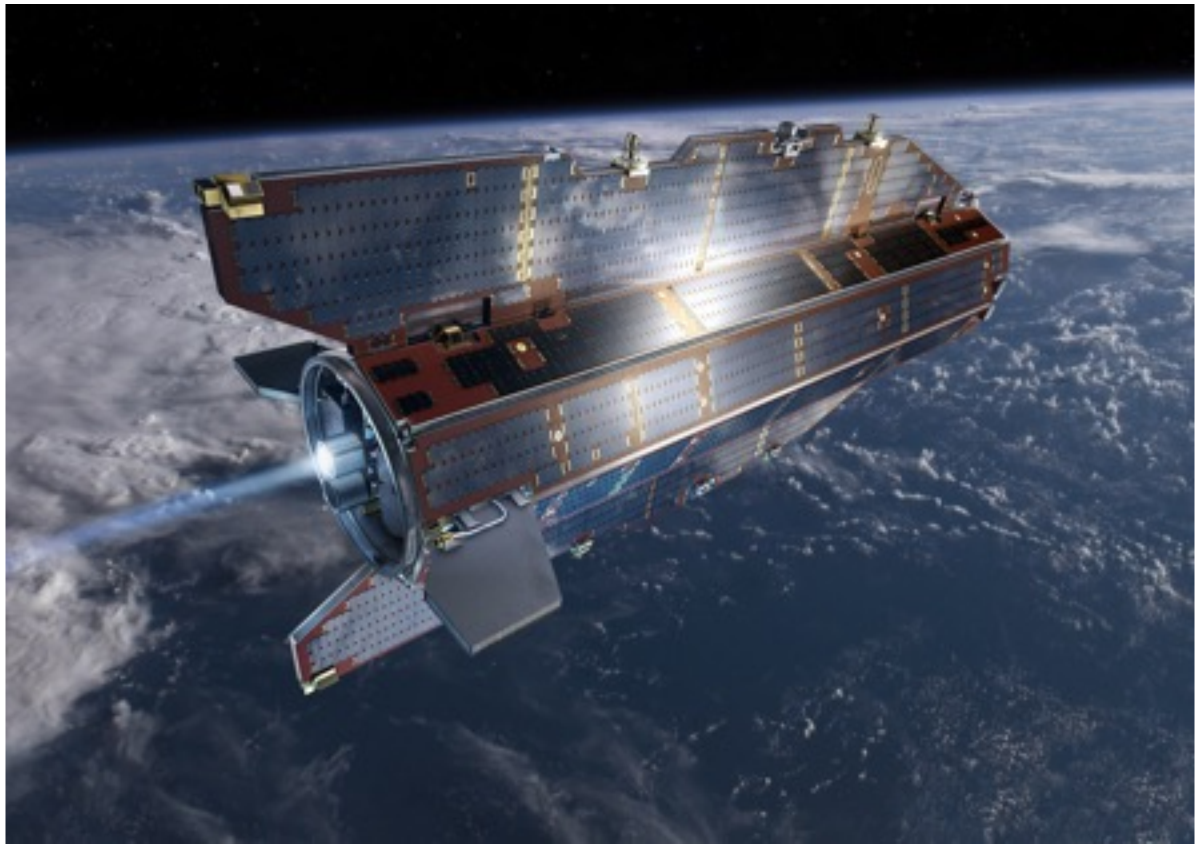
- Magnetic Plasma Deorbit (MPD) is unique and suitable deorbit method for nano/microsatellite
- In MPD, no additional component is required
- The deorbit period is estimated as 10 years, if 100 nN is generated
- The simulated plasma drag force is ~ 80 nN for 10 Am^2 magnetic torquer at $n_0 = 10^{11}$ m^{-3} (moderate solar activity)
- Currently, the optimal operation method of MPD is considered

- Other applications (attitude control, relative position control)

Orbit Decay and LEO Example (GOCE)



Lifetime for propulsion-less satellites[1]
Best case: 200 kg/m^2 with min. solar activity.
Worst case: 20 kg/m^2 with max. solar activity.



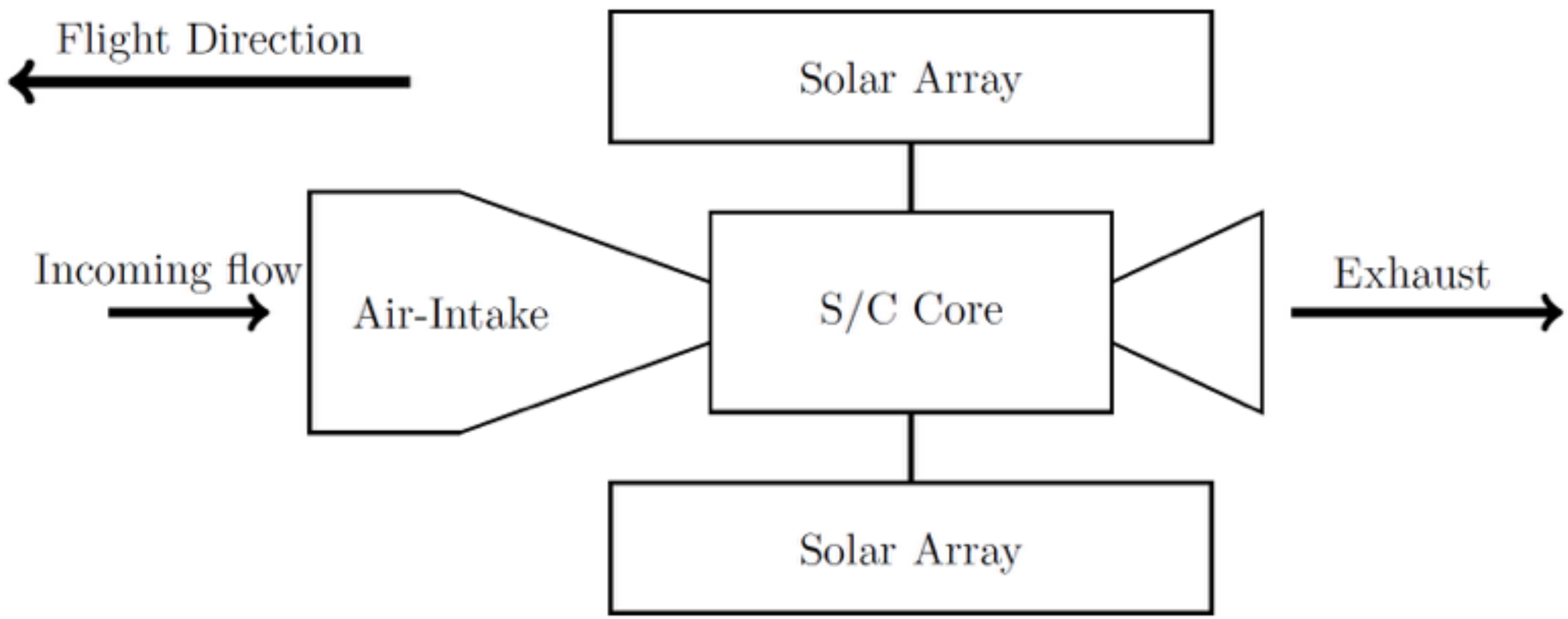
GOCE (ESA) at altitude: 260 km.
Ballistic coef.: 1077 kg / 3.7 x 0.9 m^2
= 323 kg/m^2
Use of fuel-efficient ion thrusters

Designed lifetime: 20 months
Actual lifetime: 56 months

[1]Shönherr et al., IEEE Tras. on Plasma Sci. 43 (2015).

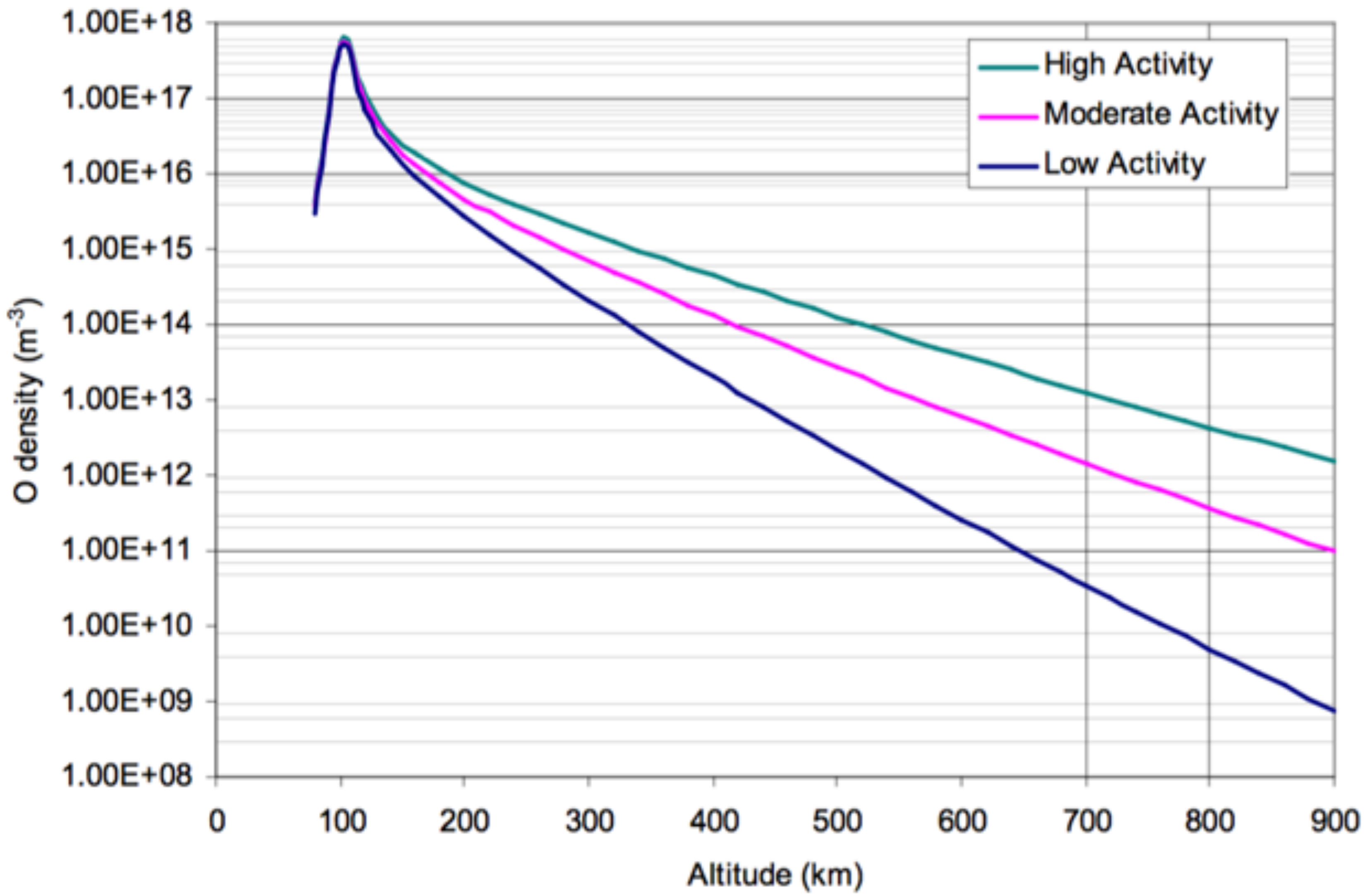
Concept of Air-breathing EP

- Air-breathing propulsion system
  - Intake to collect necessary mass flow and pre-compression
  - Accumulation and further compression in the spacecraft core
  - Thruster suitable to handle the atmospheric gases



LEO Environment Properties

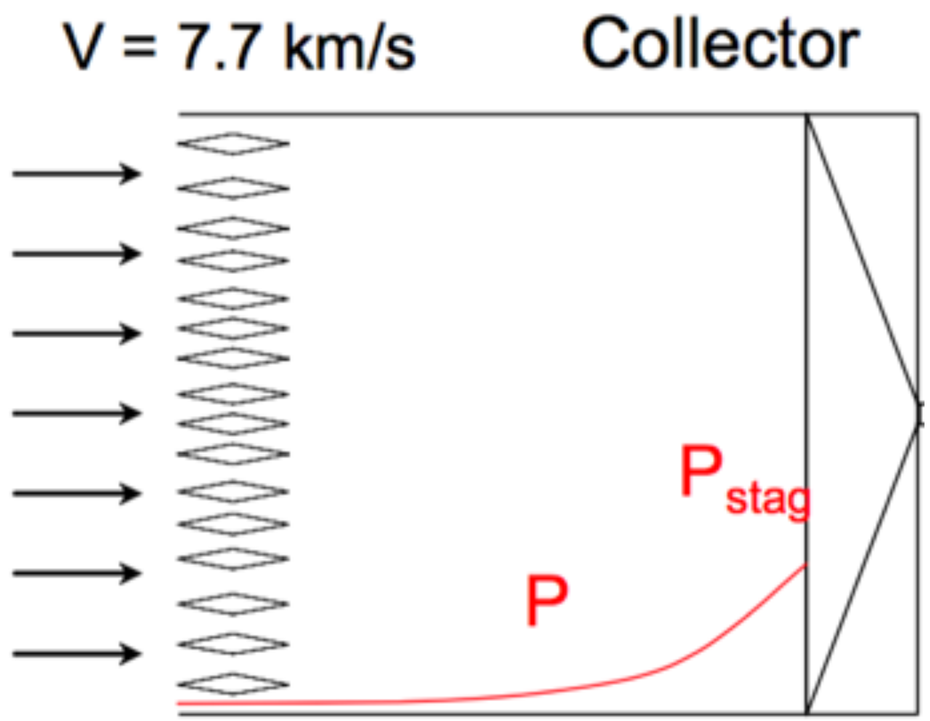
- Satellite velocity: 7.8 km/s, Main gas species: O
- NRLMSISE-00 space environment model:



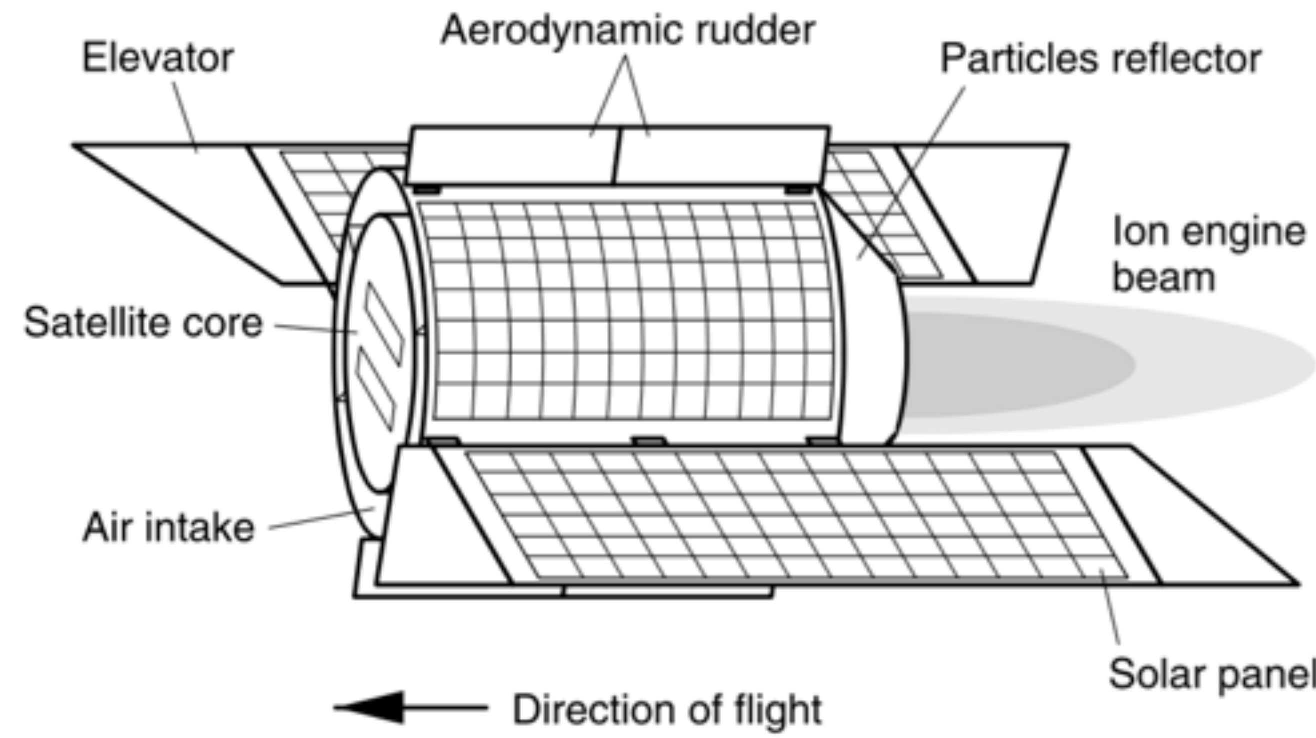
Atomic oxygen density for high, moderate and low solar activities[1]

[1]ESDD Secretariat, ECSS-E-ST-10-04C, 2008.

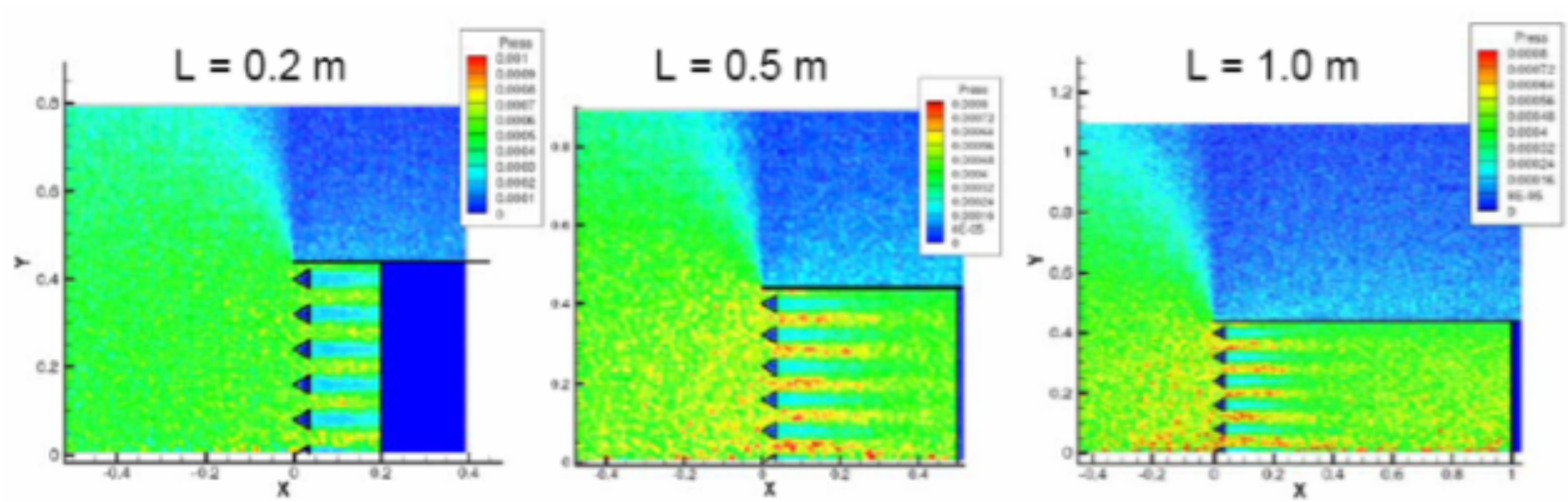
Structure of Air Intake



Funnel type air intake[1]



Bypass type air intake[2]

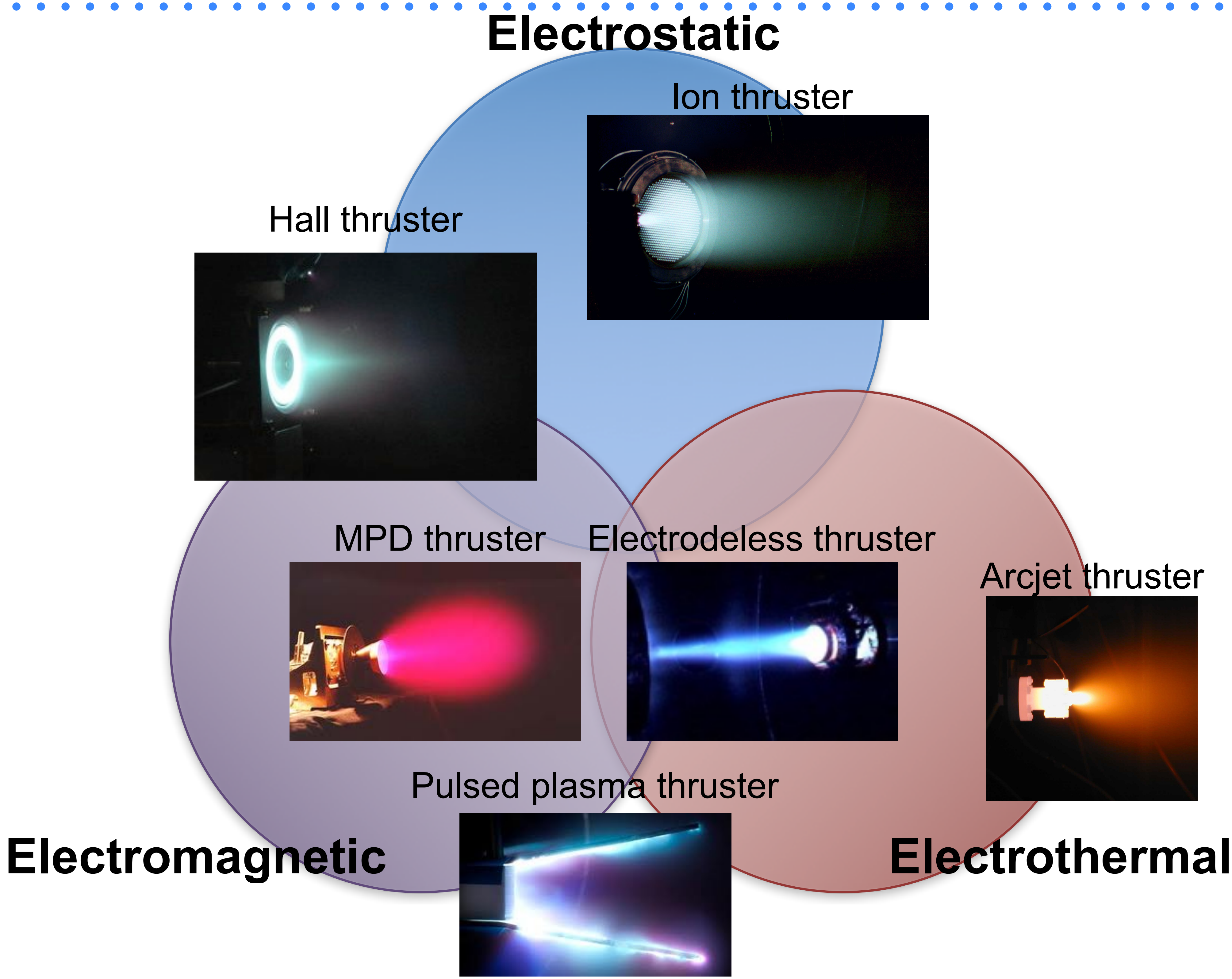


→ About 1 mPa achievable

DSMC simulation[1]

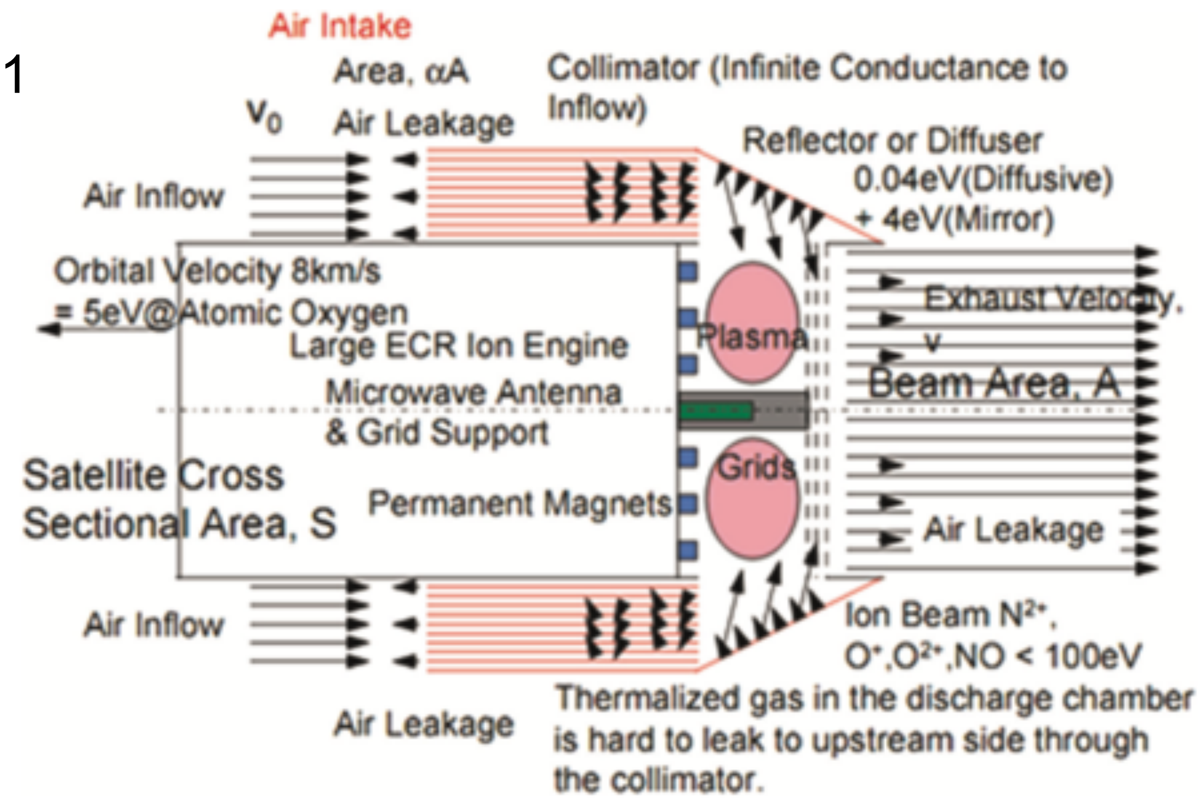
[1]Cara et al., IEPC-2007-162, 2007. [2]Fujita, 日本航空宇宙学会論文集 52 (2004).

Propulsion Options



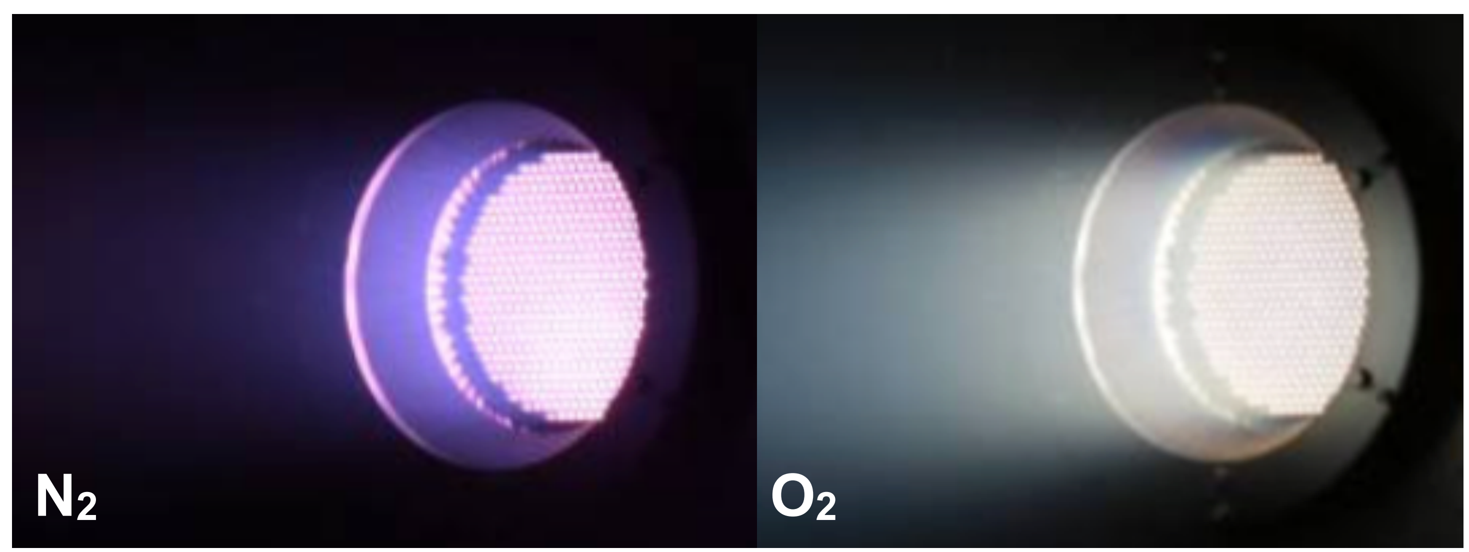
Air-breathing Ion Engine

- Air-breathing ion engine (ABIE)[1]
  - Microwave discharge IE
  - Aimed for altitude: 150 - 200 km
  - T/P around 10 mN/kW



Conceptual schematic of ABIE[1]

- Radiowave ion thruster (RIT) tested with atmospheric gases[2]
  - $\mathbf{N_2}$, O_2
  - Power: 450 W
  - Thrust: 5.25 mN
  - Efficiency: ~ 17%

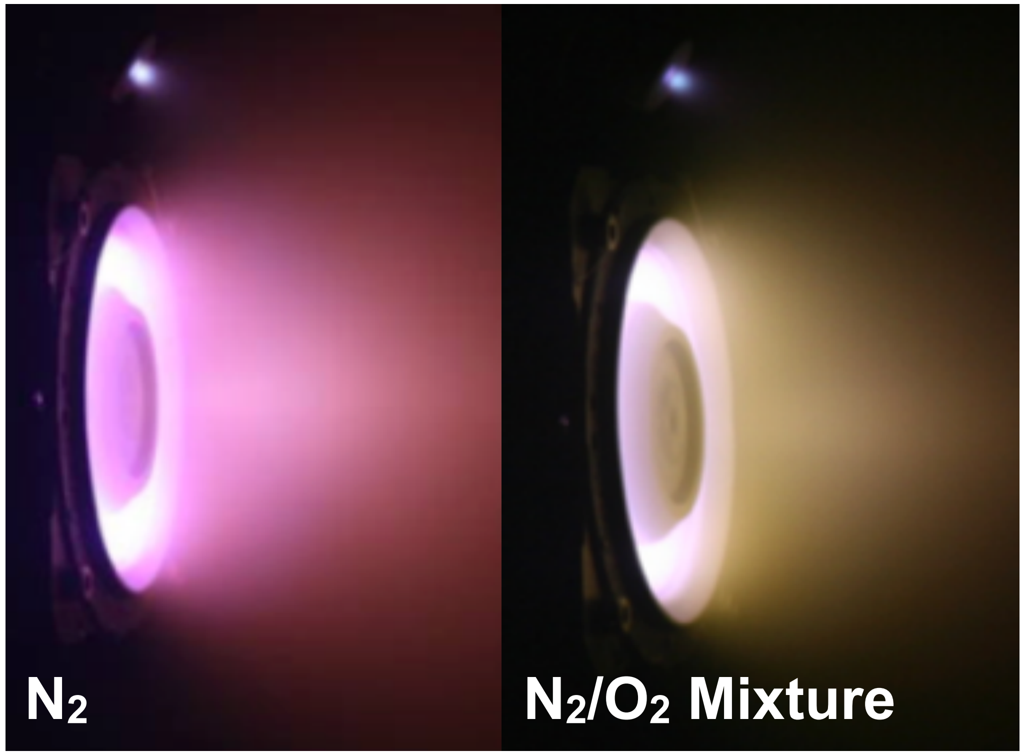


Ion engine operation with N_2 and O_2[2]

[1]Nishiyama, IAC-03-S.4.02, 2003.
[2]Cifali et al., IEPC-2011-224, 2011.

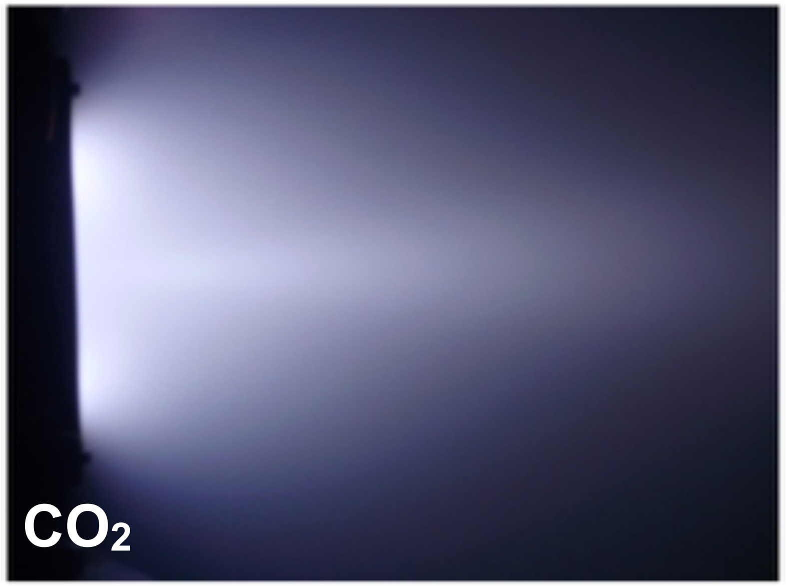
Air-breathing Hall Thruster

- PPS1350 (SPT) tested with atmospheric gases[1]
  - **N_2**, N_2/O_2 Mixture
  - Power: ~ 1 kW
  - Thrust: ~ 26 mN
  - Efficiency: ~ 12%



PPS1350 operation with N_2 and N_2/O_2 mixture[1]

- Mars atmosphere breathing HT is under investigation (NASA-Busek)[2]
  - Power: ~ 2 kW
  - Thrust: ~ 60 mN
  - Efficiency: ~ 26%



Busek Hall thruster operation with CO_2[2]

[1]Cifali et al., IEPC-2011-224, 2011.
[2]Hotman, NIAC Spring Symposium, 2012.

Summary: Air-breathing EP

- Air-breathing electric propulsion enables long-term missions in the very low earth orbit
- Achievable pressure at the air intake: 1 mPa
- Air-breathing Ion engine: Operation feasible
  - Nitrogen and oxygen successfully yield thrust
  - Thrust level sufficiently high to overcome drag force
  - Propellant storage and compression are necessary
- Air-breathing Hall thruster: Operation feasible
  - Use of nitrogen, oxygen, air, and CO_2 demonstrated
  - High thrust density yields small drag to be compensated
  - Propellant storage is necessary

Summary of the Lecture

Solar Wind Utilization

- Magnetic Sail
  - Never flow, no feasible design was shown
- Electric Sail
  - Small demonstration satellite is in progress

LEO Environment Utilization

- Magnetic Plasma De-orbit
  - Feasibility confirmed
- Air-breathing Electric Propulsion
  - No feasible design was shown