Air-Breathing Electric Propulsion

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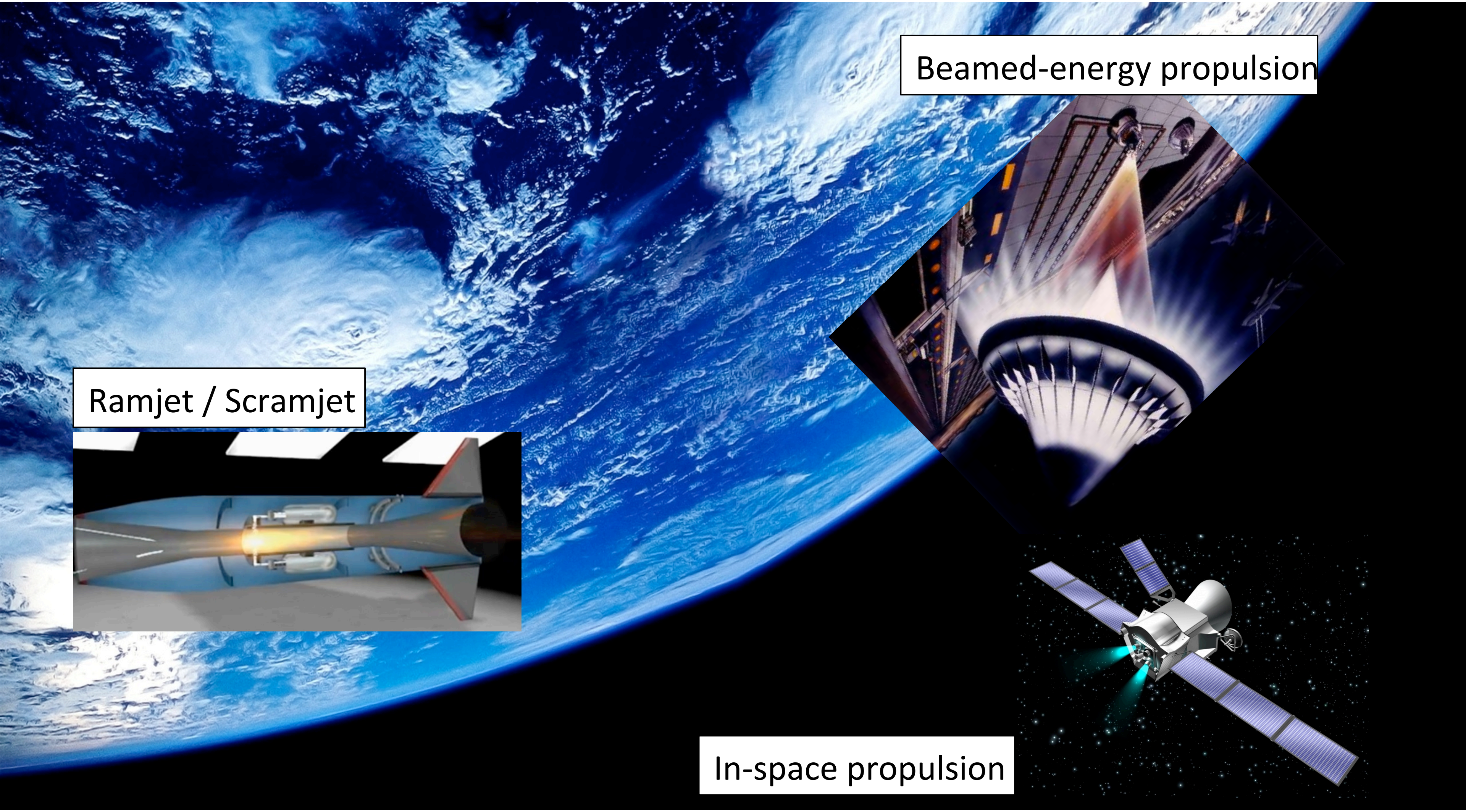
Classification of air-breathing propulsion

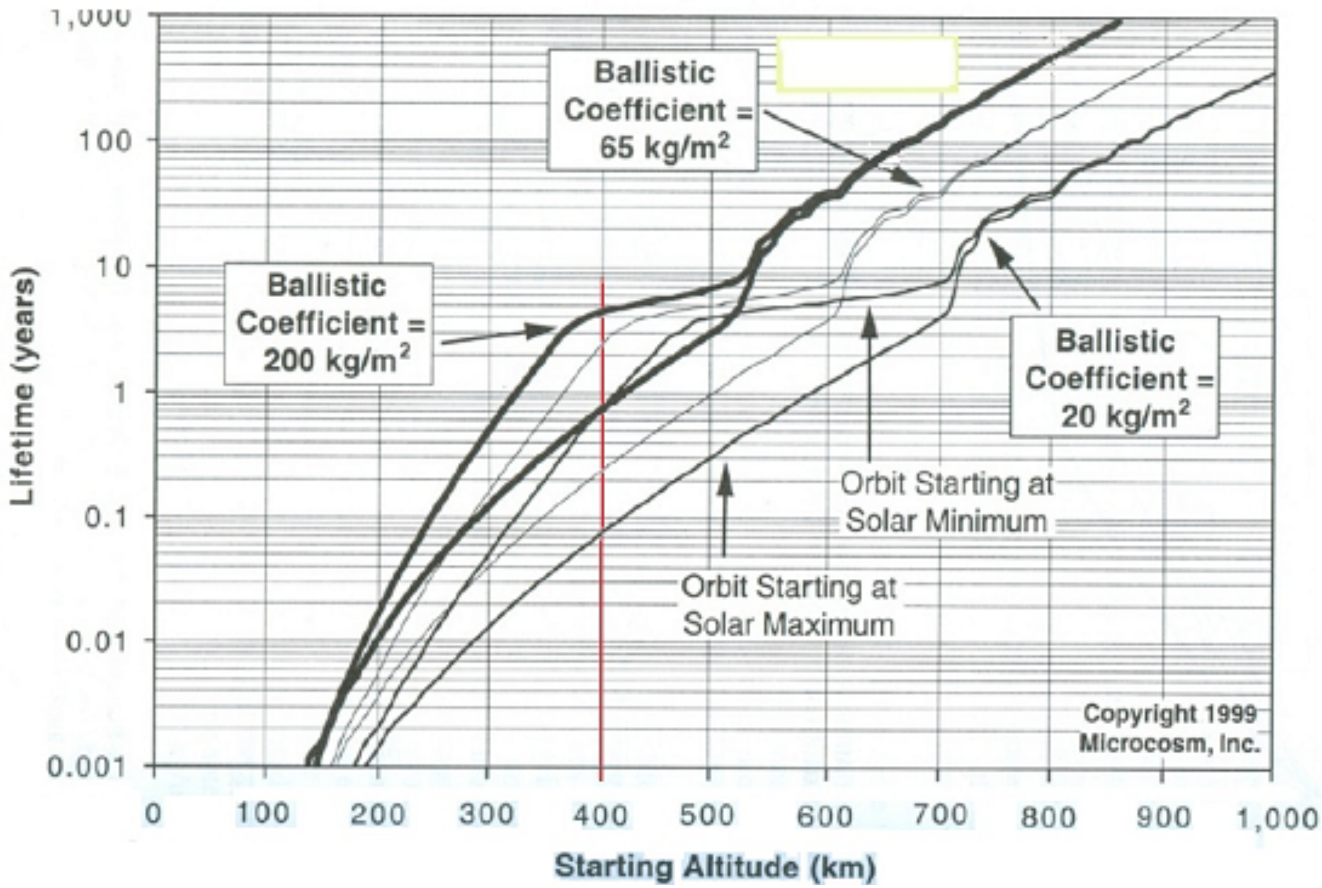


Classification of air-breathing systems

- Ramjet / Scramjet
  - (Supersonic) air-breathing jet engine
  - Fuel-efficient ascent to mesospheric altitudes and half-orbital velocity
- Air-breathing beamed-energy propulsion (see lectures 10/26 and 11/02)
  - Laser or microwave propulsion
  - Fuel-efficient ascent to orbital altitudes
- Atmosphere-breathing in-space propulsion
  - Use of atmospheric residual gases in spacecraft propulsion
  - Reduction of atmospheric drag in lower altitudes
  - Extension of in-orbit lifetime

Orbit decay without propulsion

- Orbit decay of satellites is driving factor for lifetime in LEO



Larson, W. J. and Wertz, J. R., *Space Mission Analysis and Design*, Microcosm, Inc., Torrance, CA, and Kluwer AP, Dordrecht, Netherlands., 2nd ed., 1992.

Ballistic coefficient

$$\beta = \frac{m_{\mathrm{SC}}}{C_{\mathrm{D}} \cdot S}$$

β is high:
- high momentum
- low drag

β is low:
- low momentum
- high drag

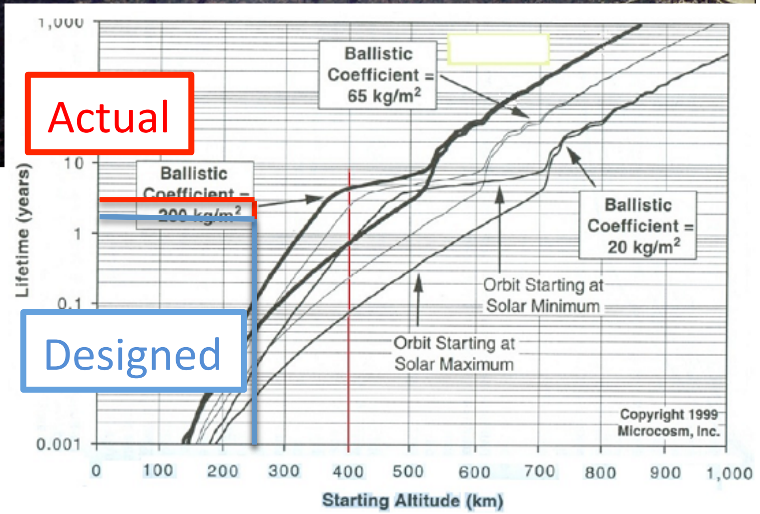
For altitudes lower than 400 km, orbit decay overtakes commercial benefit

Example for LEO spacecraft

- GOCE (ESA)
  - 260 km orbit
  - Designed lifetime:
    - 20 months
  - Actual lifetime:
    - 56 months
    - Lower solar activity than expected
  - Use of fuel-efficient ion thrusters
  - Very high ballistic coefficient to extend possible lifetime

$$\beta = \frac{1077\,\mathrm{kg}}{3.7 \cdot 0.9\,\mathrm{m}^2} = 323\frac{\mathrm{kg}}{\mathrm{m}^2}$$

  - Reason for end of life:
    - Fuel depletion, decayed



Purpose of air-breathing propulsion

- Extension of satellite lifetime in LEO for orbit altitudes less than 400 km
  - Increase data outcome of Earth observation satellites, scientific platforms, reconnaissance/espionage satellites, etc.
  - Increase profit margin for commercial satellites
- Enable scientific missions in very low Earth orbits (VLEO) of less than 160 km in altitude

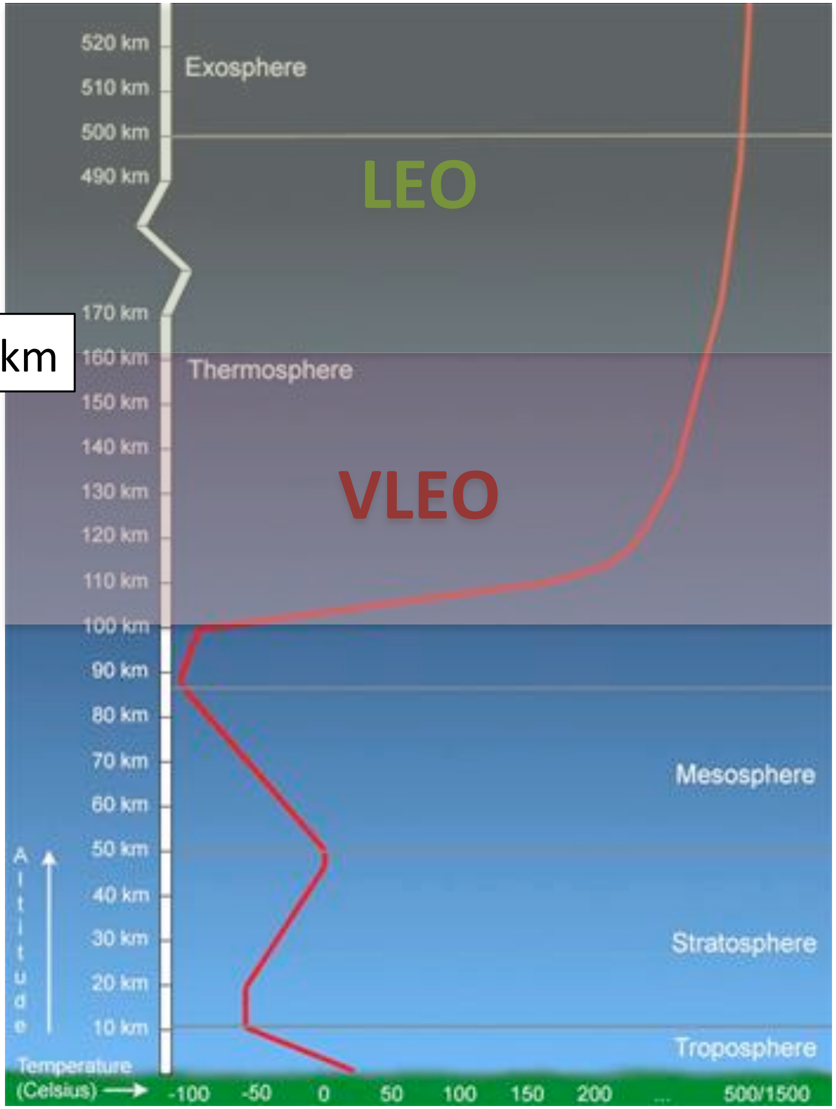
↓

Air-breathing space propulsion

Atmosphere

- Thermosphere and especially the VLEO are scientifically interesting due to strong gradients in physical profile
- Satellites in orbits closer to Earth could enable new missions
  - Earth observation
  - Scientific applications
  - Military use
  - …

160 km



Atmospheric properties

- Necessary properties for design of spacecraft and breathing propulsion system
  - Mass density (translates to eventual usable mass flow rate and drag force)
  - Temperature, conductivity (influence on collector and satellite design)
  - Atomic, ionic, and molecular species; molar composition (usage as propellant)
  - …

- De facto standard model for description of the atmospheric properties is the 1975 International Standard Atmosphere (ISA) with amendments in 1985 and 1997

Atmospheric models (a brief review)

MSIS: Mass Spectrometer and Incoherent Scatter

1960

Jacchia model (1965, 1971)
- Total density as f(h)
- Temperature as f(h)

1970

MSIS (1977)
- Species composition included (N_2, O_2, O, He, Ar, and H)
- 120-150 km

1980

MSIS-83
- 80-220 km

MSIS-86
- Atomic nitrogen added

1990

MSISE-90
- Revision for 120 km and below (down to mesosphere)

Current most accurate model for total density

2000

JB2006
- Improved density description
- New temperature as f(h)

NRLMSISE-00
- Anomalous oxygen
- Improved modeling

Current most accurate model for composition

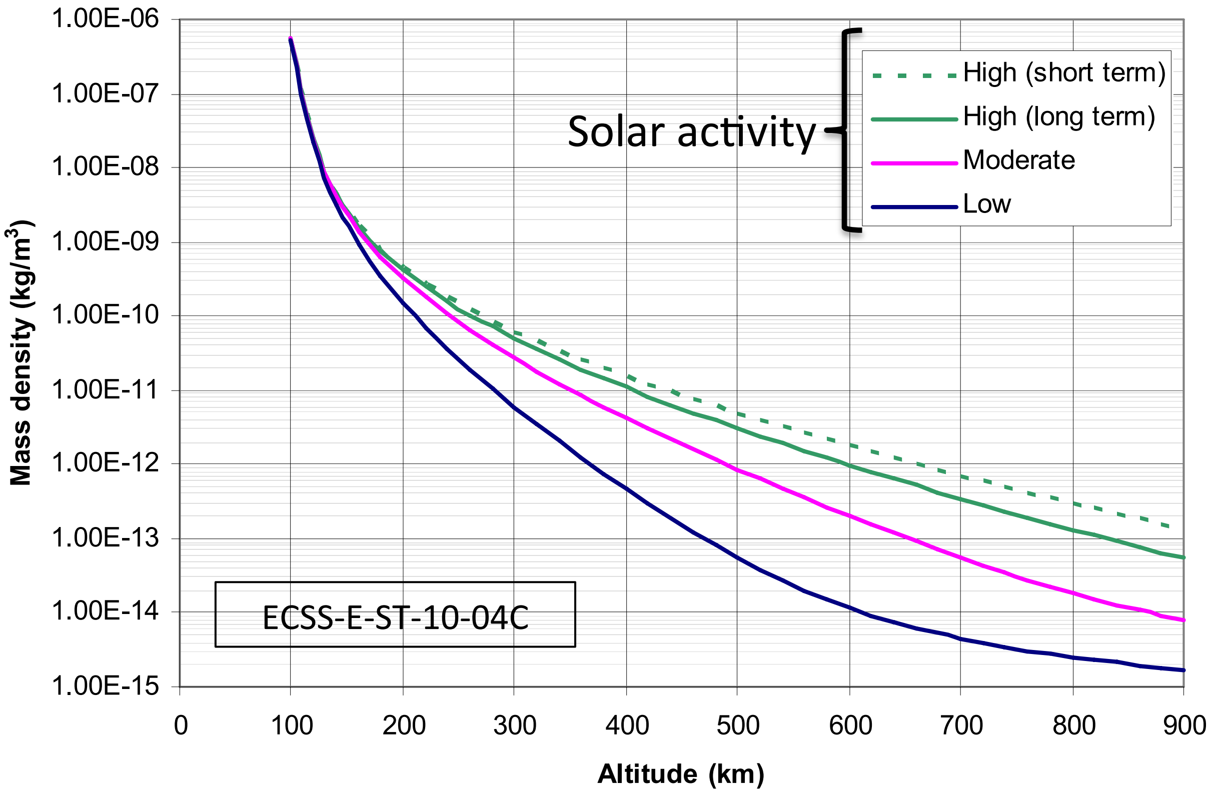
now

JB2008
- Even better temperature function

Both models adapted to the 2008 ECSS standard ECSS-E-ST-10-04C

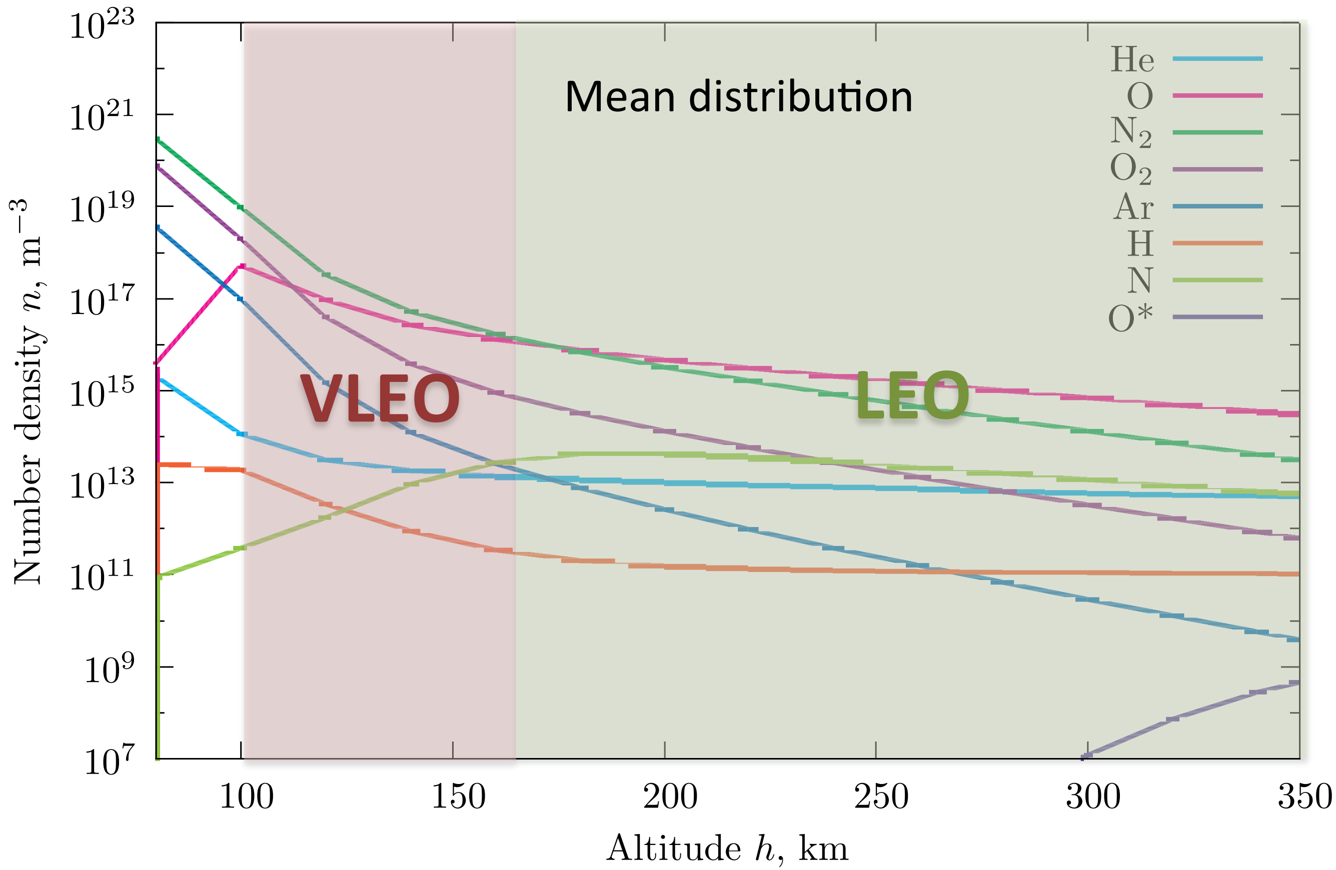
Atmospheric properties

- Atmospheric density as a function of altitude and solar activity
- Several parameters affect density
  - Location
  - Time of year
  - Solar activity



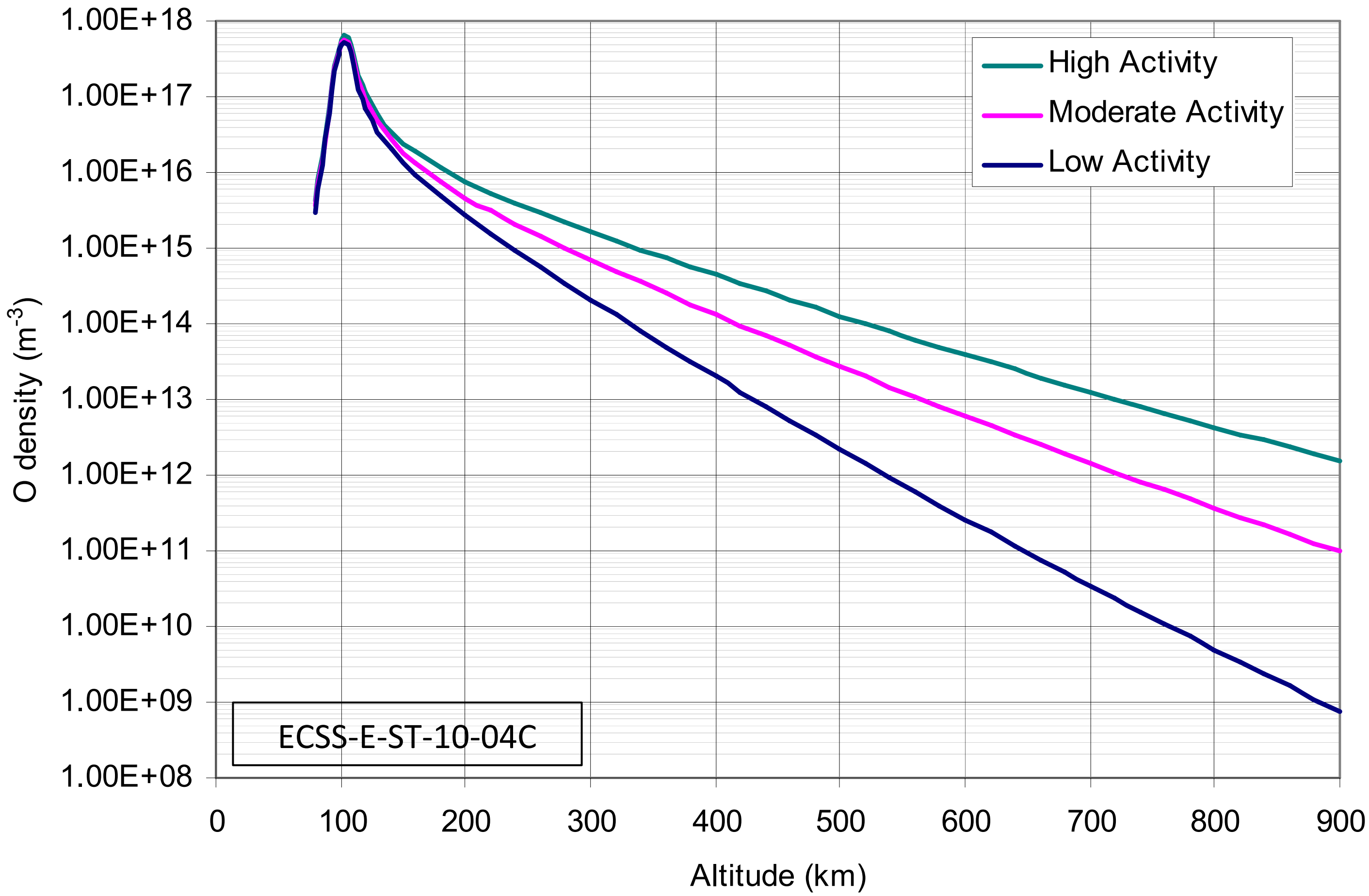
Composition of species

- Strong gradients of temperature and variation of solar radiation yield distribution of species over altitude
- For most orbit altitudes residual air consists of molecular nitrogen and atomic oxygen
- Negligible degree of ionization



Atomic density

- Influence of solar activity on densities of individual species



Consequences for the satellite

- Atmospheric drag force imposed on satellite

$$F_D = \frac{1}{2}\underbrace{\rho}_{JB2006}\cdot\underbrace{v^2}_{7.8\ \mathrm{km/s}}\cdot S\cdot\underbrace{C_D}_{2.1-2.7}$$

Orbital speed

$$v \approx \sqrt{\frac{GM}{r}}$$

G … Gravitational constant

M … Earth's mass

r … Orbit radius

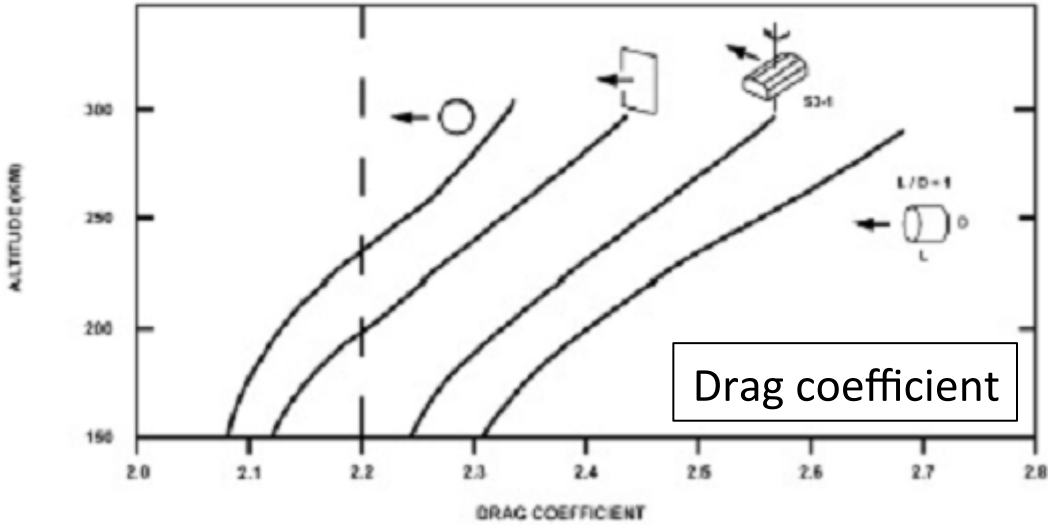


Figure 3.5: Coefficient of Drag Values: sample c_D values [RD8]

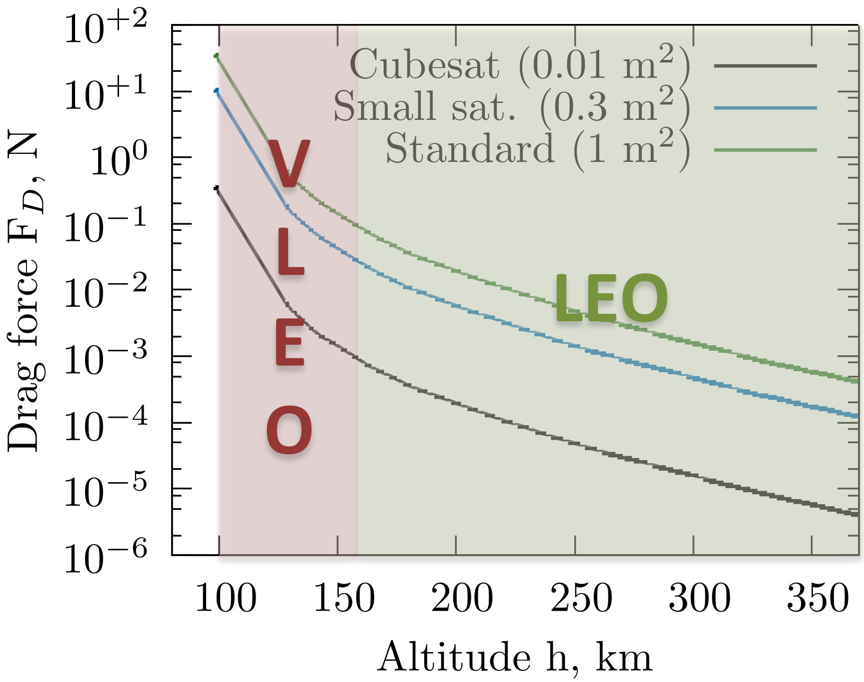
Sentman, L. H., "Comparison of the Exact and Approximate Methods for Predicting Free-Molecular Aerodynamic Coefficients," *American Rocket Society Journal*, Vol. 31, 1961, pp. 1576–1579.

Drag coefficient

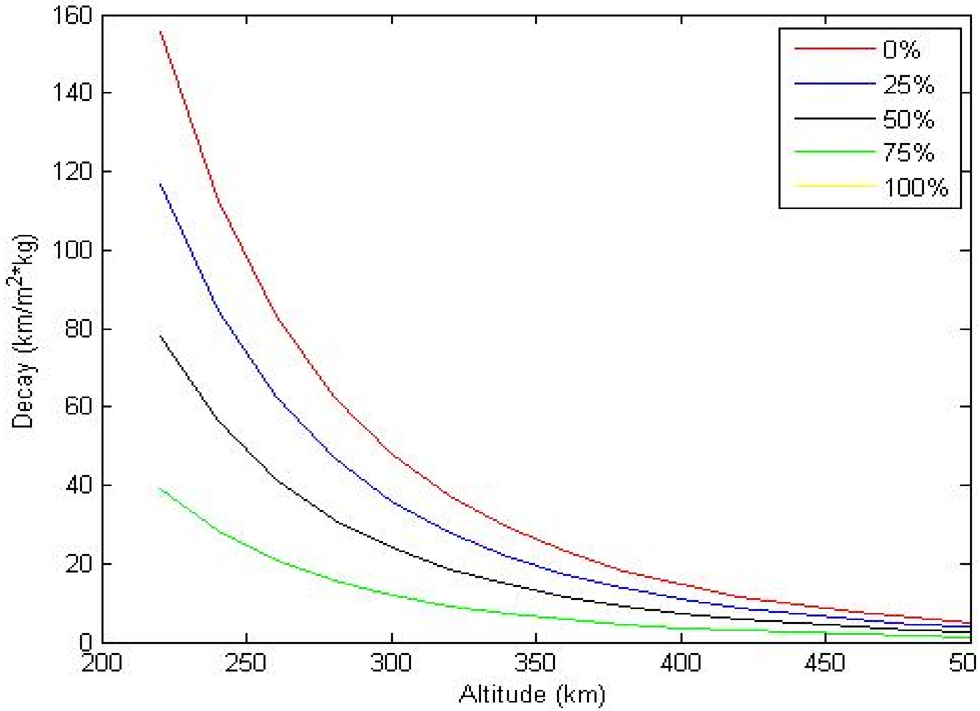
- Drag coefficient is influenced by several parameters
  - Atomic oxygen can adhere to surfaces altering their physical properties
  - Temperature changes can affect material characteristics of outer surfaces
  - Long, slender spacecraft design increases drag coefficient due to friction on the side walls (e.g., GOCE had a drag coefficient of 3.7)
  - Solar arrays and other hardware features affect drag

Drag force

- Resulting drag force (at mean solar activity; for C_D = 2.2)



- Orbit decay as a result of partial drag compensation



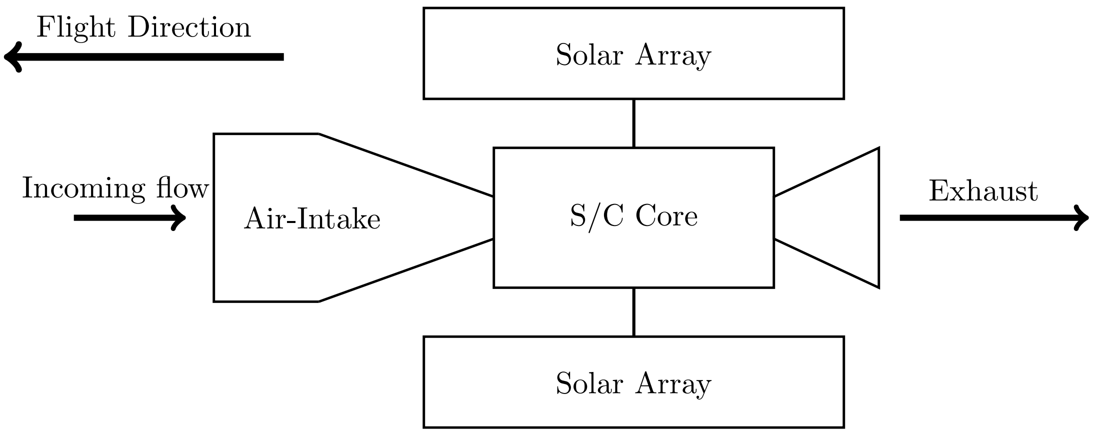
ESA study (IEPC-2007-162)

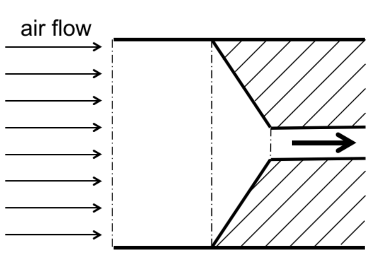
Conclusions from atmosphere analysis

- Obviously, as size of the satellite decreases, drag force necessary to be compensated decreases as well
- Depending on altitude and targeted lifetime, propellant necessary to overcome the total drag force might be small enough to be carried on board of the satellite
- Resulting from an ESA study, application of air-breathing technology to satellites in orbits above 250 km is not competitive with „conventional“ electric propulsion (propellant break-even point)

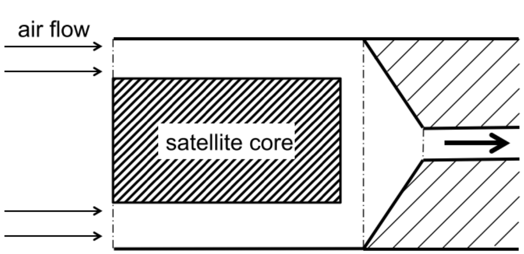
System design for air-breathing propulsion

- Air-breathing propulsion **system** requires more than just a thruster
  - **Intake** to collect necessary mass flow and pre-compression
  - Accumulation and further compression in the **S/C core**
  - **Thruster** suitable to handle atmospheric gases





(a) Air-Intake Simple Cone Concept.



(b) Air-Intake By-Pass Concept.

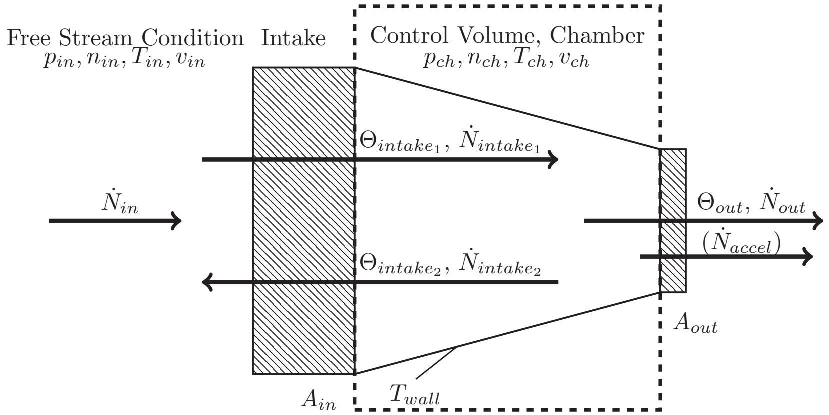
Collector system

- Collector is necessary to gather propellant from residual atmosphere to yield a mass flow rate for the thruster
- Due to low degree of ionization, electromagnetic collector systems can be discarded
- Mechanical system has many parameters
  - Width, length, material, wall temperature, …
  - Numerical simulation (e.g., DSMC PIC) essential in design process
- Performance values:
  - Compression ratio

    $$p_{prop}/p_{in}$$

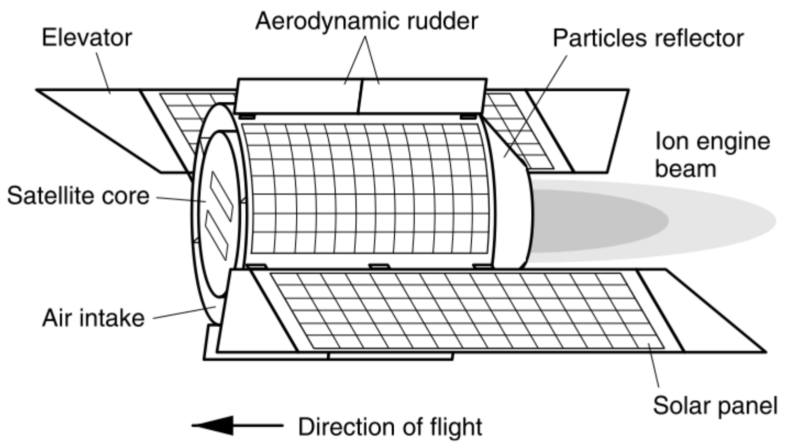
  - Collection efficiency

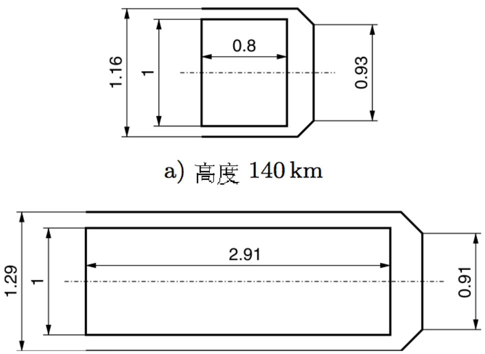
    $$\dot{m}_{prop}/\dot{m}_{in}$$



Air inlet examples

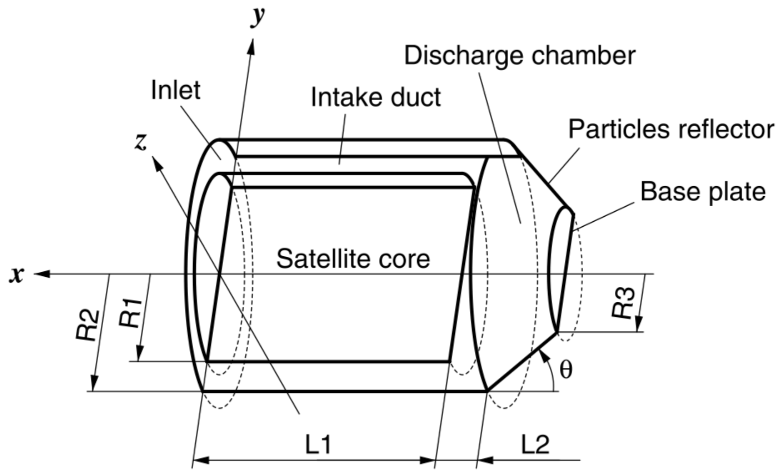
- 1st comprehensive study conducted at JAXA (Nishiyama/Fujita)
  - ABIE: air-breathing ion engine
  - Variation of parameters to analyze possible performance
  - Compression ratio derived to be around 100-200
  - Optimum collector design depends on altitude





a) 高度 140 km

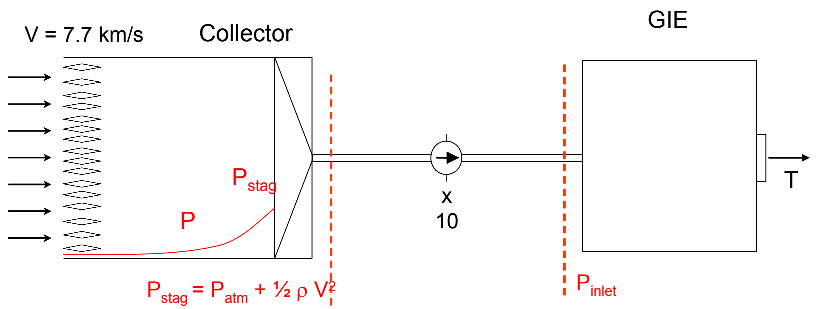
b) 高度 200 km



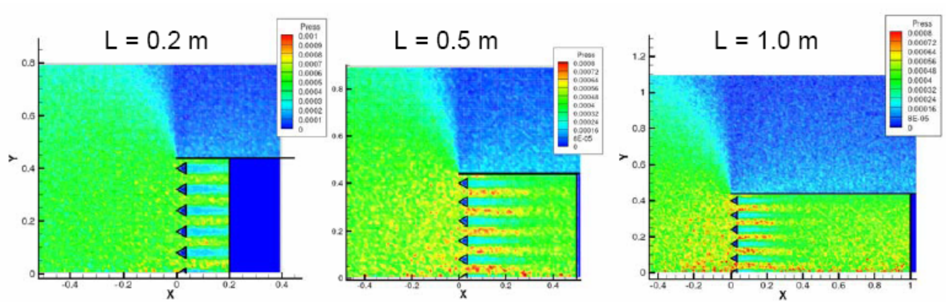
Air inlet examples

- Subsequent studies at ESA and Busek (US company)

ESA, 2007

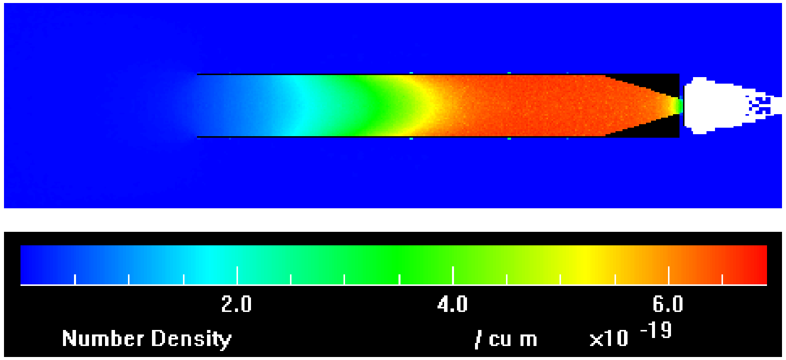


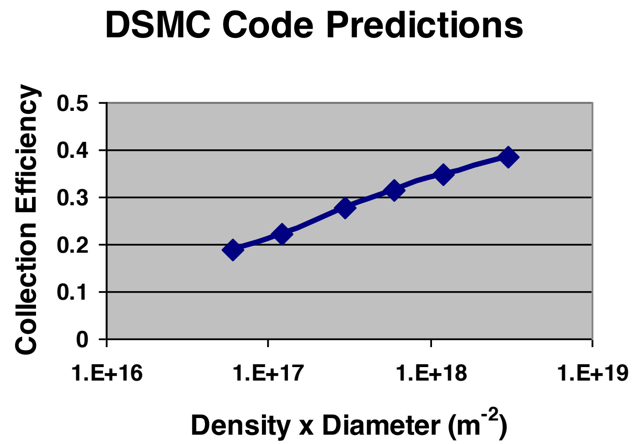
Pressure for different aspect ratios



→ about 1 mPa achievable

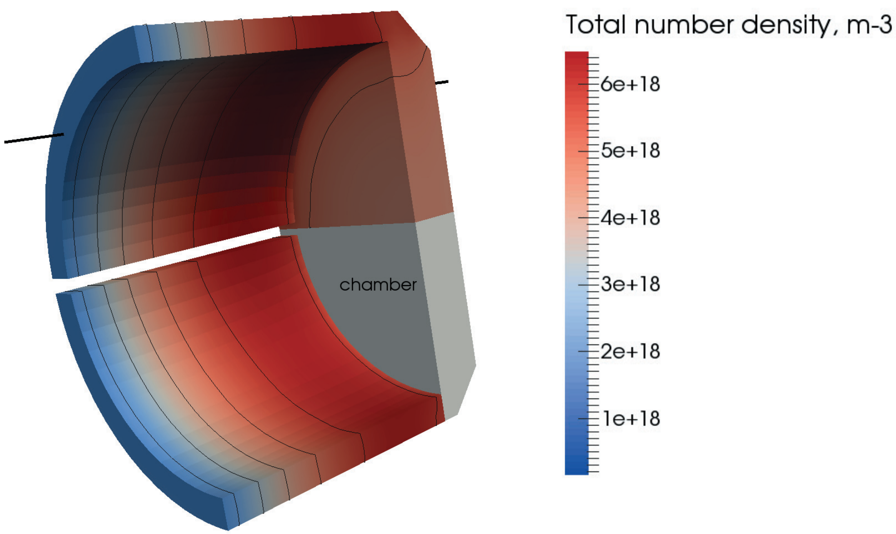
Busek, 2012

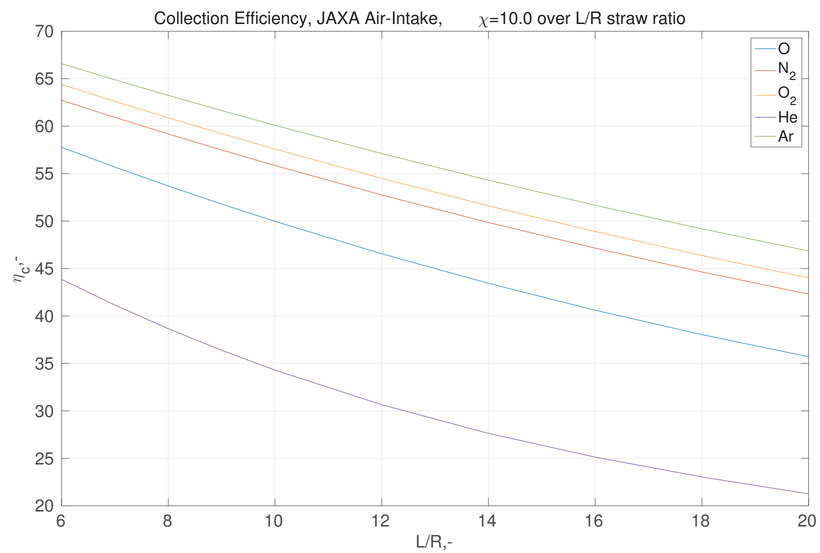




Air inlet examples

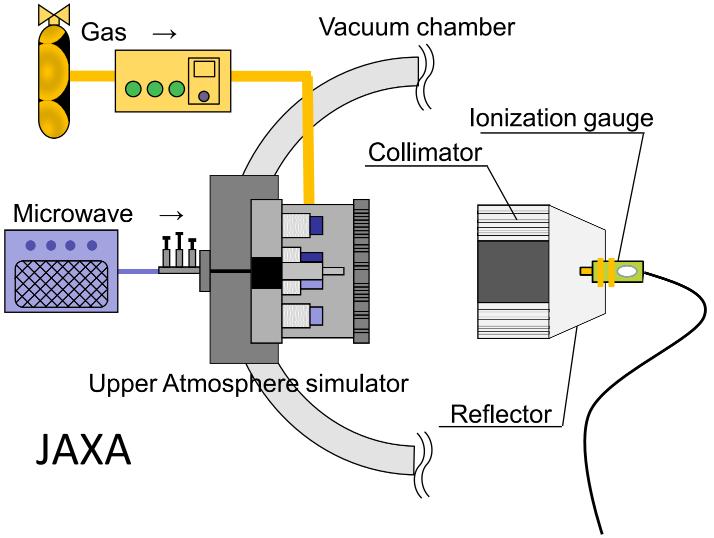
- Study at U Stuttgart (Germany)
  - Rarefied flow computation with coupled 3D full-PIC DSMC
  - Numerical analysis necessary as incident flow is not a continuum flow
  - Geometrical variation can yield optimum collection efficiency
  - Addition of straws in the intake flow increases efficiency
  - Tracking of individual species feasible





Air inlet – what to expect

- Compression ratio
  - Achievable results around 100-200
  - Typical p_{prop} around 1 mPa
- Collection efficiency
  - Typical values in the order of 40 %
- Experimental verification by upper atmosphere simulators

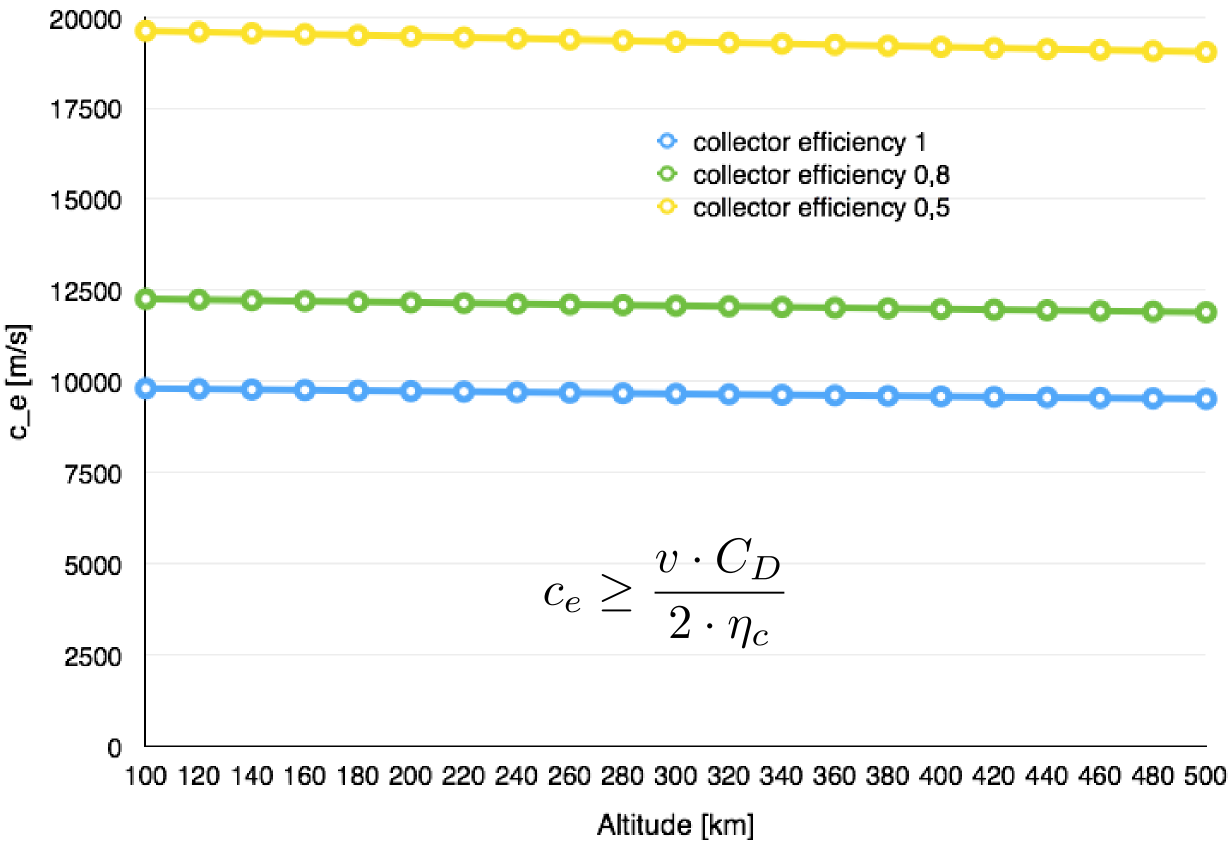


JAXA

ATOX at ESA-ESTEC

Consequences for the satellite

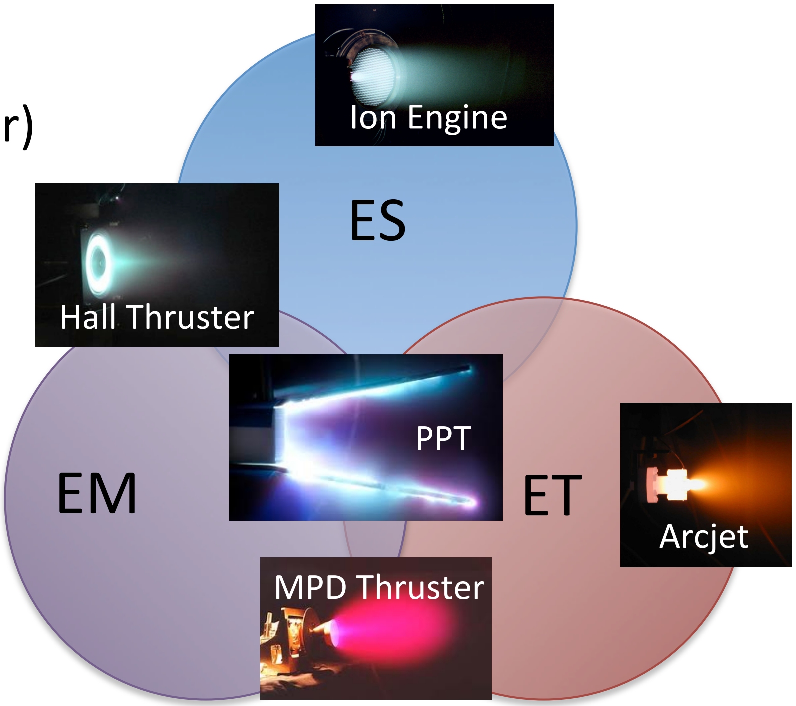
- As collection efficiency decreases, thrust and, hence, exhaust velocity have to increase to compensate the drag force



$$c_e \geq \frac{v \cdot C_D}{2 \cdot \eta_c}$$

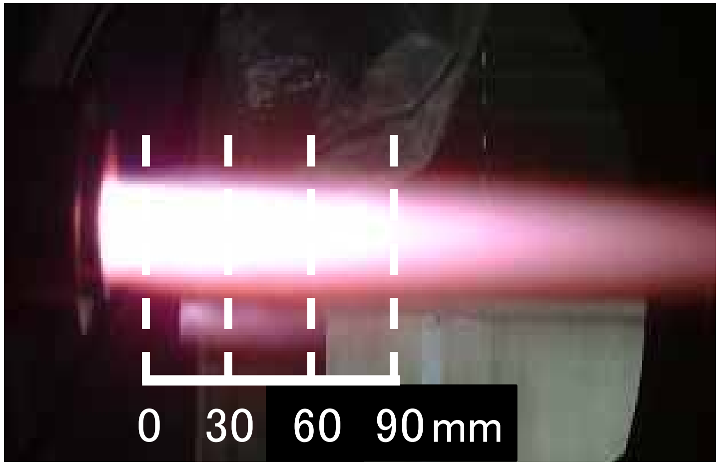
Possible propulsion options

- Chemical propulsion
  - Maximum exhaust velocity of 4.5 km/s far less than requirement
  - No favorable reaction with molecular nitrogen
- Electric propulsion (see also lecture 10/19)
  - Electrothermal (resistojet, arcjet)
  - Electrostatic (ion thruster, Hall thruster)
  - Electromagnetic (MPD, PPT)
- Other concepts



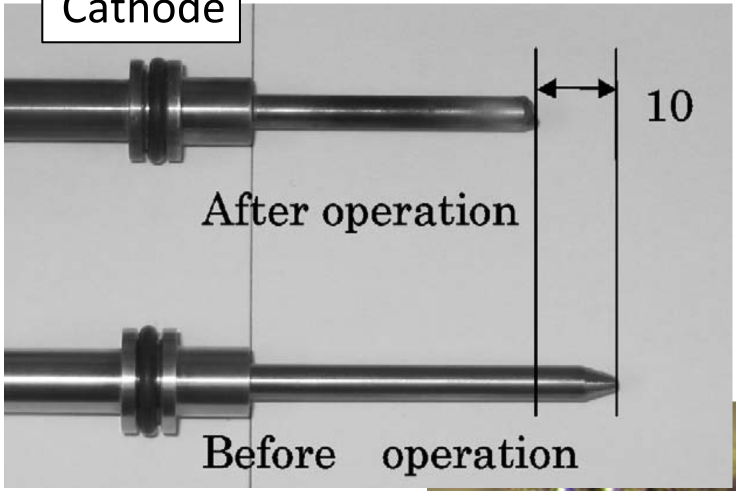
Electrothermal propulsion

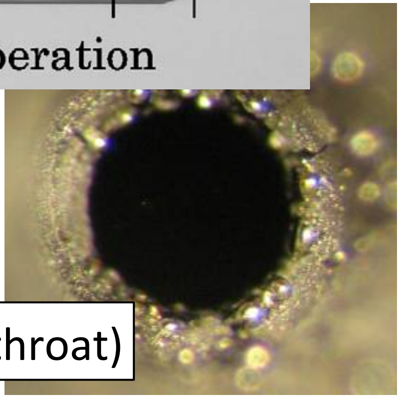
- Resistojets and arcjets are basically capable of using atmospheric propellants, but erosion due to oxygen will decrease the lifetime of thruster dramatically



Arc-heated plasma generator
using argon/oxygen

Cathode

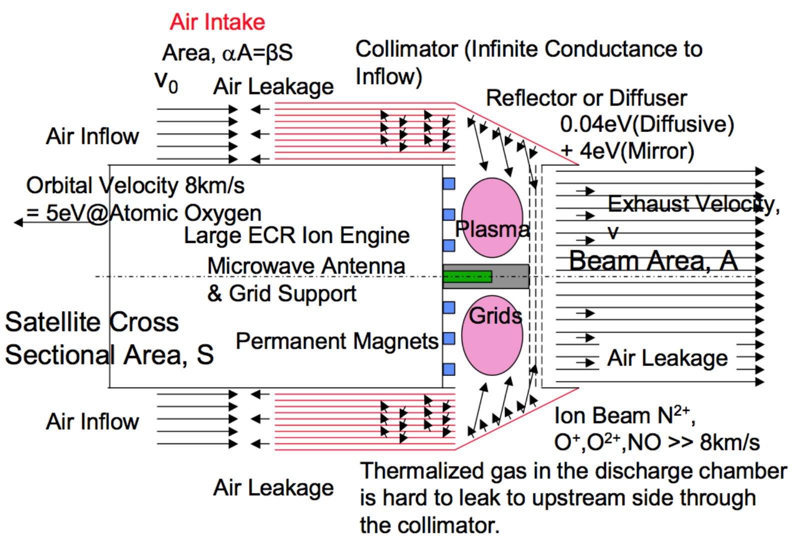




Anode (nozzle throat)

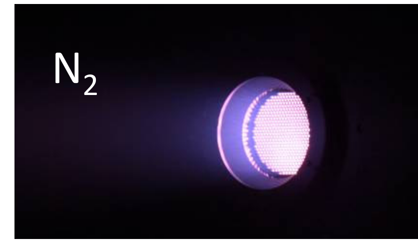
Electrostatic propulsion - Ion thruster

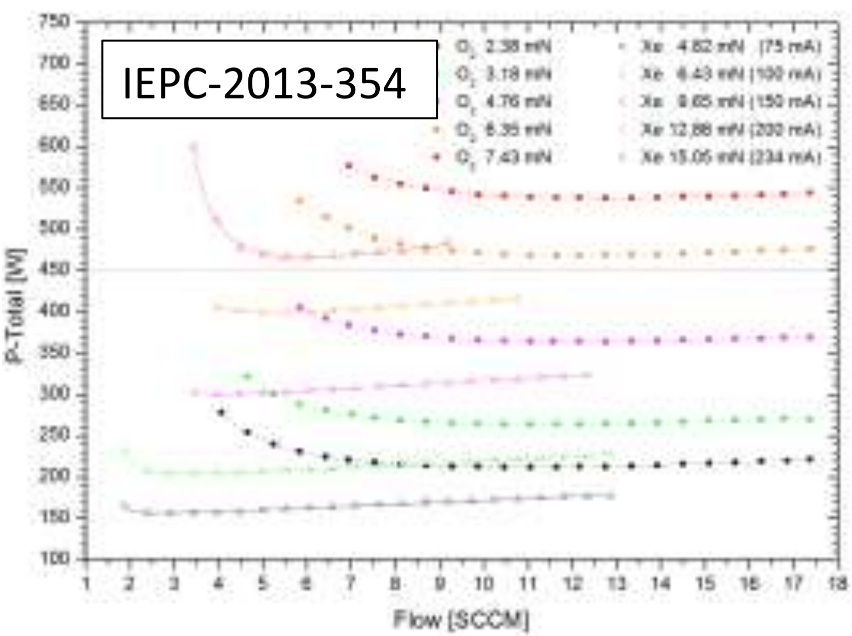
- ABIE (JAXA, 2003)
  - Aimed for 150-200 km of altitude
  - Microwave discharge ion thruster
  - Operation at low injection pressures of 5 to 500 mPa
    (→ additional compression required)
  - T/P around 10 mN/kW
  - Size would require a compensation of 50 to 100 mN of drag
    → significant power requirement



Electrostatic propulsion - Ion thruster

- Feasibility evaluation of atmosphere-breathing ion thruster
  - RIT-10 tested on atmospheric gases (N_2, O_2, Xe)
  - 450 W nominal power
  - → Thrust level of around 7 mN (~140 km)
  - Grid erosion not a crucial issue (after 500 h)





RIT-10	Xe	N_2	75% O_2 25 % O
Power (W)	467	574	540
MFR (mg/s)	0.489	0.194	0.170
P_{prop} (mPa)	78.13	115.1	86.93
Thrust (mN)	14.71	6.83	6.79
I_{sp} (s)	3100	3636	4328

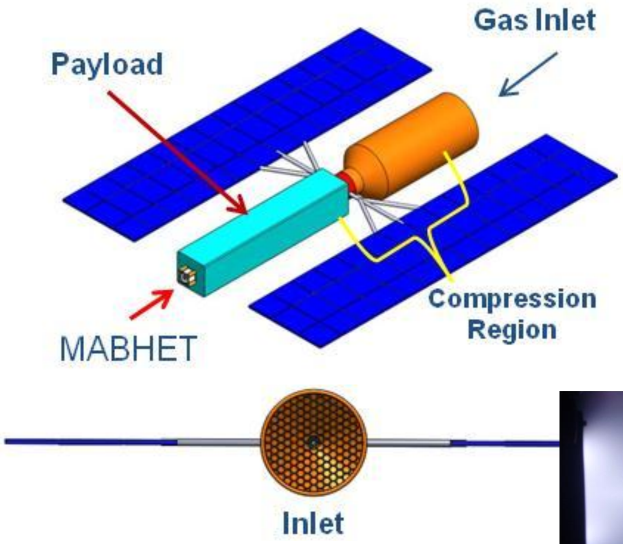
Conclusions ion thruster

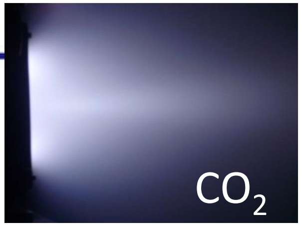
- Operation basically feasible
  - Nitrogen and oxygen successfully yield thrust at a range of MFR
  - Thrust level sufficiently high to overcome drag force
  - Erosion not seen threatening to thruster lifetime
- However:
  - Power necessary to use low MFR exceeds on-board capabilities
  - Thrust density (thrust/surface area) too small; tested MFR are only feasible if propellant is stored during off-times
  - Propellant storage and compression to achieve usable pressure will increase system weight on satellite

Electrostatic propulsion - Hall thruster

- Proposed firstly by Busek Company in the early 2000s (US patent 6,834,492 B2)

- Proposal of Mars-based atmosphere-breathing system
  - Thrust/power of 30 mN/kW at 120 sccm of CO_2 mixture
  - 20 % of thrust efficiency
  - Inlet pressure of few 100 mPa
  - Martian atmosphere less studied
  - Planned maiden flight by 2025

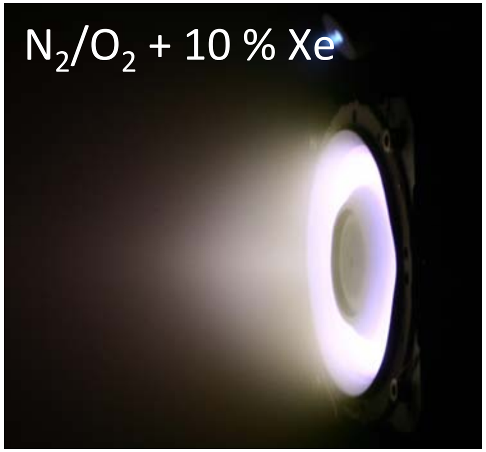


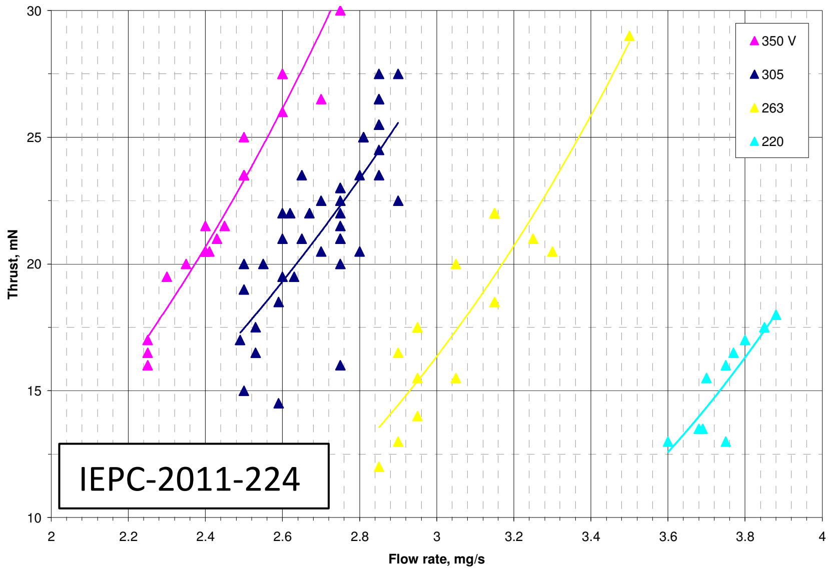


All images: Courtesy of Busek

Electrostatic propulsion - Hall thruster

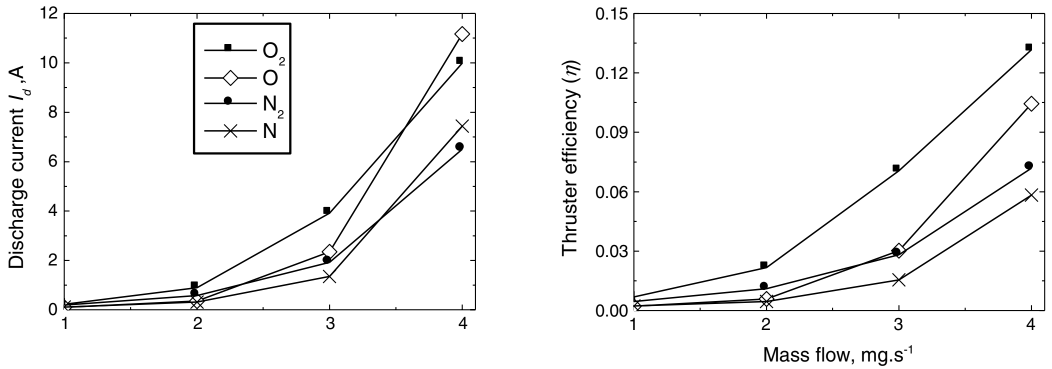
- PPS®1350 (SPT) tested with atmospheric gases
  - N_2, N_2/O_2 + additive of xenon
  - Thrust of 20 mN at power input of 1 kW and MFR of 2.5 mg/s
  - Adding Xe increases thrust by 4-40 %
  - Wall erosion very severe
    - → New materials required
    - → Reconfiguration of magnetic field for shielding might reduce effects



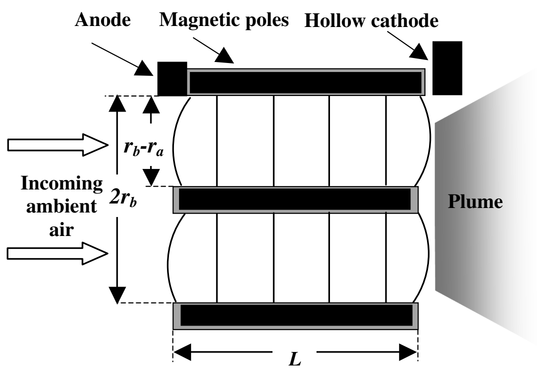


Electrostatic propulsion - Hall thruster

- Computational studies
  - University of Toulouse, 2012
    - Target values: 20 mN, 1 kW, 10 % @ 250 km → 3 mg/s
    - Propellant storage necessary



  - George Washington U / US AirForce, 2012
    - High power (700-800 kW), high thrust (9 N) for an application below 100 km (VVLEO)

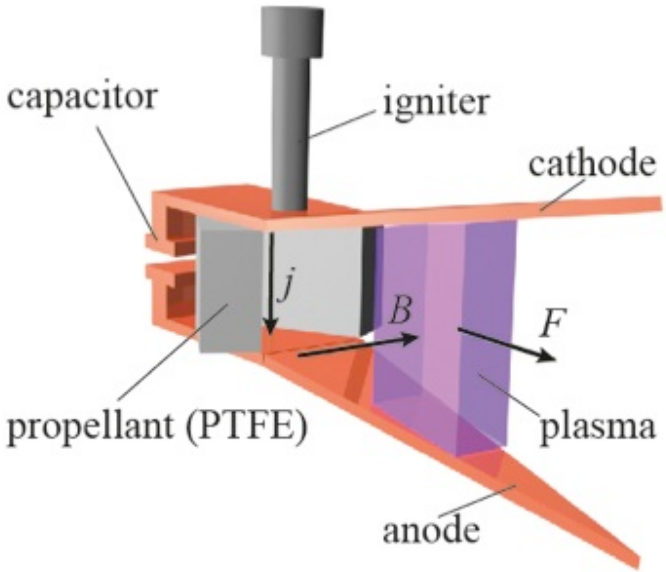


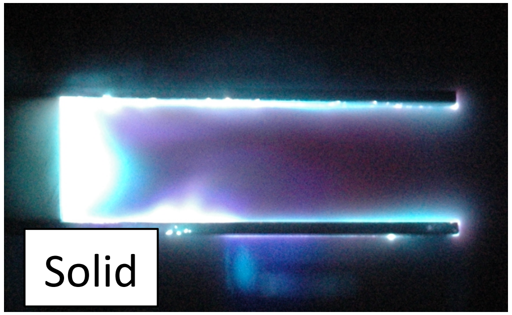
Conclusions Hall thruster

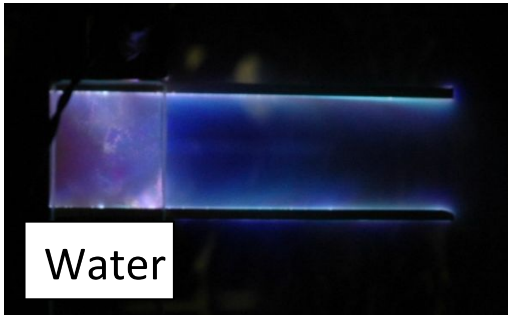
- Operation basically feasible
  - Usage of nitrogen, oxygen, air mixture, CO_2-based mixture
  - Higher thrust density yields smaller drag to be compensated
  - Measures to reduce wall erosion exist
- However:
  - Minimum MFR for operation high compared to collectable inflow
  - On-board propellant storage necessary
  - *"The Hall-effect thruster application to compensate the atmospheric drag force for a spacecraft in a low orbit altitude is* ***not*** *possible because a large amount of propellant must be stored to compensate for the continuous force acting on the spacecraft for a long time, which increases the weight of the spacecraft and mission requirements."* (U Toulouse, 2012)

Electromagnetic - Pulsed plasma thruster (PPT)

- Short-time pulsed electrical arc discharge
  - Across a solid or non-volatile liquid propellant surface (ablative PPT)
  - Or: through an injected liquid or gaseous propellant
- Usable at very low power inputs (few watts) and very low propellant masses per shot (few µg)

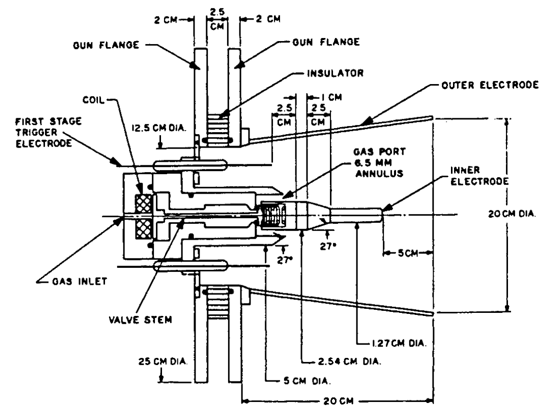






Electromagnetic - Pulsed plasma thruster (PPT)

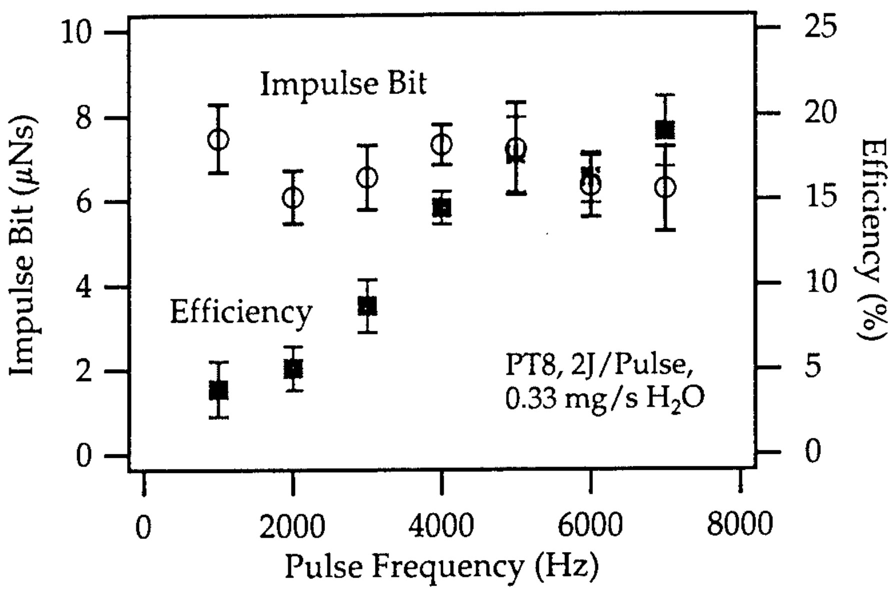
- PPT never explicitly evaluated on air-like propellants
- Gas-fed PPT research started as early as the 1960s, e.g. at General Dynamics, General Electric
  - Usage of N_2, Xe, H_2
  - High propellant utilization efficiency of 60 % for N_2
  - Thrust/Power ratio around 10-20 mN/kW
  - High discharge energies of 50-100 J

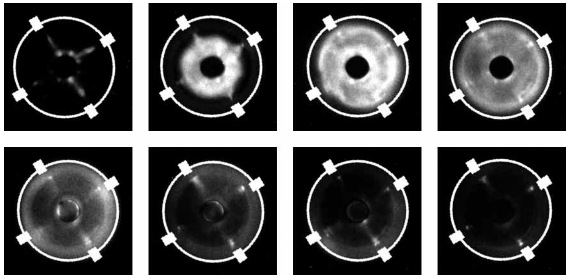


- 540 J-GPPT at Republic Aviation (later: Fairchild Industries), 1960s
  - Successful ignition with 10^{20} m^{-3} (from simulation at inlet: 10^{18} m^{-3})

Electromagnetic - Pulsed plasma thruster (PPT)

- 1990s/2000s Princeton University
  - Low energy at high frequency (up to several kHz)
  - 6 mN/kW with argon





Princeton, 2001

Electromagnetic - Air-breathing PPT

- Performance estimation – what to expect
  - For a typical ratio of 5 J of discharge energy per µg of injected mass
    - I_{sp} = 5000 s
    - T/P = 15-20 mN/kW (unoptimized; 1960s) → ≈30 mN/kW (optimized)
    - Discharge frequency variable

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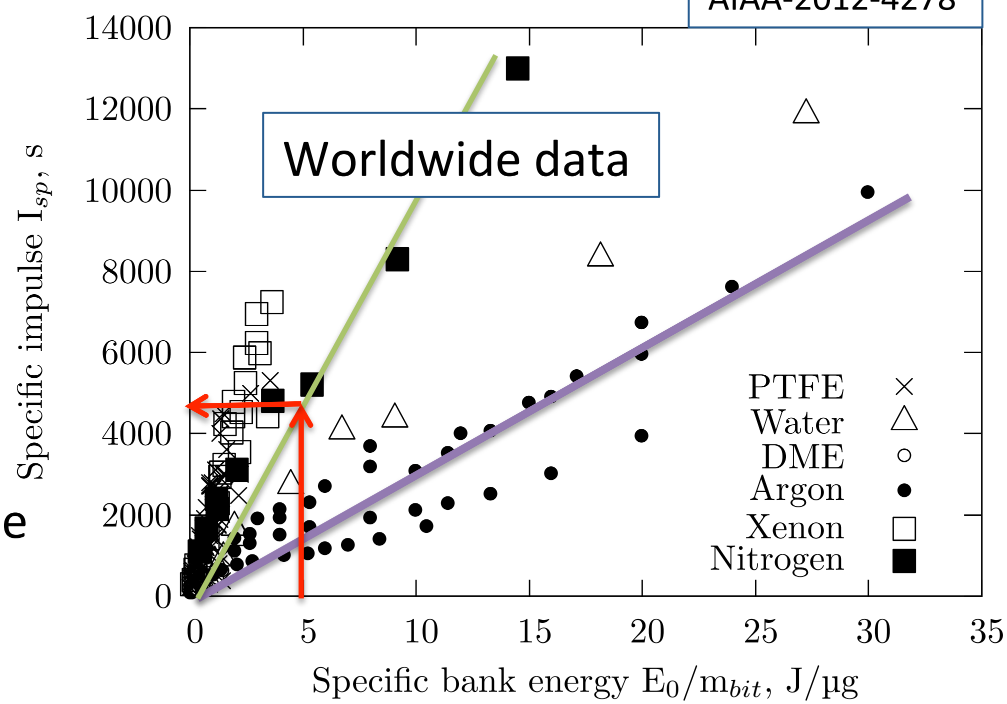
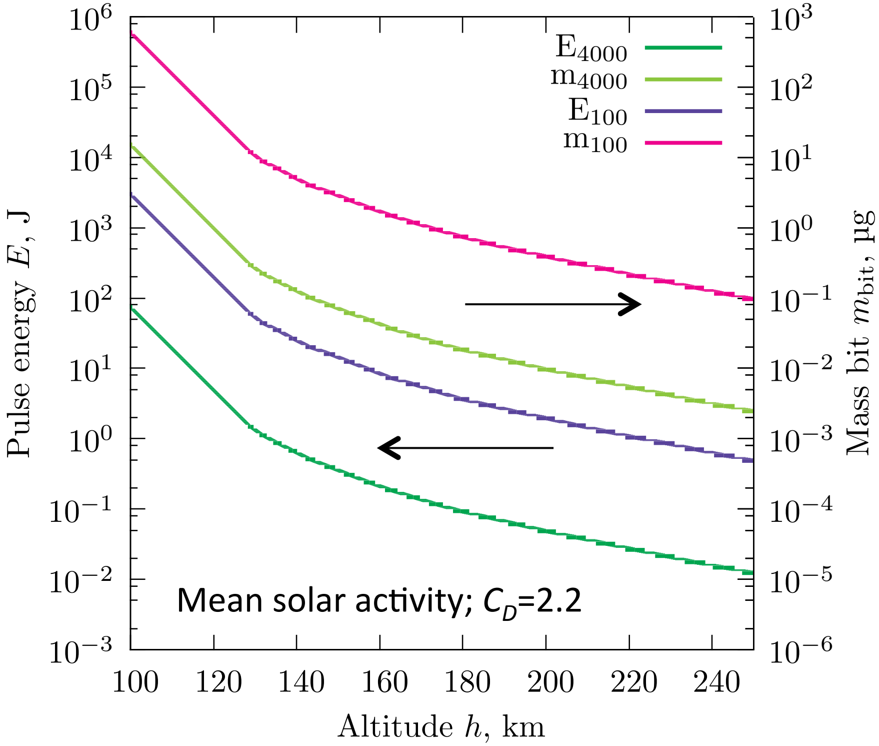


h → Drag = f(h) →(T/P) **Necessary power** →(f) **Necessary energy** →(5 J/µg) **Necessary m_{bit}**

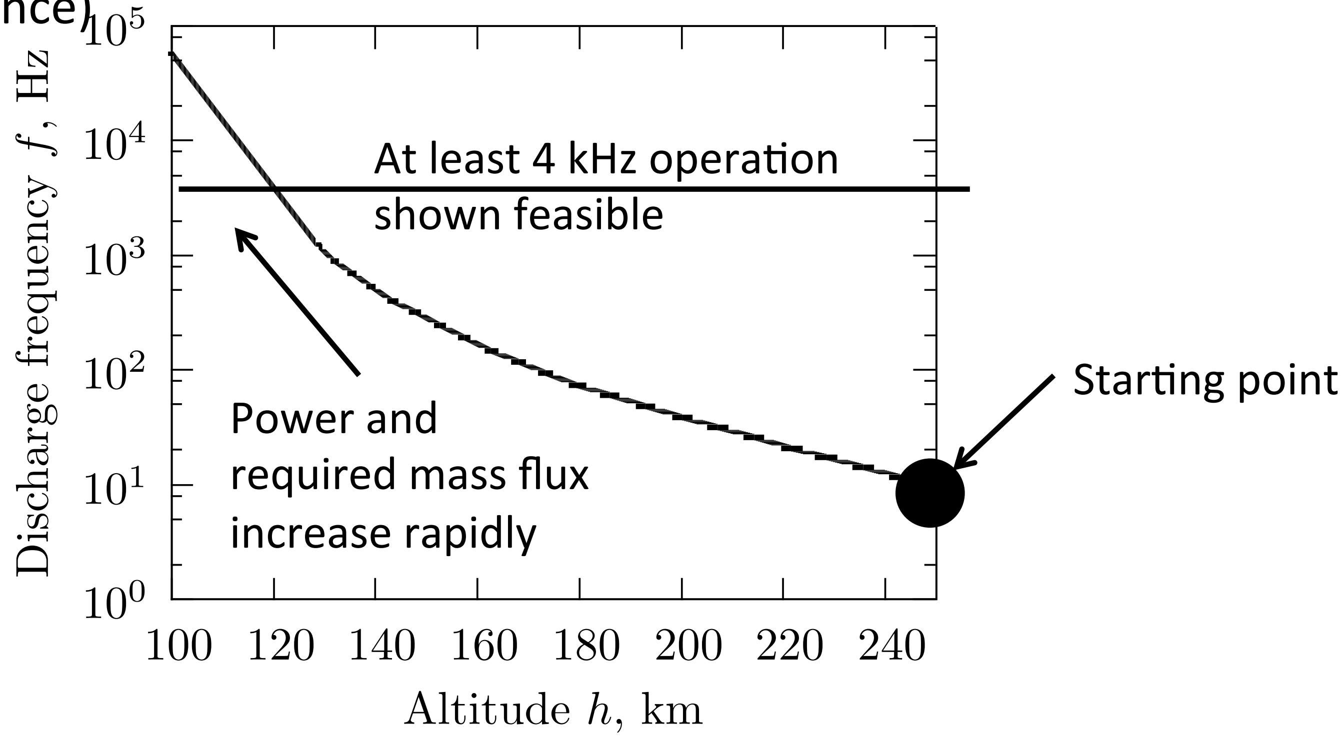
Air-breathing PPT – exemplary mission

- Exemplary mission scenario 1
  - FULL drag compensation for a small satellite (0.3 m^2)
  - Then: Optimum discharge frequency depends on altitude
  - Still requires storage of propellant, thus full compensation might be difficult



Air-breathing PPT – exemplary mission

- Exemplary mission scenario 2
  - PARTIAL drag compensation resulting in a slowed-down orbit decay
  - As altitude decreases, PPT discharge frequency can be adjusted to keep energy and mass bit constant (thus: constant single-pulse performance)



Conclusions electromagnetic propulsion

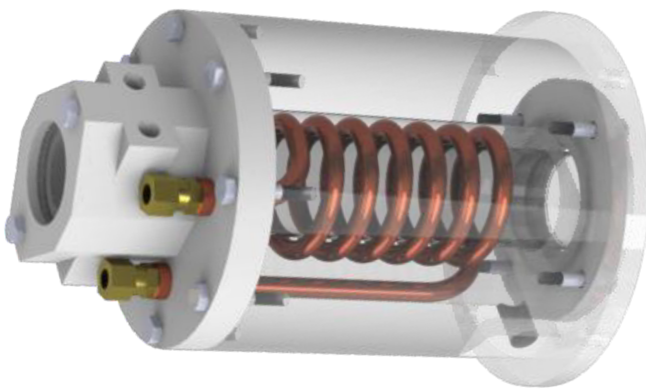
- Operation theoretically feasible
  - Preliminary tests with gaseous propellants show high potential, but tests with atmospheric gases still missing
  - Thrust/power ratio in similar magnitude as electrostatic propulsion
  - Operation at low energy and mass inputs reduces need for on-board propellant storage
- However:
  - Electrode erosion phenomena unclear

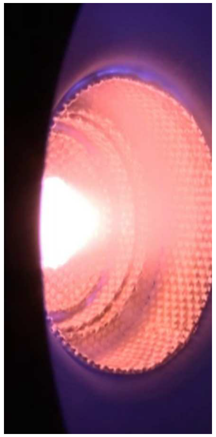
Comparison of breathing electric propulsion systems

Parameter	Electrothermal	Ion thruster	Hall thruster	PPT
Operation with atmospheric gases	Partially tested	Feasible	Feasible	Partially tested
Operation at low MFR	Not feasible	At high power	Not feasible	Feasible
Necessary exhaust velocity	Not feasible	Feasible	Feasible	Likely feasible
Thrust/power	Sufficiently high	Sufficiently high	Sufficiently high	Sufficiently high
Thrust density	High	Low	High	Medium
Erosion	Severe	Low	Still severe	Unknown
Propellant storage	Very necessary	Very necessary	Very necessary	Necessary

Advanced concept - Inductively coupled plasma

- IPG 6^{th} generation at U Stuttgart
  - Mass flow rates of 20 to 400 mg/s (air, CO_2)
  - Current PG power: 15-20 kW with 22 %





  - Electrode-less design implies no erosion, thus, suitable for all compositions of atmospheric gases

Advanced concept - ICP thruster

- ICP propulsion system design criteria
  - 4.4 mN per 1 mg/s for 10 MJ/kg (estimation from PG data)
  - As PG, same overall efficiency for continuous operation and pulsed operation of 1-10 ms
  - No optimization yet for propulsion purposes, but high potential
  - Scaling for lower power and reduced mass flow rates necessary
- Extension in future to propulsion system includes application of nozzle technology (mechanical, magnetic)