A collisional Hall thruster

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In this talk

- Increasing thrust over power by introducing ion-neutral collisions during the acceleration (on account of thrust over mass flow rate).
- The mechanism will be explained.
- Experimental confirmation will be presented.
- Possible application (air breathing?)
- A way to enhance the efficiency
- Difficulties in implementation

Trade-off in electric propulsion

In electric propulsion, high thrust over mass flow rate

$$\frac{F}{\dot{m}} = v$$

high specific impulse

$$I_{sp} = \frac{F}{\dot{m} g}$$

At maximal efficiency there is this trade-off: high thrust over mass flow rate

$$\frac{F}{P} \leq \frac{\dot{m} v}{\dot{m} v^2 / 2} = \frac{2}{v}$$

or high thrust over power

$$\eta \equiv \frac{F^2}{2 \dot{m} P} = \frac{1}{2} \frac{F}{P} \frac{F}{\dot{m}} \leq 1$$

Ion-neutral collisions can increase the flow momentum

- When an Ion beam collides with a neutral-gas
- during the acceleration,
- the electric force on the ion flow is larger, and

  a larger momentum is delivered to the flow.
- One way to explain:

  The electric energy delivered to the ions is the same

  (power = current x voltage) but the momentum they acquire is

  larger, since their residence time is larger.

  Momentum (impulse) = electric force x time
- Second way to explain:

  The same directed kinetic energy is delivered to a

  larger mass – larger momentum.
- More mass and a lower velocity. High thrust over power.

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How much larger is the force over power

a length of the acceleration region

λ ion collision mean free path

$\frac{a}{\lambda}$ number of collisions in the acceleration region

Collisionless ions: $F = \frac{I_i}{e} m_i v_0 \quad v_0 = \sqrt{\frac{2eV_a}{m_i}}$

$\frac{a}{\lambda} >> 1 \qquad F = \frac{I_i}{e} m_i v_0 \sqrt{\frac{a}{\lambda}}$

$P = I_i V_a \qquad \frac{F}{P} = \sqrt{\frac{m_i a}{eV_a \lambda}} = \frac{2}{v_0}\sqrt{\frac{a}{\lambda}}$

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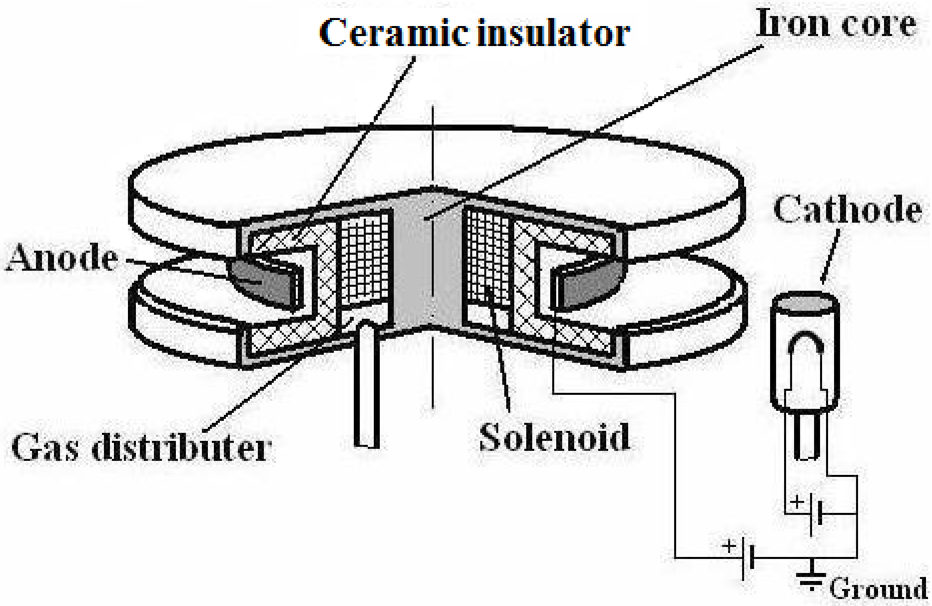
Purpose of experiment

- Measure the momentum imparted to a mixed ions-neutrals flow by an applied voltage.
- The method: measure 1. the ion flux into and 2. the exerted force on a balance force meter (BFM).

Radial plasma source

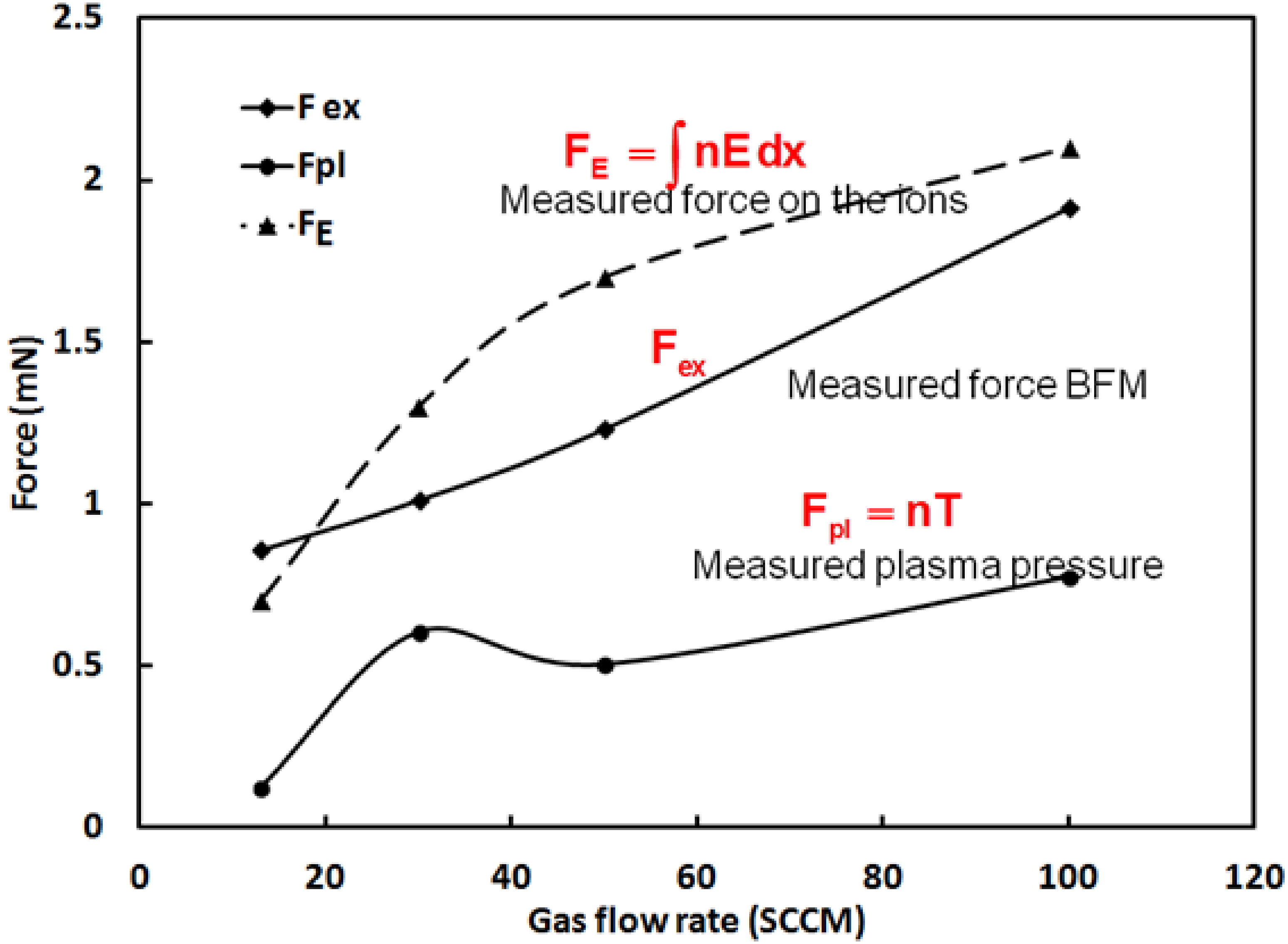


RPS parameters:

- Discharge power- (30-500W),
- Gas – Ar, Xe, He, N_2, C_2F_6, NH_3
- Pressure – 3-300 mTorr,
- RPS diameter - 80mm.

Discharge current	0.9 - 2A
Magnetic field	< 400 G
Gas	Ar, N_2, He
Anode gas flow rate	10 - 700 sccm
Cathode gas flow rate	4 sccm
Pressure	2.5 - 300 mTorr
Discharge voltage	240 - 35V

Force deduced from local measurements



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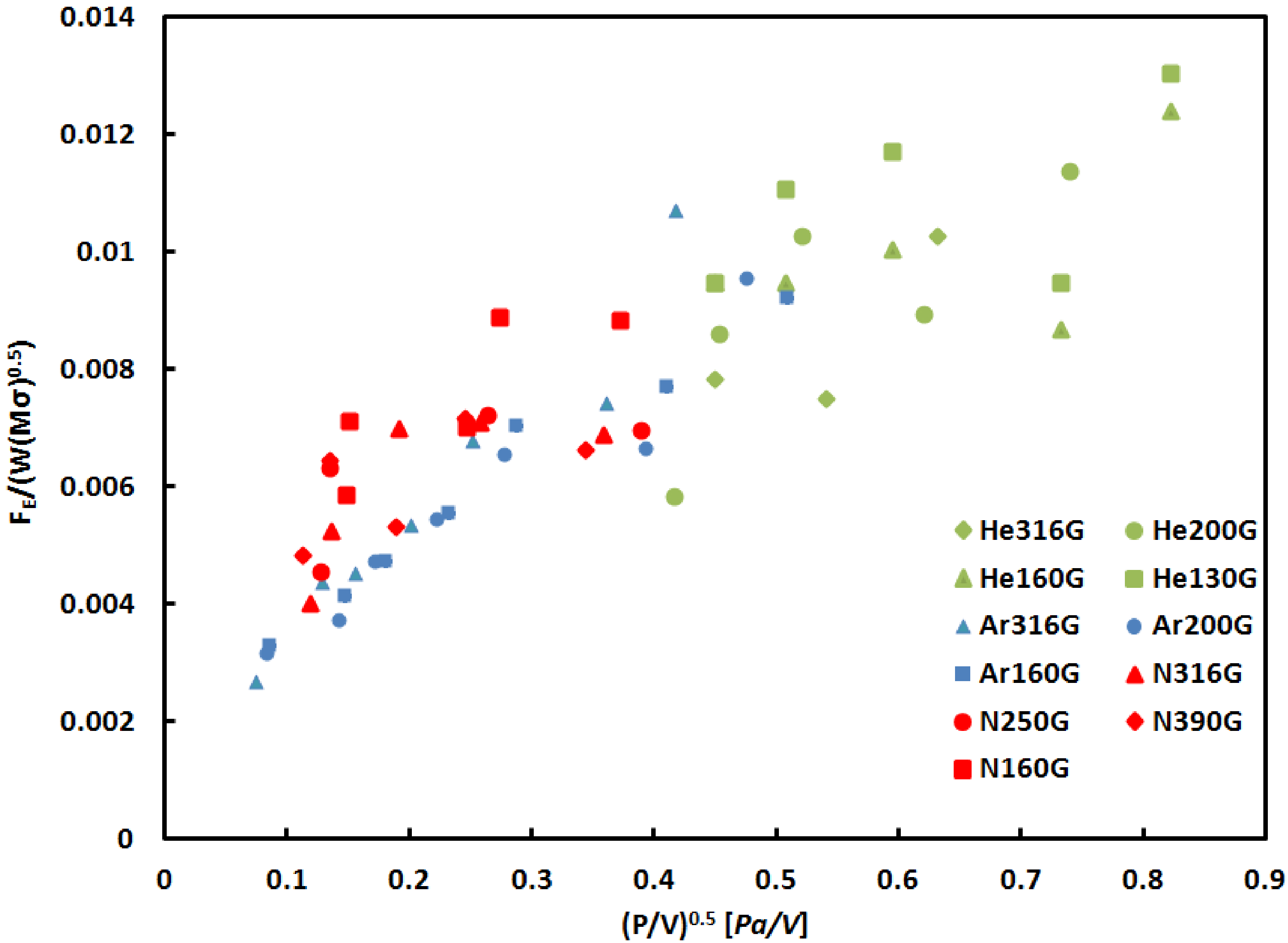
Electric force over power (deposited in ions)



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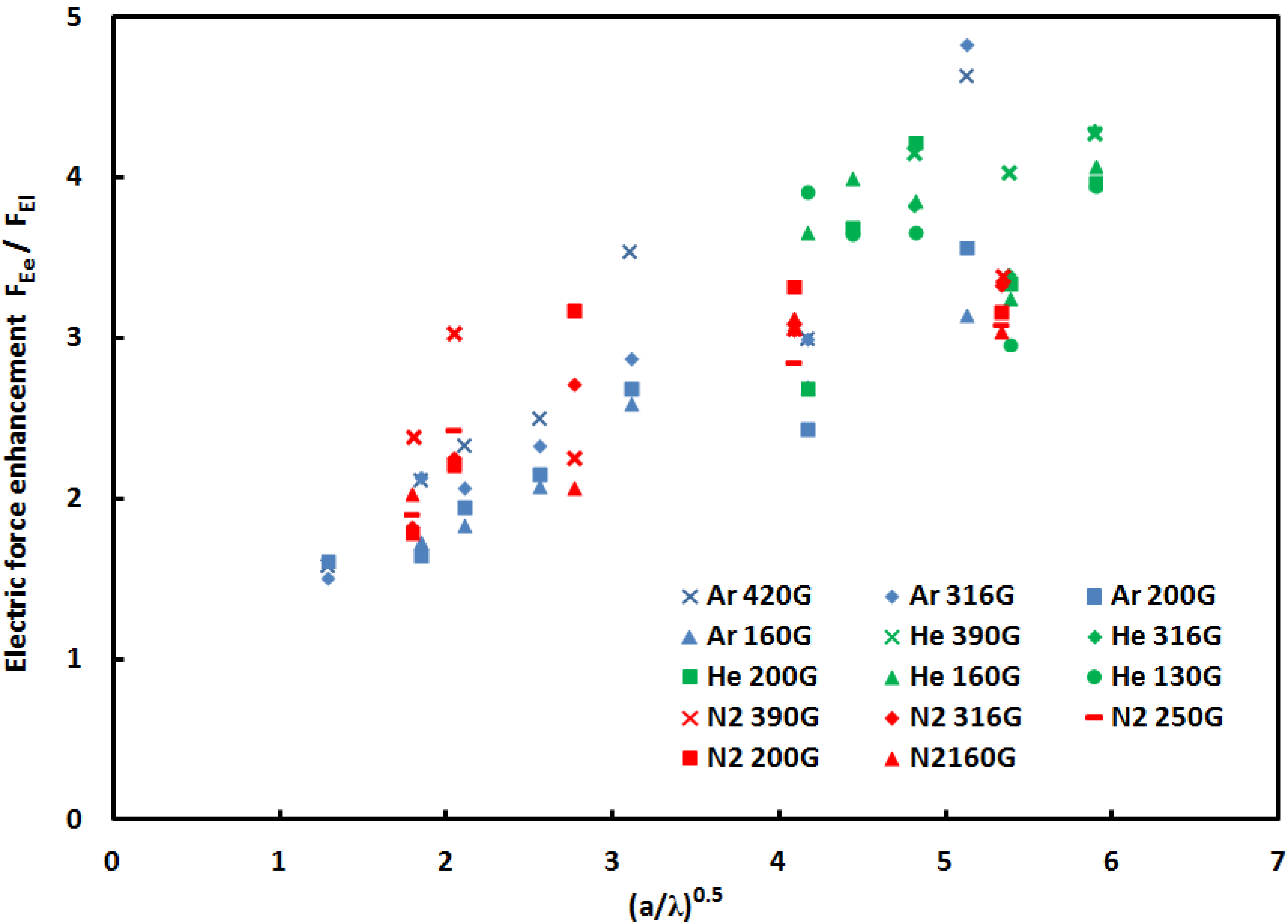
I_d = 1.1A, M_{Ar} = 40, M_{N2} = 28, M_{He} = 4, σ(Ar, N_2, He)× 10^{20} [m^2] ,F_E [mN], W [W]
Pressure range: Ar = 4-68, N_2 = 9.4 - 86, He = 150 - 300 mTorr



Electric force enhancement F_{Ee} / F_{EI}
$(a/\lambda)^{0.5}$
0
1
2
3
4
5
6
7
Ar 420G
Ar 316G
Ar 200G
Ar 160G
He 390G
He 316G
He 200G
He 160G
He 130G
N2 390G
N2 316G
N2 250G
N2 200G
N2160G

Enhanced thrust by collisions

- Controlling thrust over power not by the applied voltage.
- Variable thrust by varying gas flow rate.

Space missions

- Fast maneuver that requires a large thrust in a short time.
- Space debris removal
- Suitable for all-electric-thruster mission
- Air-breathing space propulsion?

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Air breathing?

Air breathing at around 150 km height

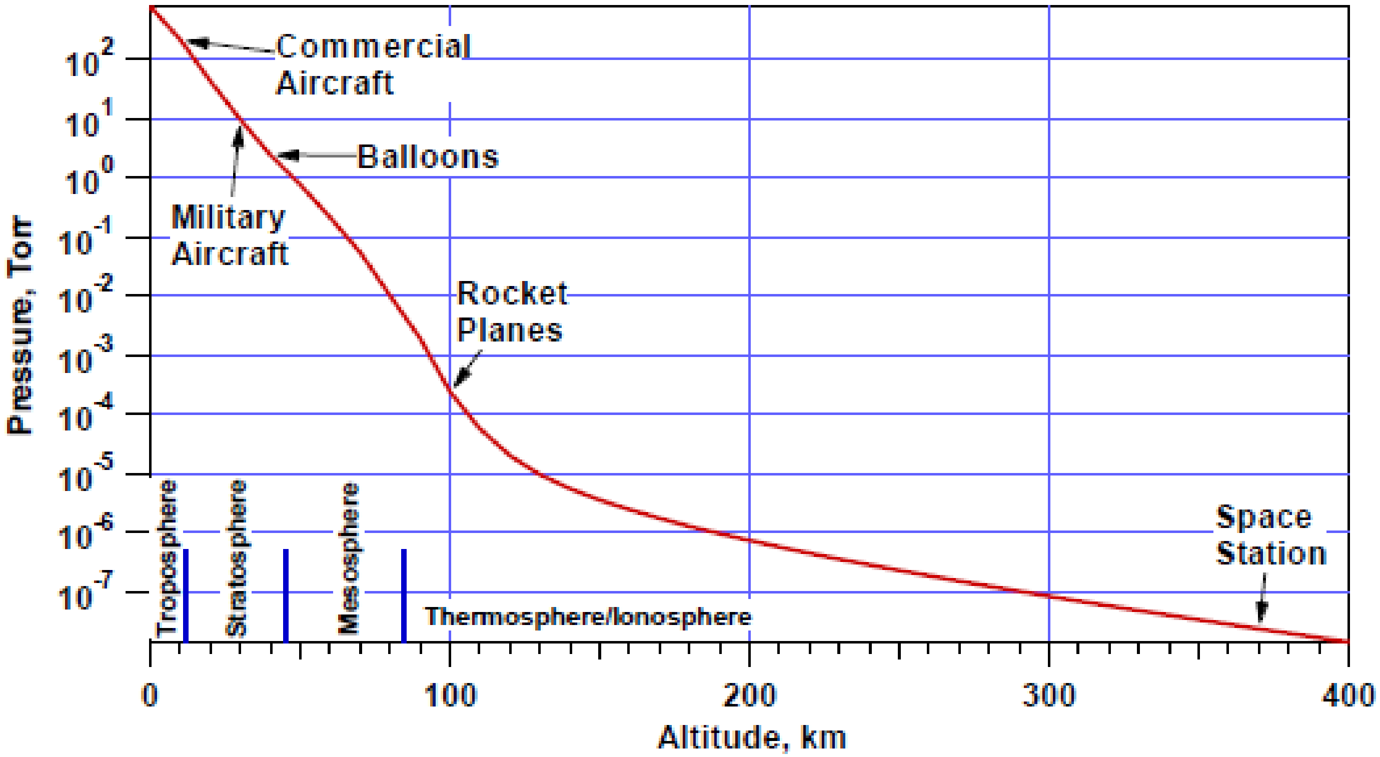
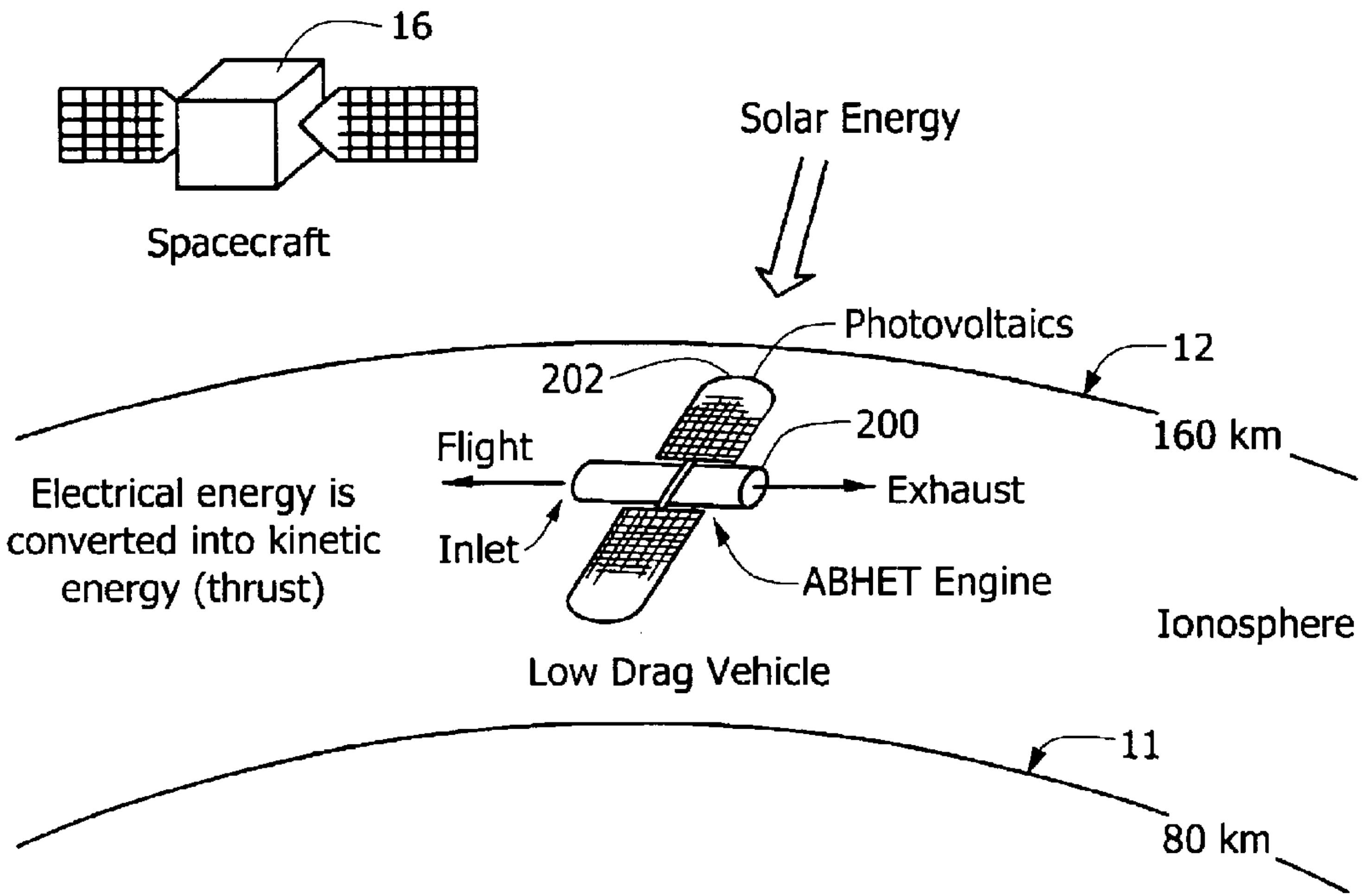


Figure 1. Atmospheric pressure vs altitude above sea level (moderate solar activity).

Diamant, 2009

400 – 800 km, satellites with on-board propellant



Hruby, US patent (2004)

Flying at around 150 km height

- Mostly O and N_2
- Pressure $8\ \mu\text{Torr} \quad (2.5\times 10^{17}\ \text{m}^{-3})$
- Velocity 7800 **m/s**
- Small satellite face area $0.5\ \text{m}^2$

- Available electric power **1 kW**
- Force: **0.25 N**

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Flying at around 150 km height

- **Force:** **0.25 N**
- **Propellant on board?**
- **Chemical - Low velocity – 1000 m/s**

$$\dot{m} = \frac{F}{v} = 0.9\ \frac{\text{kg}}{\text{h}}$$ **too large**

- **Electrical - high velocity – 30000 m/s**

$$P_T = \frac{Fv}{2} = 3.75\ \text{kW}$$ **too large**

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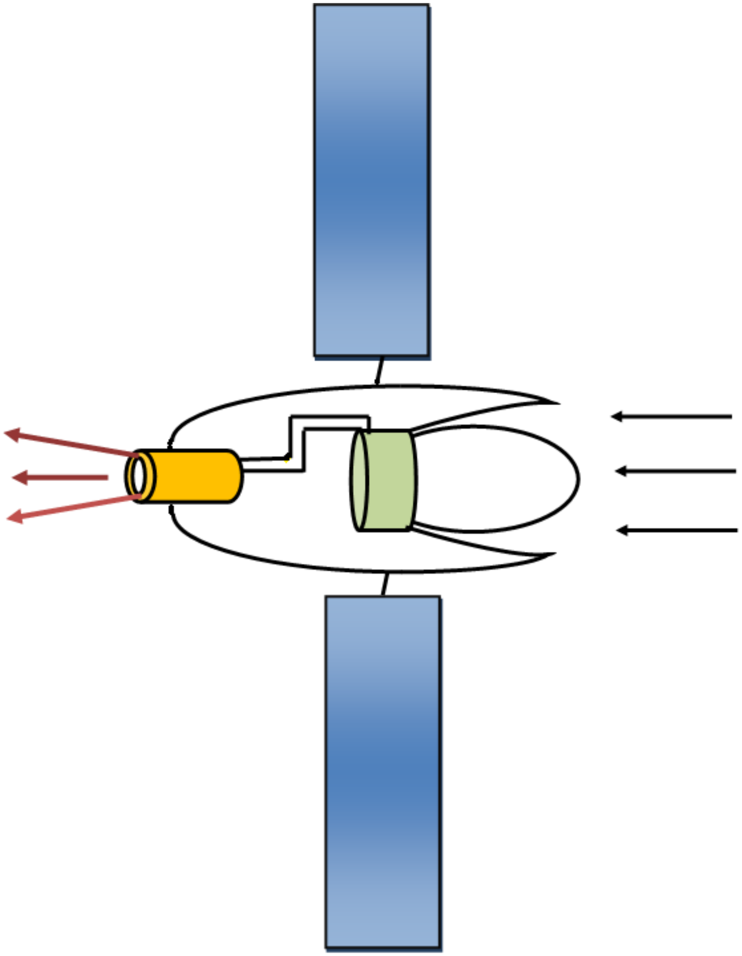
Air breathing

- **Collect all air impinging on the satellite.**
- **Accelerate the air to** 7800 **m/s.**
- **This velocity requires a low specific impulse electric propulsion.**
- **The collisional thruster could be considered for such a mission.**

Air breathing at around 150 km height

Ideally collecting all impinging gas

If all gas acquires 7800 m/s, the power is 1kW



Full ionization . is 150 A. not practical

Should design a thruster of 10A and 100 V

Each ion should collide 15 times and the gas should acquire 10 eV

Air breathing - difficulties

- Efficiency of gas collection (about 30%)
- Chemistry of the propellant
- Too low gas density for a thruster (need 100 times compression)

Back to the general discussion

There is no free l(a)unch

- Not all neutrals experience collisions – waste of propellant
- Not all neutrals acquire the same energy (loss of efficiency)
- The electron cross-field transport is very large.
- The efficiency is low.

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Equality maximizes thrust

- For a given total energy , the maximal thrust is delivered if energy is distributed equally between propellant particles (of the same mass), and generally if they acquire the same velocity.

Equality maximizes thrust

- Even if all electrical energy becomes directed kinetic energy, the efficiency is not necessarily 100%. The thrust needs to be maximized.

Optimal potential distribution

- Assume head-on charge exchange ion-neutral collisions.
- The pushed neutrals do not collide until they are ejected from the acceleration channel (actually, not a realistic assumption).

Optimal potential distribution

$$N = N_0 \exp\left(-\frac{\Gamma_i}{\Gamma_N}\frac{x}{\lambda}\right)$$

$$V_{opt}(x) = V_A \frac{\exp\left(-\frac{\Gamma_i}{\Gamma_N}\frac{x}{\lambda}\right) - \exp\left(-\frac{\Gamma_i}{\Gamma_N}\frac{l}{\lambda}\right)}{1 - \exp\left(-\frac{\Gamma_i}{\Gamma_N}\frac{l}{\lambda}\right)}$$

$$E_{opt}(x) = \frac{\Gamma_i}{\Gamma_N}\frac{V_A}{\lambda}\frac{\exp\left(-\frac{\Gamma_i}{\Gamma_N}\frac{x}{\lambda}\right)}{1 - \exp\left(-\frac{\Gamma_i}{\Gamma_N}\frac{l}{\lambda}\right)}$$

$$\lambda \equiv \frac{1}{\sigma N_0}$$

Optimal potential distribution

- The optimal potential distribution is such that the electric field is large where the neutrals density is large.
- The ion velocity is uniform along the acceleration channel.
- The neutrals velocity is uniform as well.
- Realistic assumptions about the increased pressure of neutrals result in a lower than the theoretical 100% efficiency.

CONCLUSIONS

- We propose to develop a variable-thrust thruster by varying the number of collisions.
- The thruster could operate at a low specific impulse and a high thrust over power.
- The challenges: 1. increase the efficiency by impeding the high cross-field electron transport. 2. reduce inefficiency due to propellant pressure.

GENERAL CONCLUSIONS

The sky is not the limit !

Thank you.