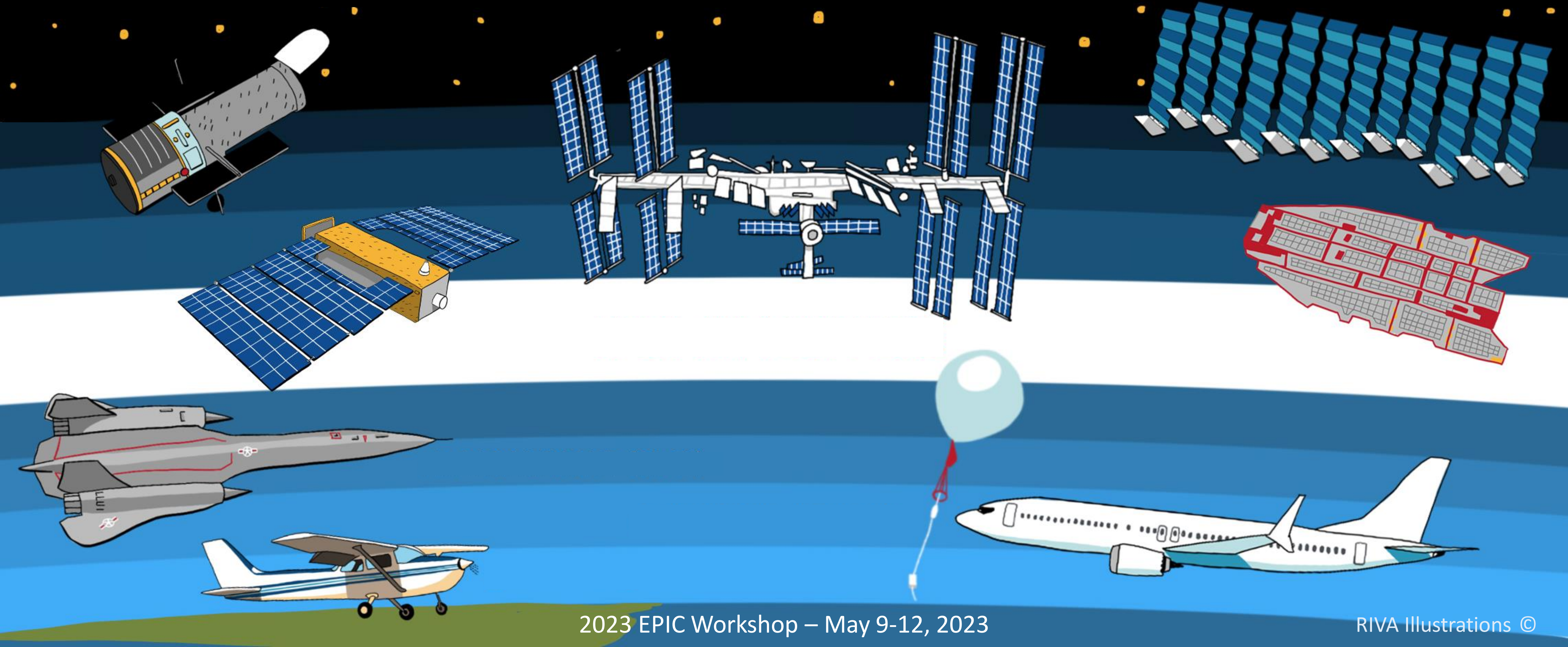
BREATHE

Building a space Revolution: Electric Air-breathing Technology for High-atmosphere Exploration

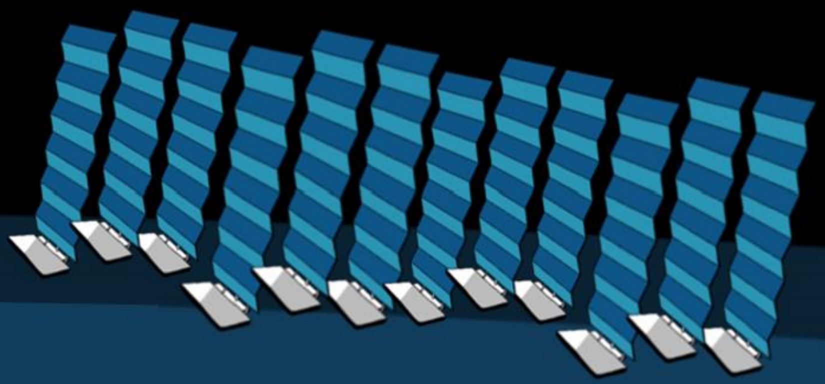
Tommaso Andreussi



2023 EPIC Workshop – May 9-12, 2023

Very-low Earth orbits

The **new space economy** is determining a significant increase in the number of satellites deployed in Low Earth Orbits (LEOs), enabling **transformative applications** but also raising concerns about **space debris**



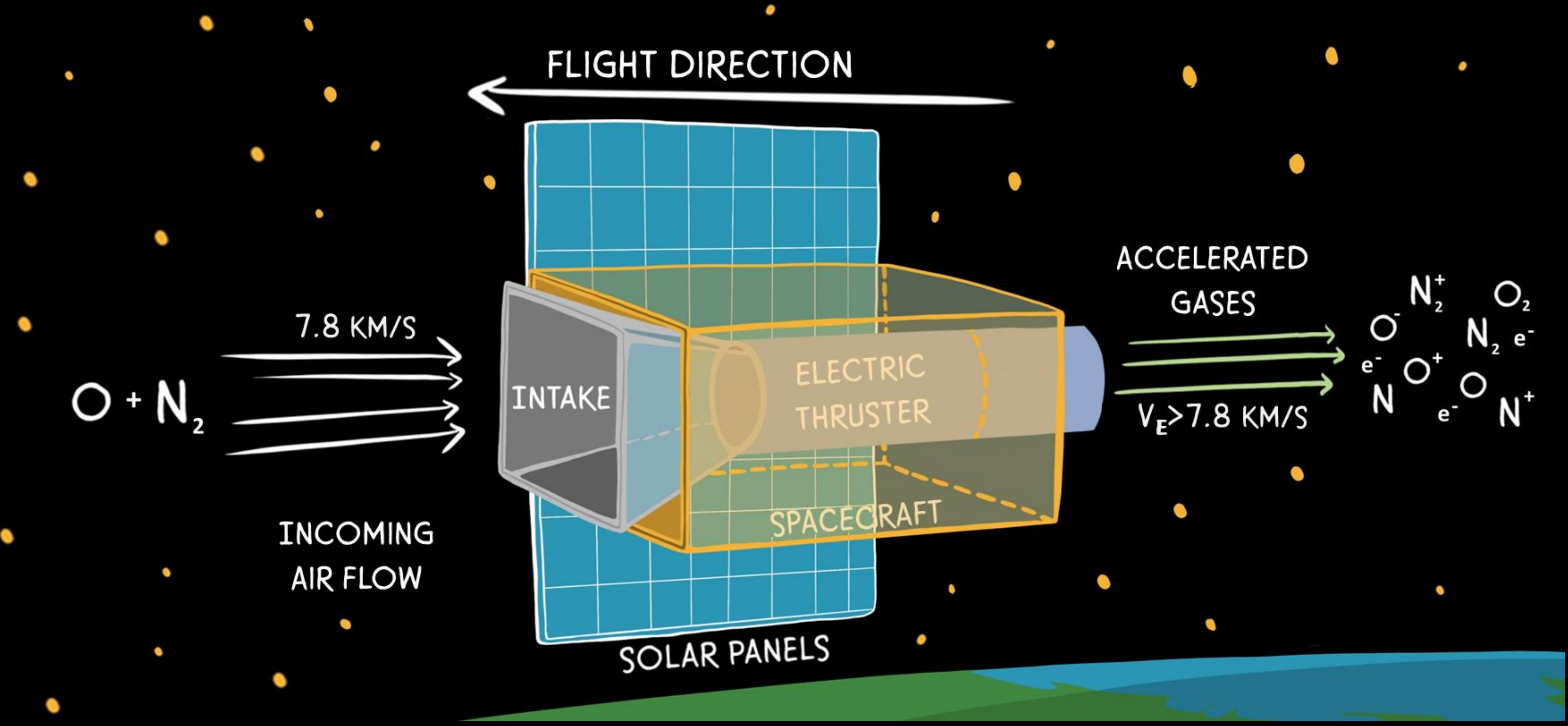
Lowering the spacecraft altitude below 450 km, in Very-low Earth orbit (VLEO), would provide significant advantages for

- Communication and connectivity
- Earth observation and monitoring
- Space and Earth science
- Satellite constellations

At the same time, the presence of a residual atmosphere offer

- Low radiation levels
- Rapid debris decay
- Automatic spacecraft re-entry

Air-breathing Electric Rocket (AER)

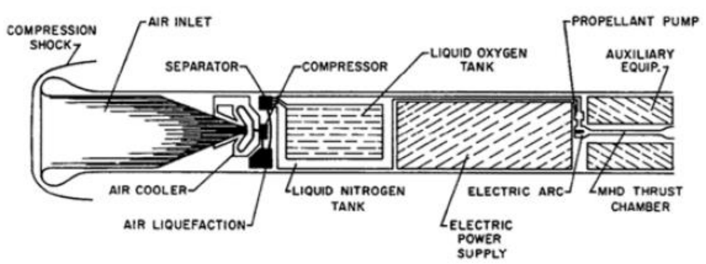


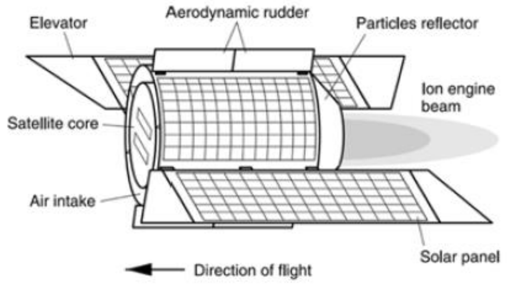
State of the art

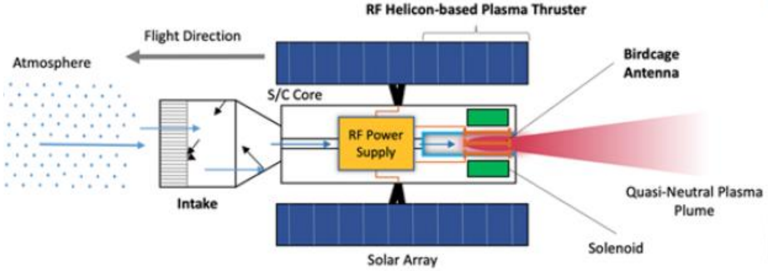
AERs combine an **electric thruster** with an **air intake**, thus bonding propulsion, platform, and environment.

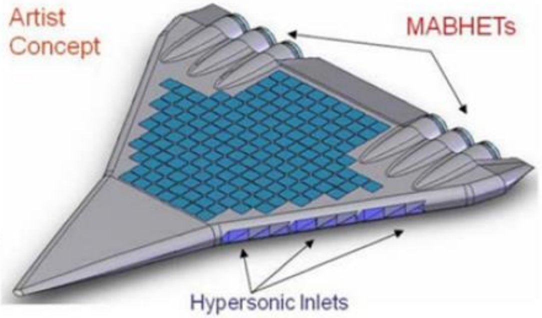
Several researchers[1] investigated the concept feasibility, which relies on the minimization of platform drag and the optimization of available power, as well as on the AER performance.

Concept	Orbit	h[km]	$M_{S/C}$[kg]	$P_{S/C}$[kW]	A_f[m^2]	C_D
Nishiyama [5]	SSO 6am	140-160	-	0.5-3.3	1.5	2
Di Cara [43]	SSO 10:30	200-250	1000	2.9	1	2
Hruby [44]	-	150	-	2-3	-	2.2
Diamant [45]	-	200	400	1	0.5	2.2
Shabelowitz [46]	-	180-200	325	0.3	0.36	-
Schonherr [47]	-	200	-	-	0.3	2.2
Romano [48]	-	150-250	<1050	3.5	1	2.2
Andreussi [49]	SSO 6am	190-240	500-750	2.5-3	0.7	-
Tisaev [50]	SSO 6am	170-200	200	0.6	0.1	3.2-4.2
Ovchinnikov [51]	SSO 6am	175	120	0.2-0.4	0.2	-
Vaidya [52]	-	160-250	1000	1.6	1	3.7
Crandall [53]	0°-90° inclination	160-250	7.5-10.5	0.01-0.1	0.01	3-6







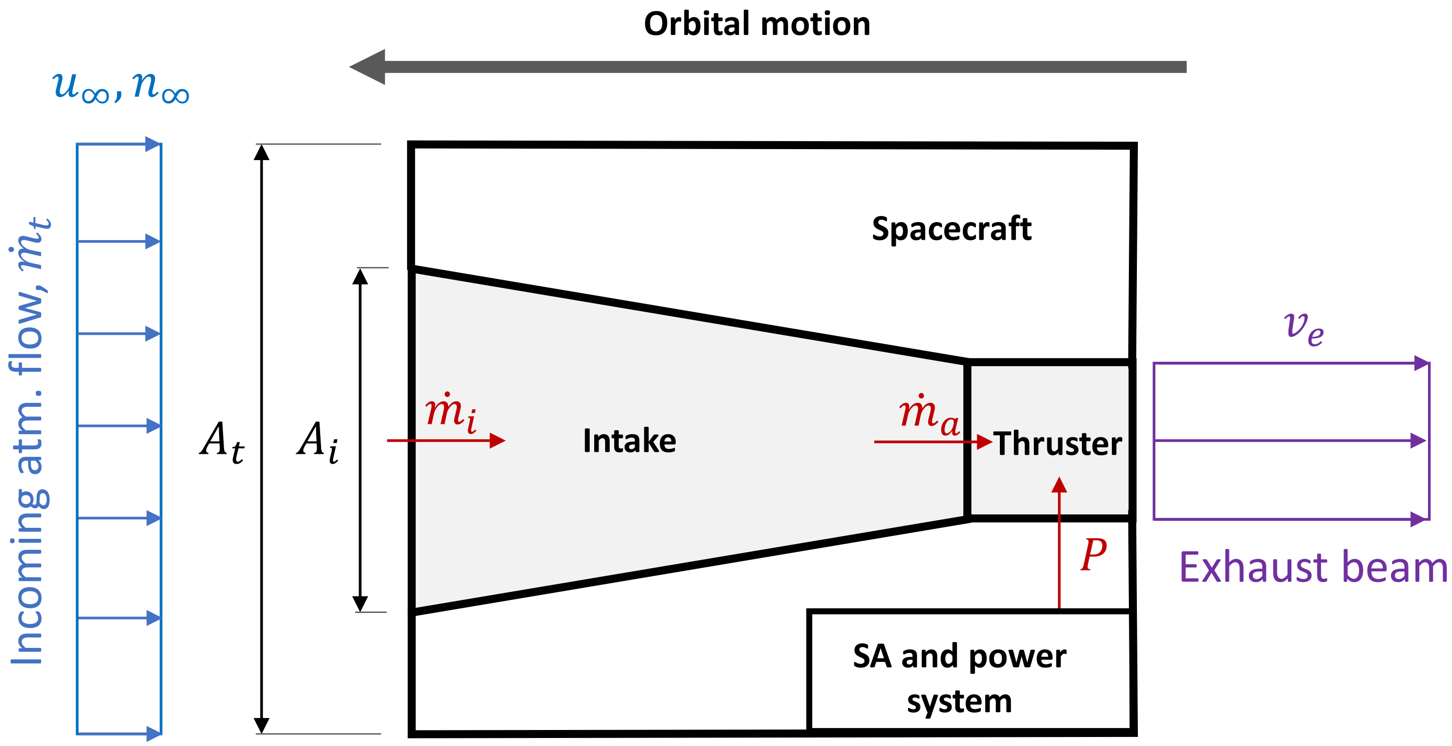


[1] Andreussi et al. (2022), A review of air-breathing electric propulsion: from mission studies to technology verification, Journal of Electric Propulsion 1

A single constraint

AER performance relies on:

- How efficiently we use the total (drag-inducing) frontal area to collect propellant $\eta_A = \frac{A_i}{A_t}$
- How efficiently the intake collects the propellant and transfers it to the thruster $\eta_c = \frac{\dot{m}_a}{\dot{m}_i}$
- How efficiently the thruster uses the available power to generate thrust $\eta_T = \frac{T^2}{2\dot{m}_a P}$

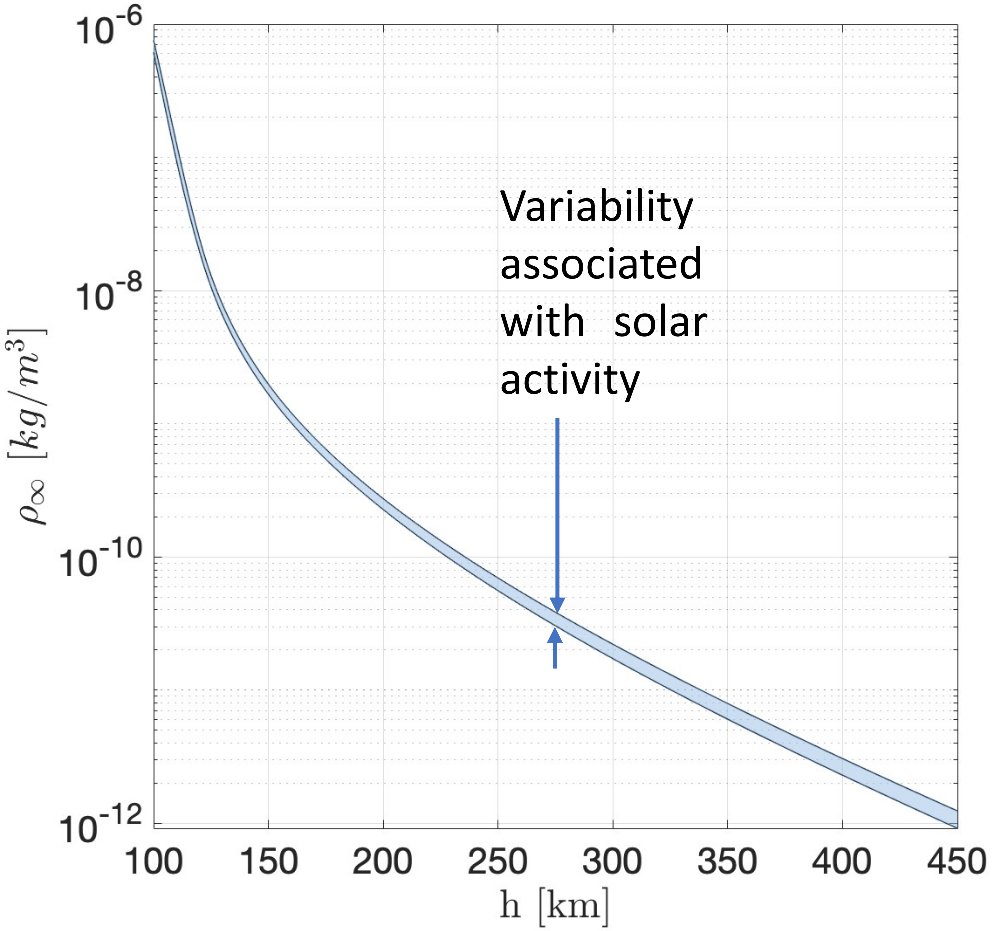


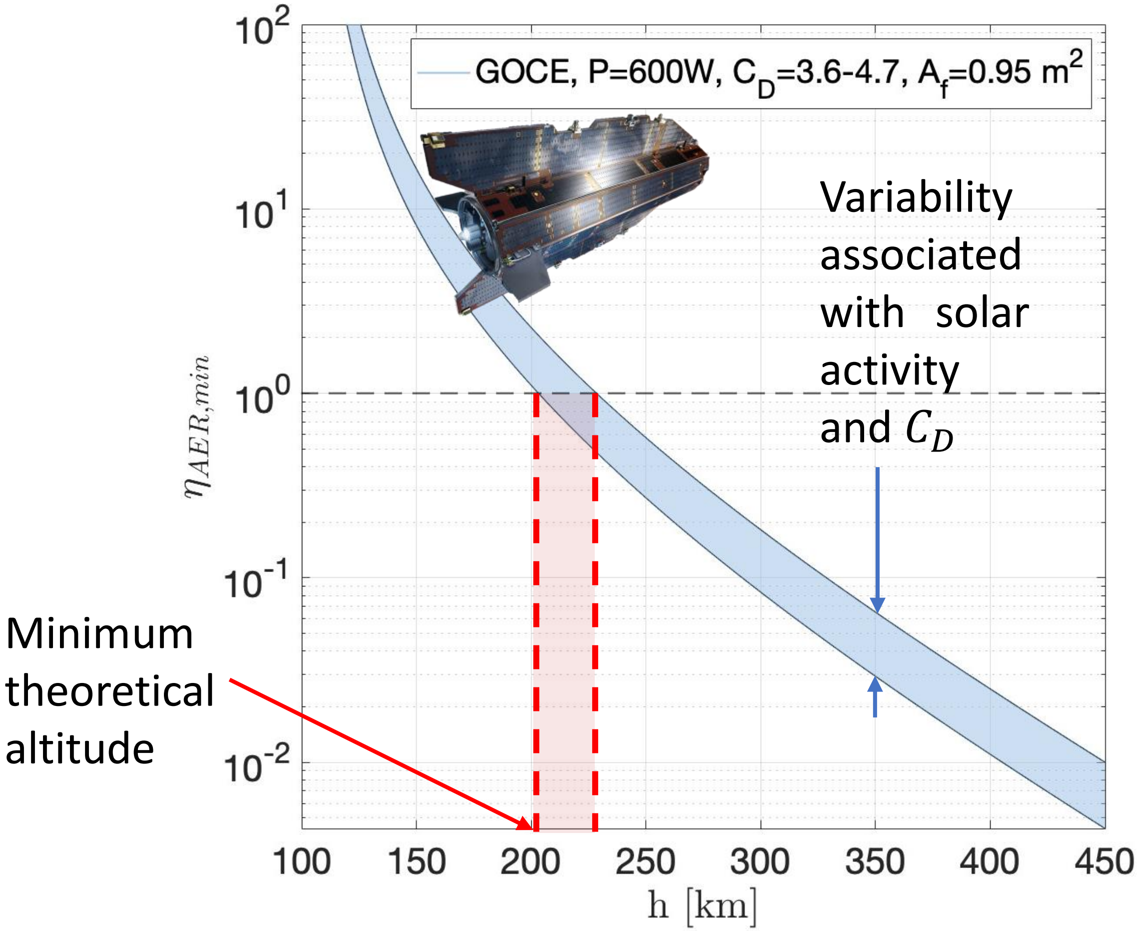
The condition $T > D$ then translates to:

$$\eta_{AER} \doteq \frac{T^2}{2\dot{m}_t P} = \eta_A \eta_c \eta_T > \underbrace{\left[\frac{1}{2}\rho_\infty u_\infty^3\right]}_{O} \underbrace{\left[\frac{C_D^2 A_t}{4P}\right]}_{S}$$

A single constraint

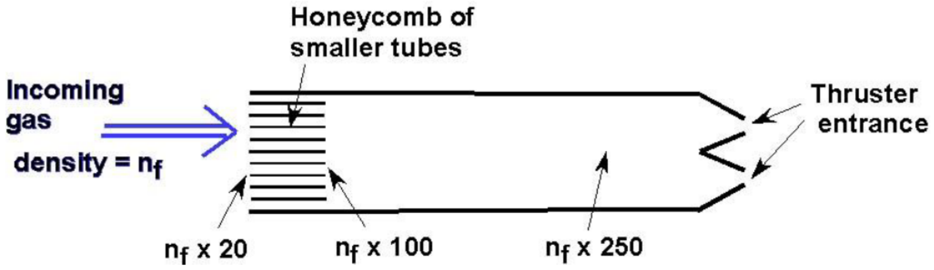
$$\eta_{AER} \doteq \frac{T^2}{2\dot{m}_t P} = \eta_A \eta_c \eta_T > \left[\frac{1}{2}\rho_\infty u_\infty^3\right]\left[\frac{C_D^2 A_t}{4P}\right]$$

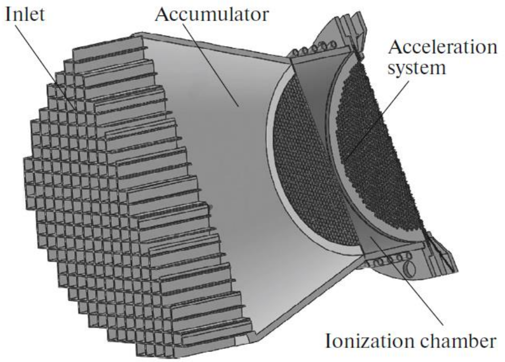


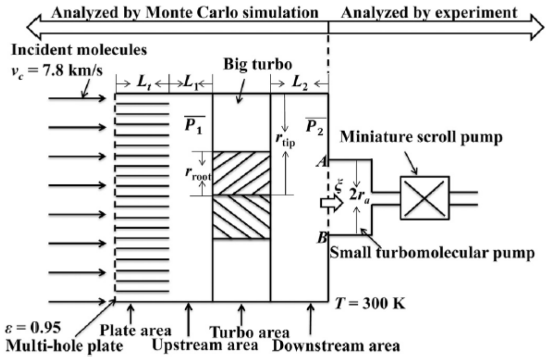


State of the art

- The AER efficiency requirement becomes more relaxed as the altitude increases.
- However, **effective propellant ionization** requires a density much higher than that available at feasible altitudes.
- The concept feasibility critically relies on an **effective air compression** (passive or active) in the intake.
- Passive compression relies on the different conductance of slender ducts for aligned or diffuse flows. However, higher compression factors implies lower collection efficiencies.



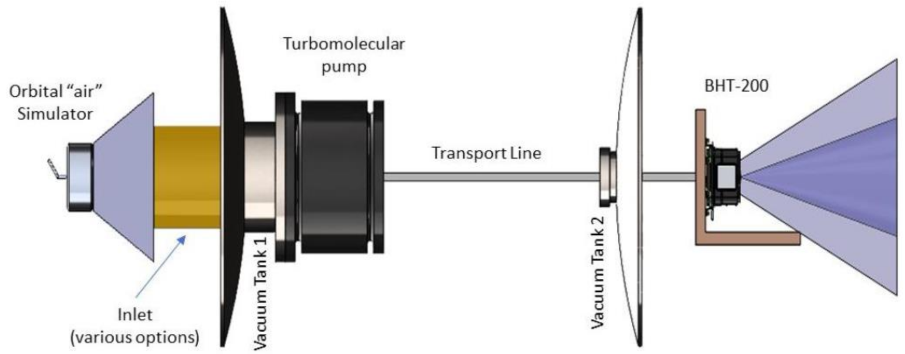




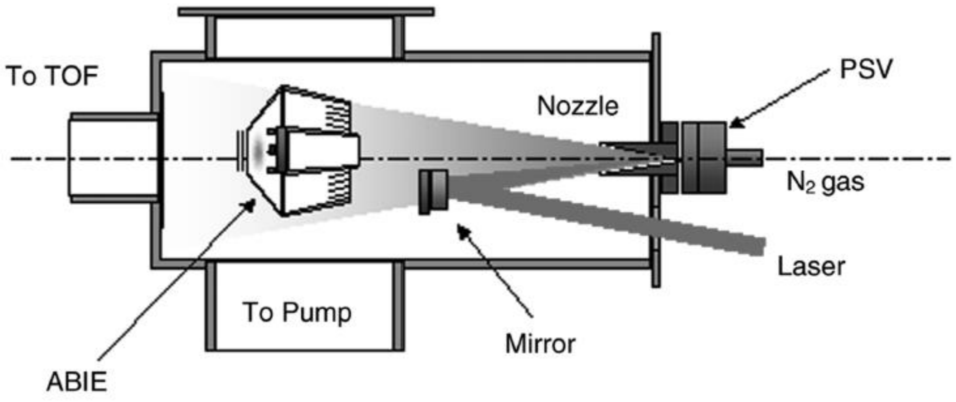
Institution	*Design*	*Reflection*	*Ducts*	*Collection*	*Compr.*
JAXA	Passive	Maxwell	Yes	0.25-0.45	100-50
Busek	Pas.\Act.	Diffuse	No	0.36-0.60	-
SITAEL ESA, VKI	Passive	Diffuse	Yes	0.28-0.32	140-95
		Maxwell	No	0.23-0.25	138-92
LIP	Active	Diffuse	Yes	0.42-0.58	-
IRS	Passive	Diffuse	Yes	0.31-0.45	-
		Specular	No	0.59-0.94	-
TsAGI RIAME	Passive	Diffuse	Yes	0.33-0.34	> 100
U. Colorado	Passive	Diffuse	No	0.31-0.35	-
		Specular	No	> 0.9	-
Skolkovo Inst.	Active	Diffuse	Yes	Up to 0.98	> 4000
NUDT	Passive	Spe.\Max.	Both	0.65-0.81	210-100

State of the art

- The VLEO flow conditions are challenging to recreate on ground.
- Intake performance are typically assessed through numerical simulations (TPMC and DSMC).
- Thruster operation with atmospheric propellant is often characterized in stand-alone condition.
- Modelling of propellant collection, thruster discharge, and intake + thruster coupling requires experimental validation.

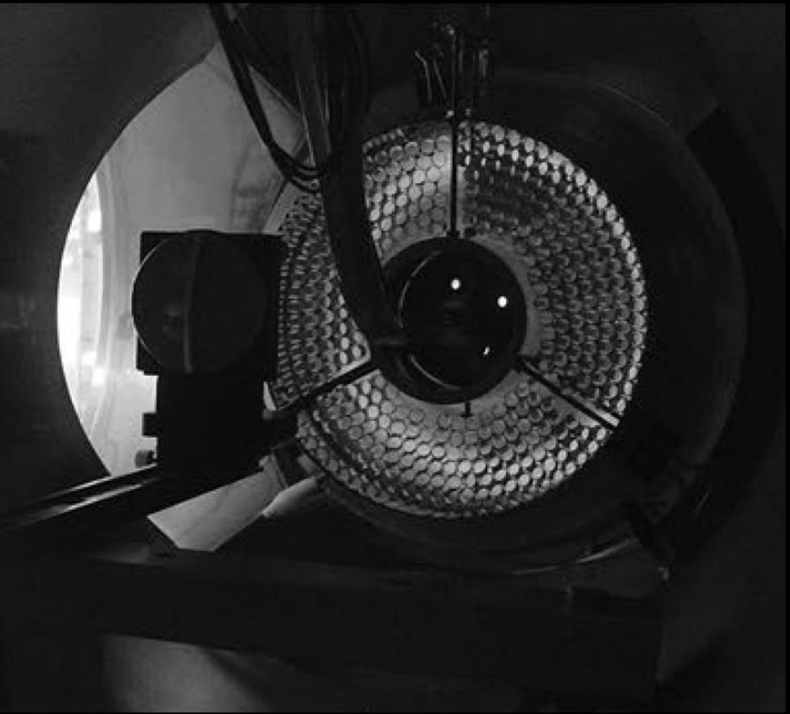


Institution	Type	Velocity	Notes
Busek	RF heater	3-4 km/s	Free jet, large AO fract., high divergence
	Arcjet	3-4 km/s	Free jet with stripping, large AO fract., high divergence
	Hall thruster	7.7 km/s	Large ion fract., small AO fract., velocity spread, Xe cathode
	RF Hall thr.	-	Large ion fract., Ar added, Xe cathode
JAXA	Laser detonation	5.8-8.4 km/s	Pulsed O_2 or N_2 operation, large AO fract.
	RF source + surf. neut.	~8 km/s	Small fract. of accel. particles
SITAEL	Hall thruster	9.1 km/s	Large ion fract., small AO fract., velocity spread, Xe cathode
	Hall thruster	6-15 km/s	Large ion fract., small AO fract., velocity spread, ceN2 cathode
TU Dresden	RF source + surf. neut.	-	Small fract. of accel. particles
Uni. of Manchester	Ele. stim. desorption	~8 km/s	Low fluxes, large AO fract.

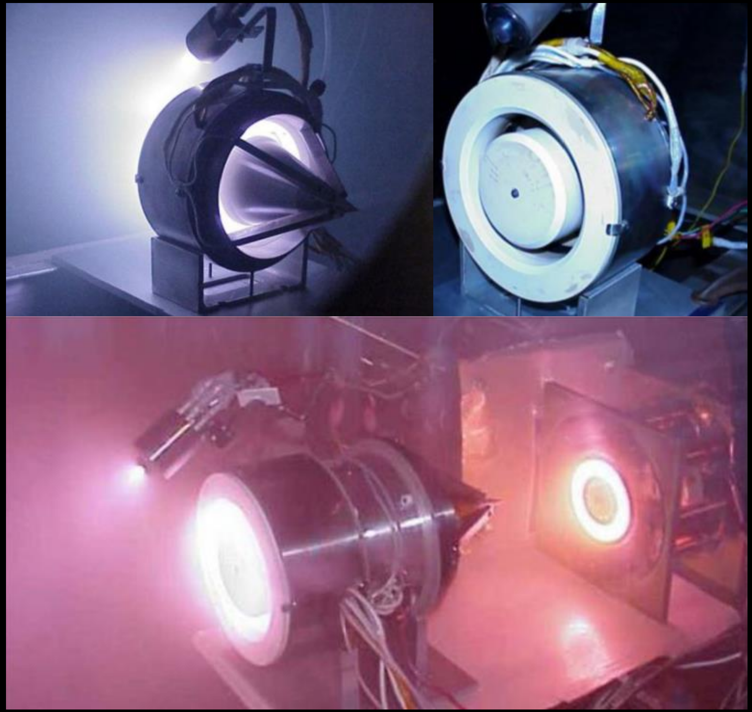


State of the art

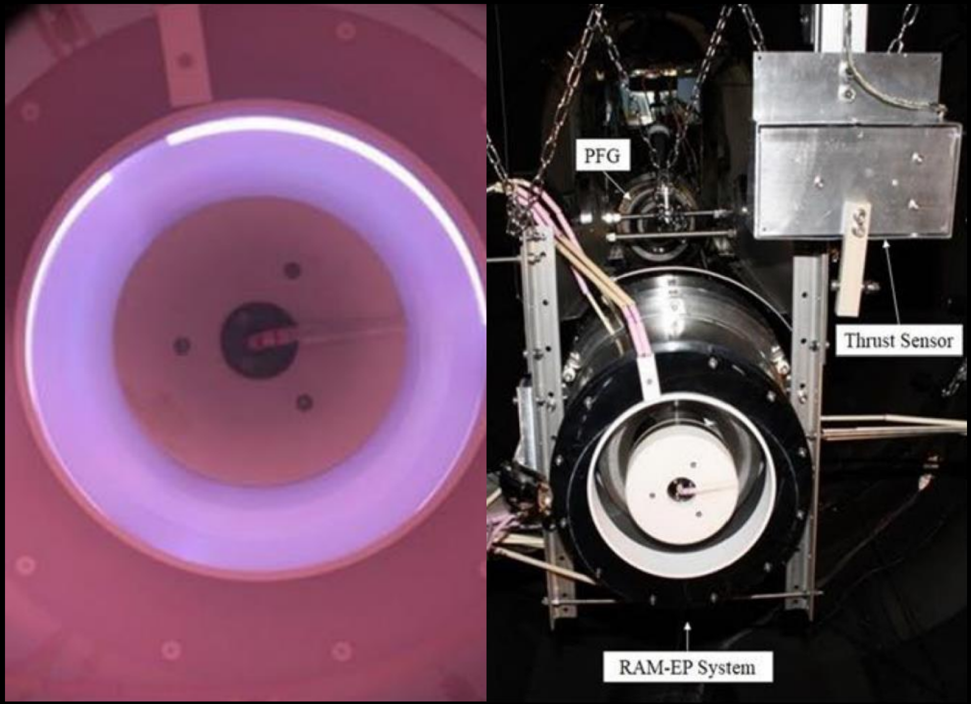
Three end-to-end test campaigns have been performed, highlighting criticalities in the VLEO flow representativeness, diagnostics, and concept performance



JAXA

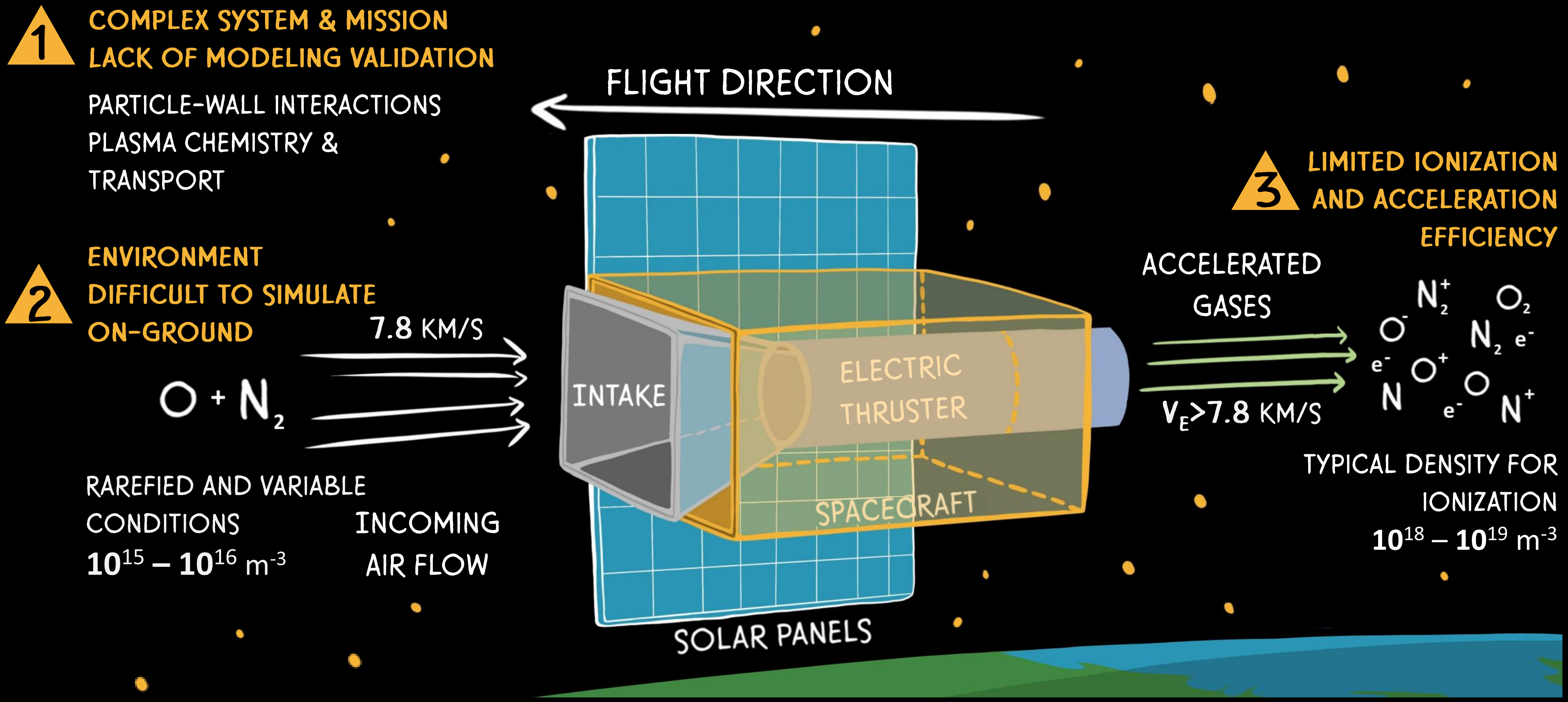


BUSEK



SITAEL

AER open issues



BREATHE project

Funded by the European Research Council with a Consolidator Grant, BREATHE is a 5-year research project aimed at

increasing the understanding of air-breathing electric propulsion to pave the way toward the in-orbit demonstration of the AER concept.

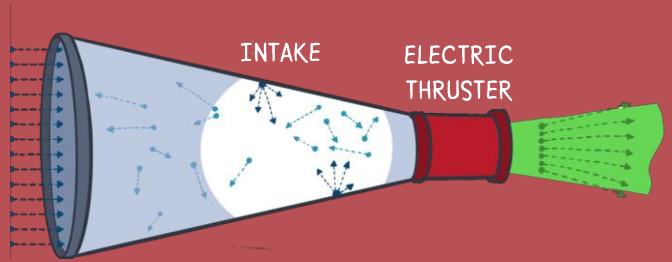
INSTITUTE OF MECHANICAL INTELLIGENCE

Sant'Anna Scuola Universitaria Superiore Pisa

BREATHE project

WP1 - Modelling

- A virtual laboratory to study AER behavior[1]

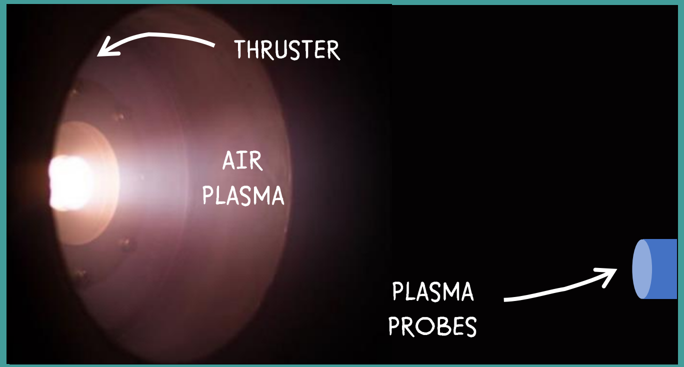


- Mission and flight environment integrated with thruster operation

[2] *Preliminary modelling results of an air-fed Hall thruster in Ferrato, …, Andreussi (2022) Plasma Sources Sci. Technol. 31*

WP2 - Environment

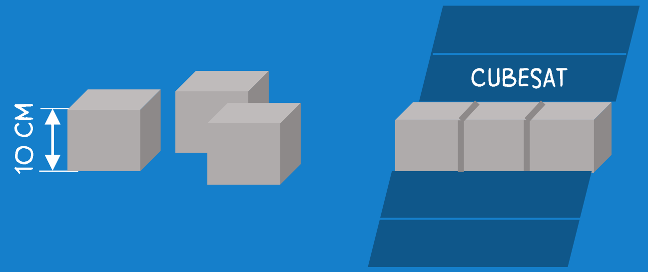
- Realization of a test facility to simulate VLEO conditions
- Setup of diagnostic system (thrust balance, plasma probes, RGA and pressure sensors)
- A mixed proof of concept



[3] *Romano (2021) PhD Thesis*

WP3 - Prototypes

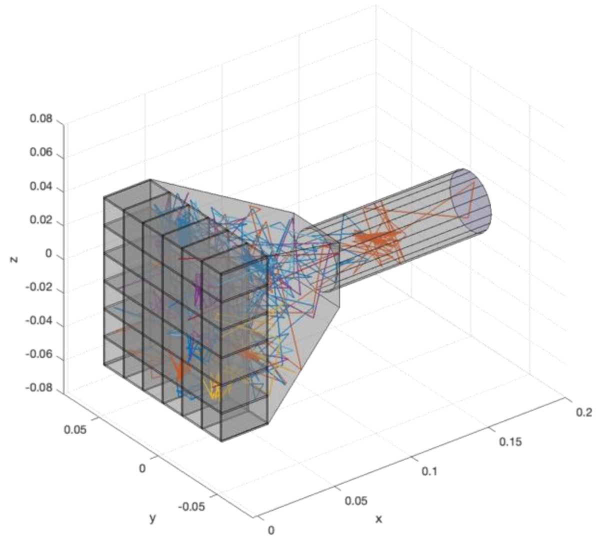
- Systematic investigation of different ionization (DC, RF, ECR)…
- …and acceleration strategies (grids, ExB discharges, nozzled expansion)
- Scaling down toward miniaturization and in-orbit demonstration

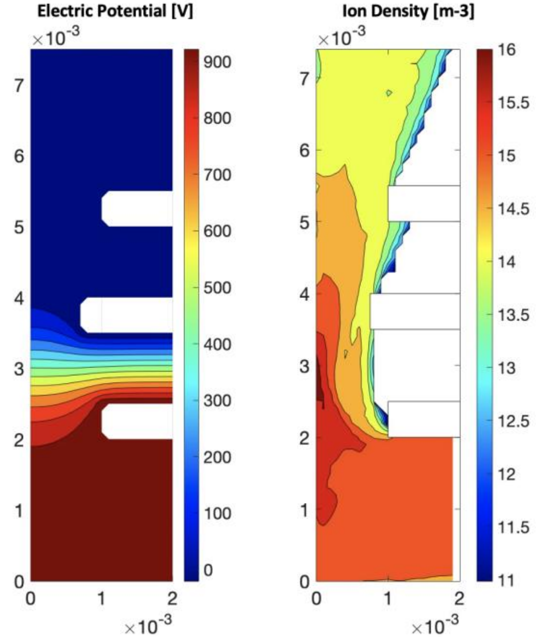


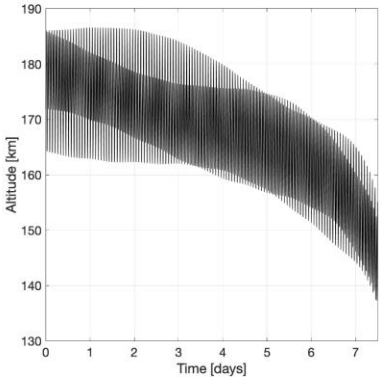
BREATHE Virtual Lab

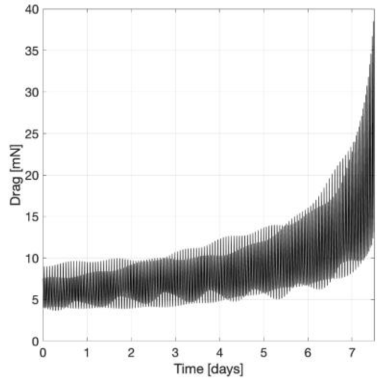
A multi-physics modelling suite for AER-based systems, missions, and operations.

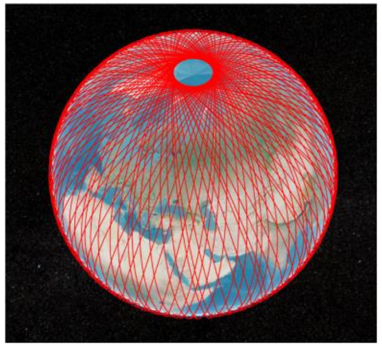
	Module	*Function*
Neutral and plasma flows	*0D-Hybrid AER Model*	Use input from 3D Monte Carlo to solve for particle continuity and electron energy in the defined AER control volumes (usually, an ionization stage + an acceleration stage), define a thrust law outputting AER performance vs inlet flow properties and operating condition.
	3D Ion and Neutral Monte Carlo	Propagate neutral and ion particles trajectories to derive relevant distributions describing heavy particles dynamics. May be used to optimize magnetic field topologies promoting ion confinement, or intake geometry enhancing flow collection and compression.
	2D/3D EM Solver	Solve for static electric and magnetic fields on which the ion particles are pushed in the 3D Monte Carlo. It also allows to estimate the RF power transferred to electrons in case an RF generator is used.
	2D Plume Expansion	A simplified plume expansion model, allowing to define plasma properties inside vacuum chamber during on-ground testing or to assess plume interaction with spacecraft for on-orbit scenarios investigations.
System and mission	*Orbit Propagator and Mission Analysis*	Includes an orbital propagator to assess the on-orbit behavior of the thruster design according to the thrust law derived from the 0D AER module and the discharge control law designed in the Discharge Control module.
	Discharge Control	Analyze discharge power and thrust frequency response to variable applied electrode voltage or electromagnet current, allowing to design and assess optimum discharge control strategies to safely operate the AER system despite the highly variable inlet flow properties.
	Thermal Model and Materials	Includes a lumped thermal model of the propulsion system, together with a material lifetime model coupled with temperature map and plasma densities from the 0D AER module.





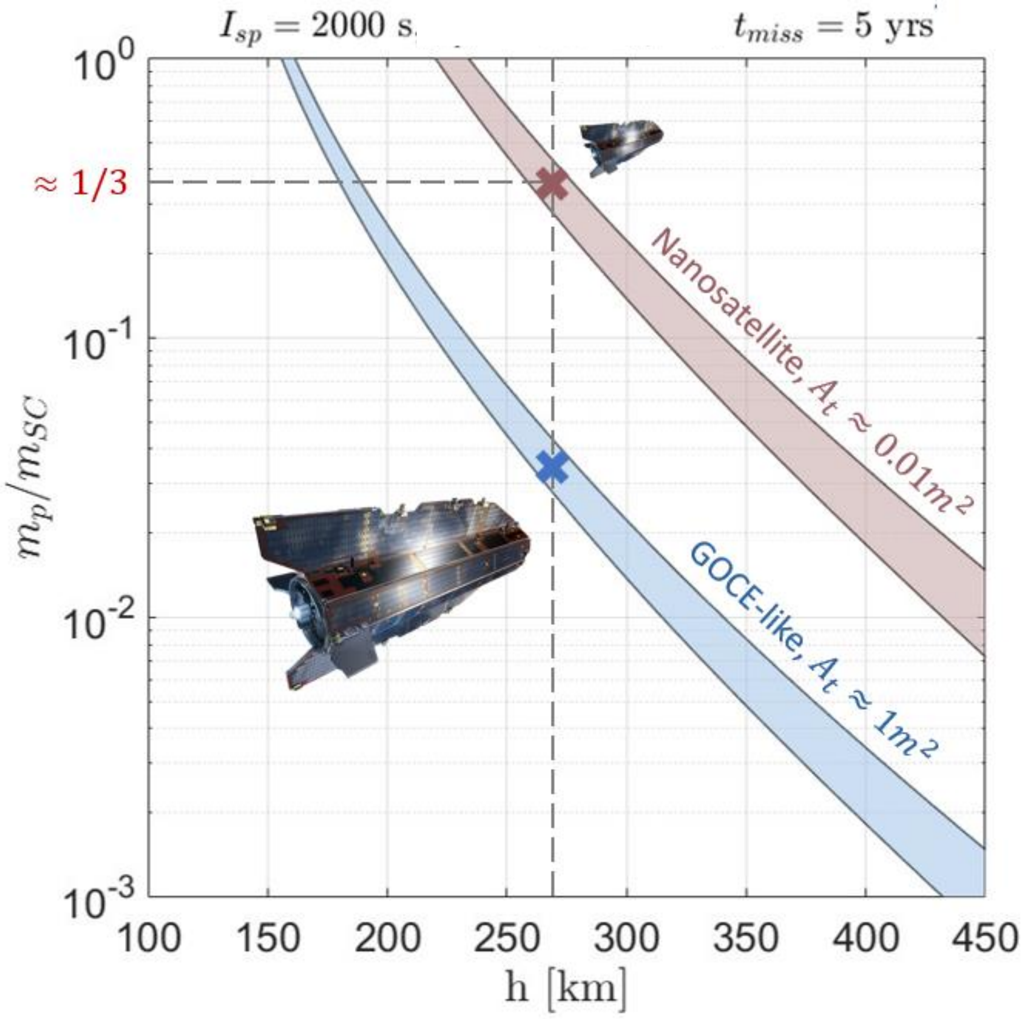




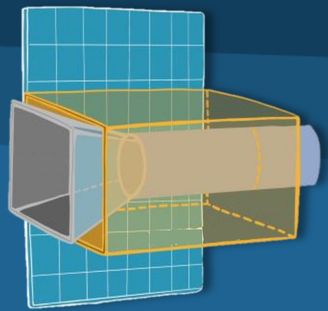


Miniaturization and scaling laws

- The BREATHE project will identify the core **scaling laws** of AER candidate technologies,
- Focusing on the **miniaturization** and optimization of the system at **CubeSat-scale:**
  - Rapid and cost-effective **In-orbit experiment** of the technology.
  - **Reduce cost** and **improve accessibility** of VLEO assets.
  - Smaller platforms provide **intrinsic system-level advantages** in the trade-off between air-breathing and traditional propulsion systems.



QUESTIONS?



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