SITAEL AN ANGEL COMPANY

TransMIT

UNIVERSITY OF SURREY

VON KARMAN INSTITUTE

Astos Solutions

DEDALOS

RHP TECHNOLOGY

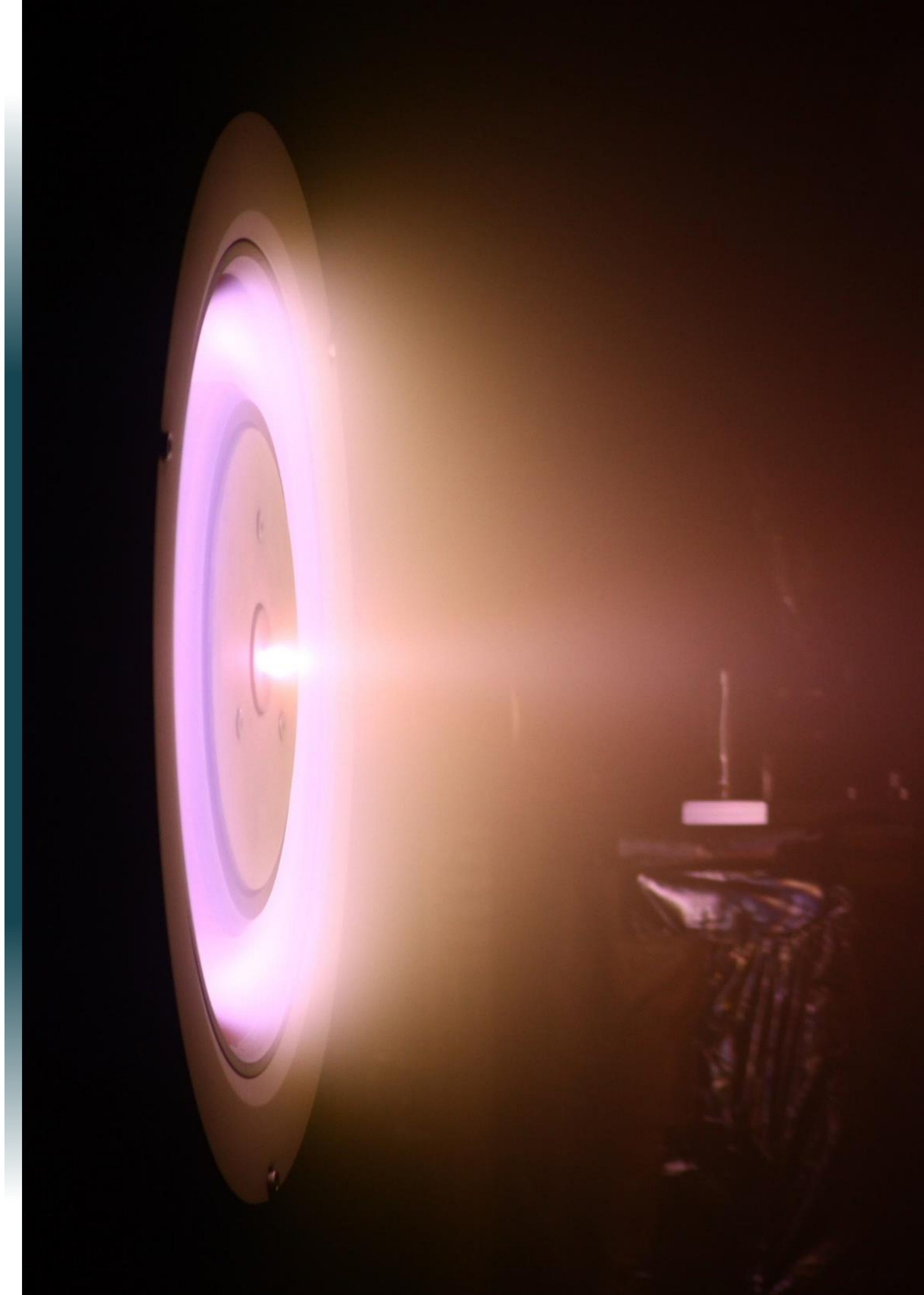
AETHER

Development of Air-Breathing Electric Propulsion for VLEO Missions

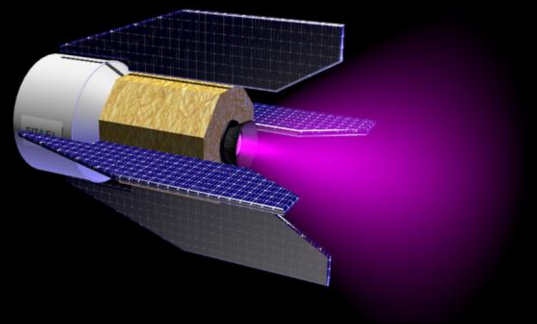
GA 870436

EPIC WORKSHOP

Naples, Italy, May 9-12, 2023



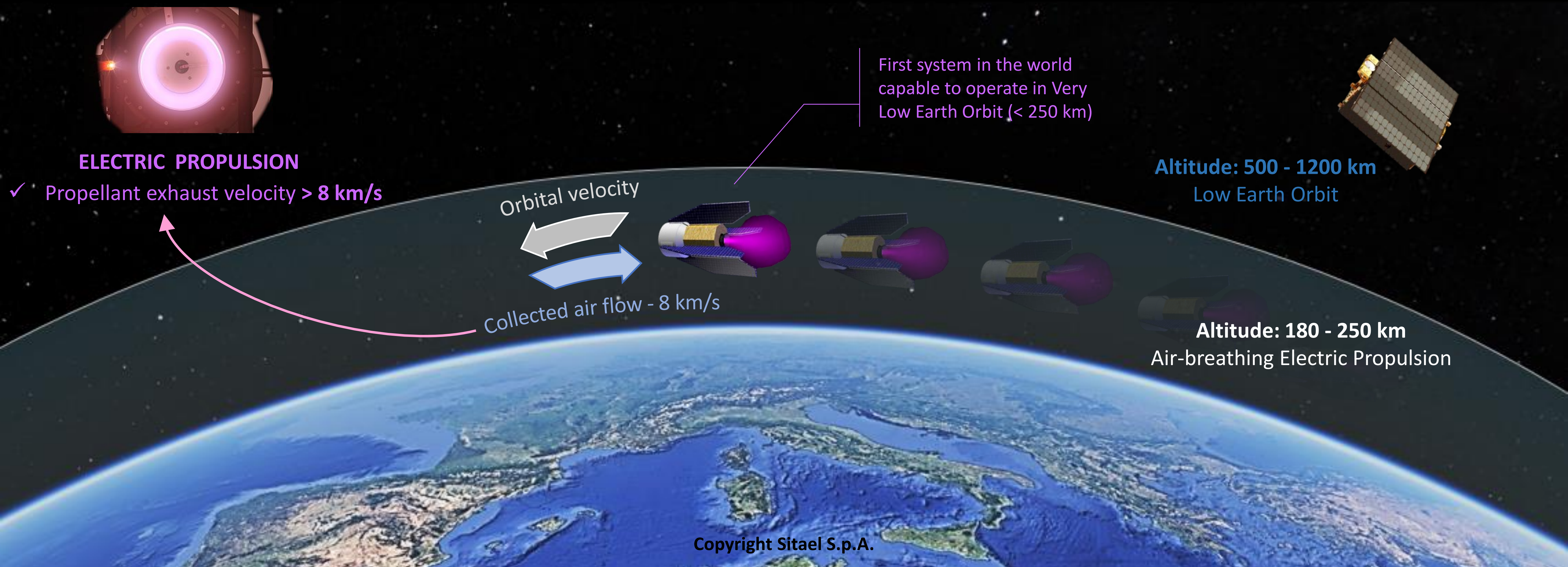
Air Breathing Space Propulsion (Concept & Rationale)



Concept: exploit the atmospheric particles to achieve a complete Drag Compensation of the S/C

Rationale: Utilization of yet unpopulated orbits (< 250 km)

- ✓ **Payload advantages:** better resolution, lower latency, higher S/N ratio
- ✓ **Environment:** easy access to space, low radiation levels, no de-orbiting issues



What are the main challenges for Air Breathing EP Satellites?

Air-breathing electric propulsion (ABEP) is a complex technology that poses several technical challenges that must be addressed before it can be used for space missions. Some of the main challenges in ABEP include:

- **Integration of air-breathing and electric propulsion:** one of the main challenges in ABEP is to design a propulsion system that can operate effectively in both the atmosphere and the vacuum of space. This requires integration of air-breathing and electric propulsion systems, which involves designing complex flow control systems and combustion chambers.

- **Power generation:** ABEP systems require a large amount of electrical power to operate, which may require the development of lightweight and efficient power generation systems.

- **Control and stability:** controlling the operation of an ABEP system is challenging, particularly during transitions between atmospheric and vacuum operation. Ensuring the stability of the propulsion system during all phases of operation is critical to its performance and safety.

- **Testing and validation:** testing and validating an ABEP system is a significant challenge, particularly in the absence of an existing flight experience base. This requires the development of advanced simulation and testing capabilities, as well as flight testing.

- **Atomic oxygen:** it is a highly reactive form of oxygen that can be found in low Earth orbit (LEO) and other space environments. It is a significant challenge for spacecraft and propulsion systems because it can cause erosion and degradation of materials and components over time. In the context of air-breathing electric propulsion (ABEP), atomic oxygen is a concern because it can react with the engine components and affect their performance and longevity.

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What are the main challenges for Air Breathing EP Satellites?

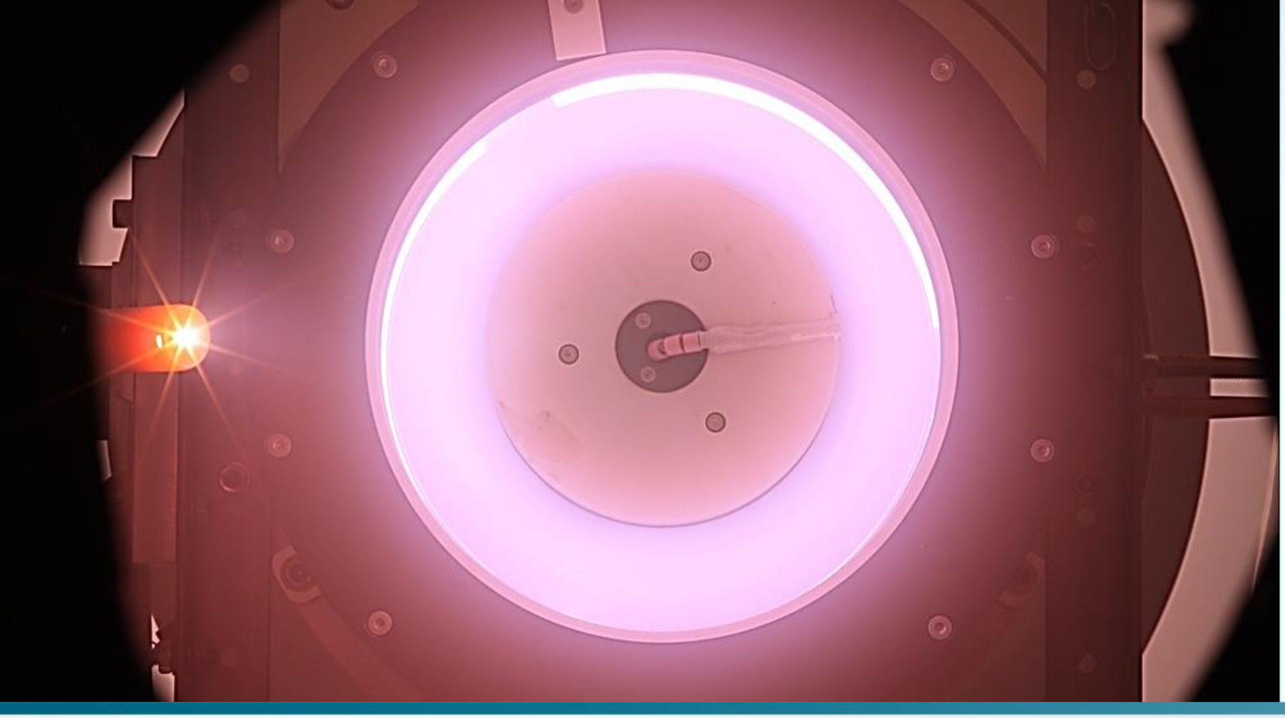
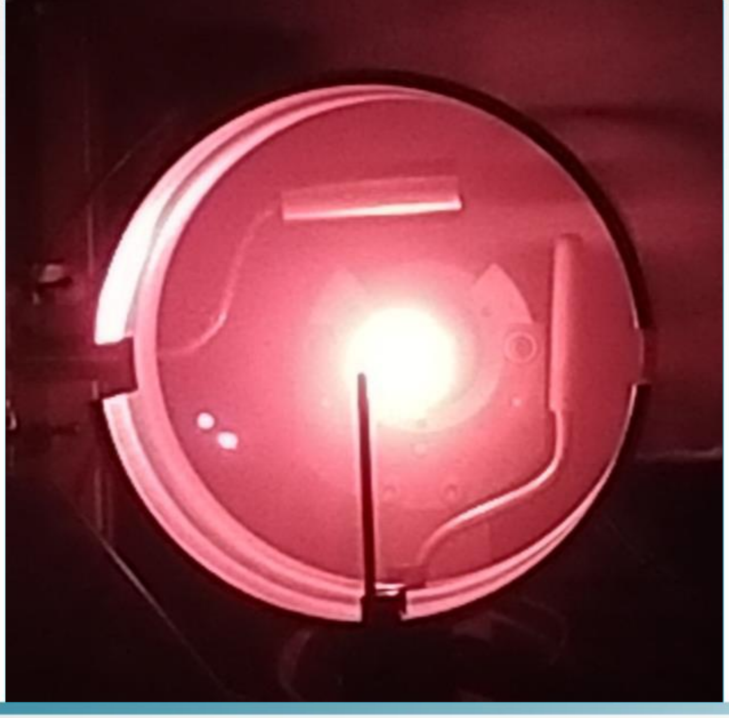
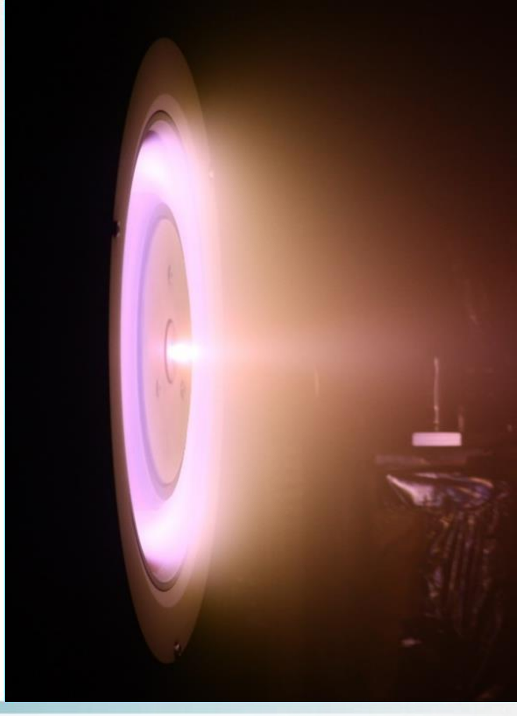
Air-breathing electric propulsion (ABEP) is a complex technology that poses several technical challenges that must be addressed before it can be used for space missions. Some of the main challenges in ABEP include:

- **Integration of air-breathing and electric propulsion**
- **Power generation**
- **Control and stability**
- **Testing and validation**
- **Atomic oxygen**

This was according to **Chat GPT**

…

Let's now see how we tried to dig deeper into some of these challenges through the **AETHER Programme**

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Project Overview

The ΛETHER H2020 project

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No *870436*

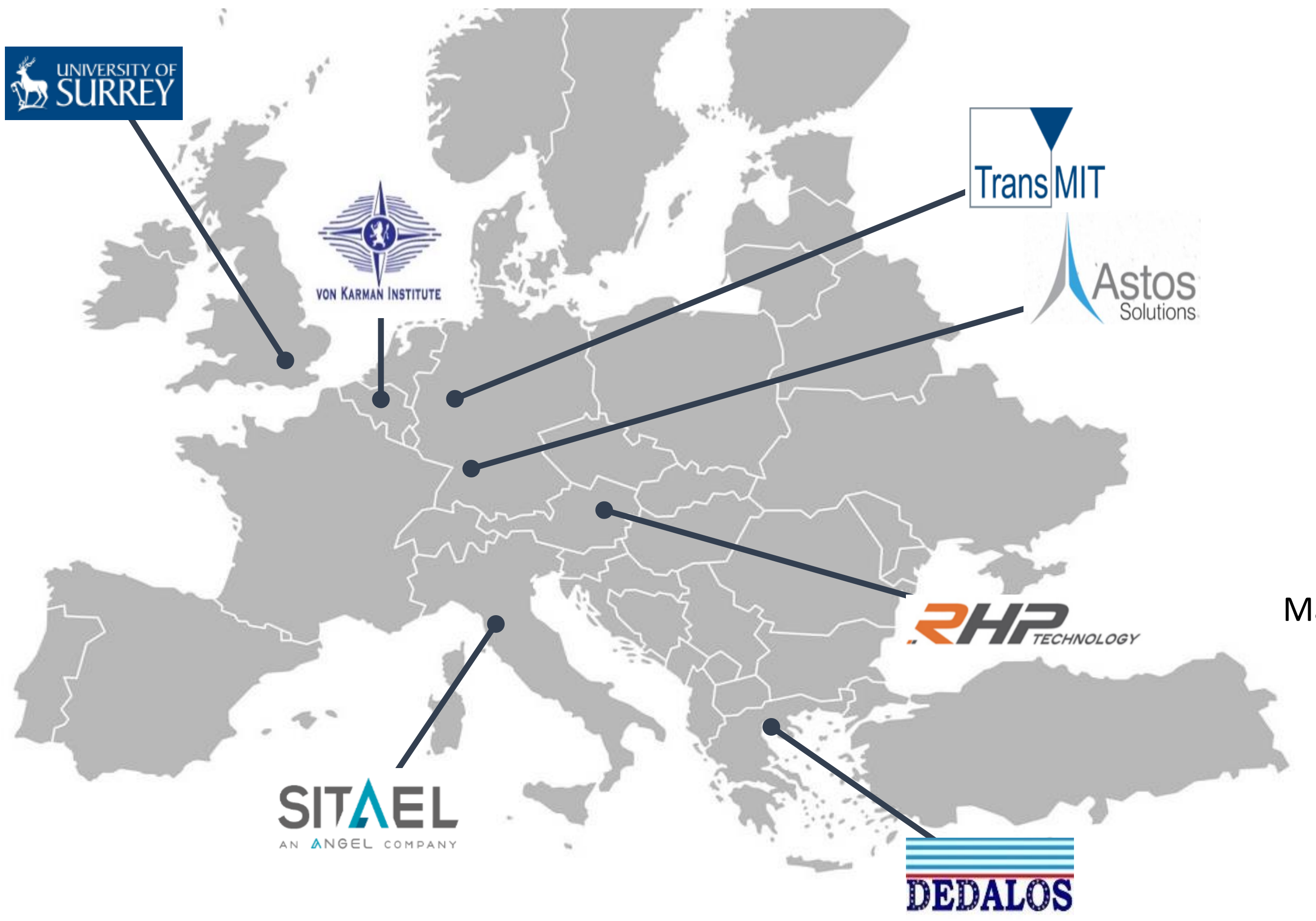
The main purpose of AETHER was to pave the way for a European RAM-EP system capable of full-drag compensation and integrable in a space platform.

The AETHER team

SITAEL – Coordinator, RAM-EP concept design, ionization and acceleration stages development, on-ground system testing

University of Surrey – Alternative cathode design and development

Von Karman Institute – Flow simulations, intake optimization, non-invasive diagnostics

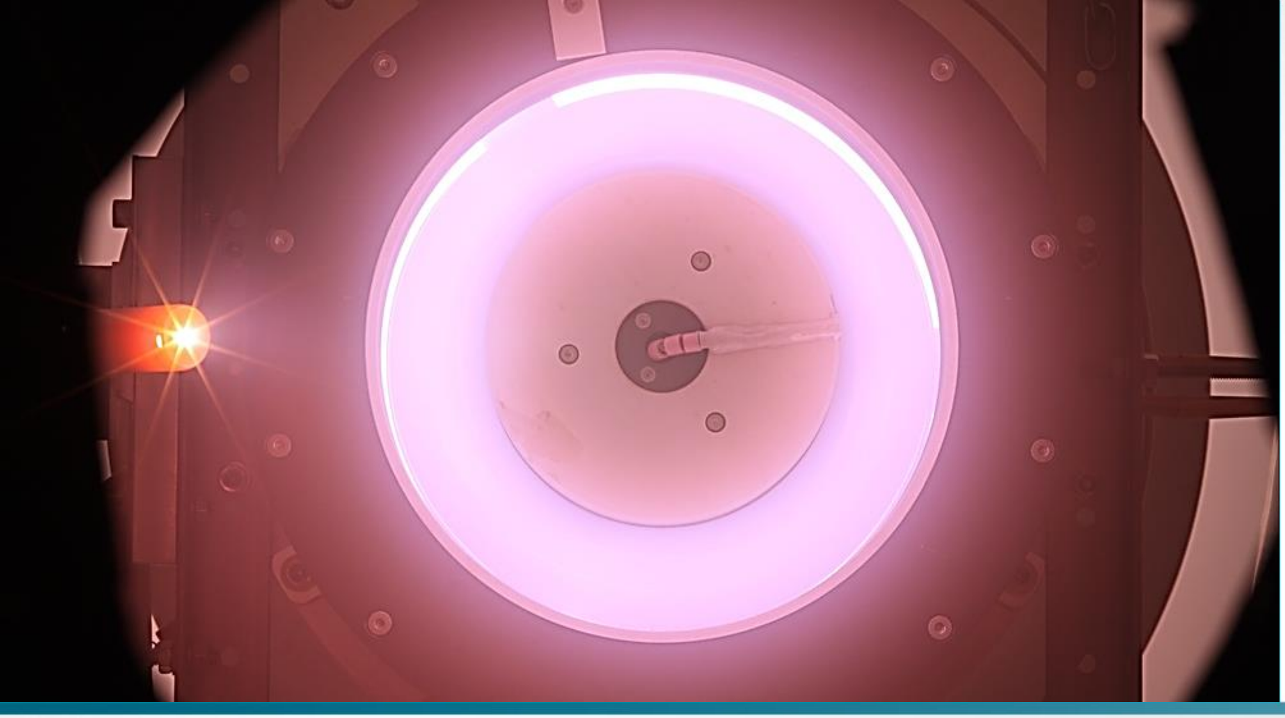
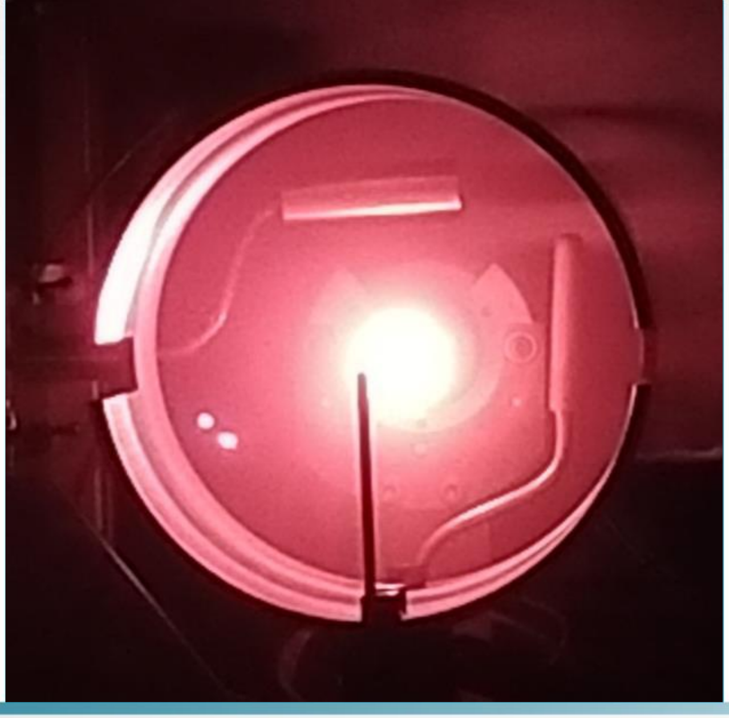
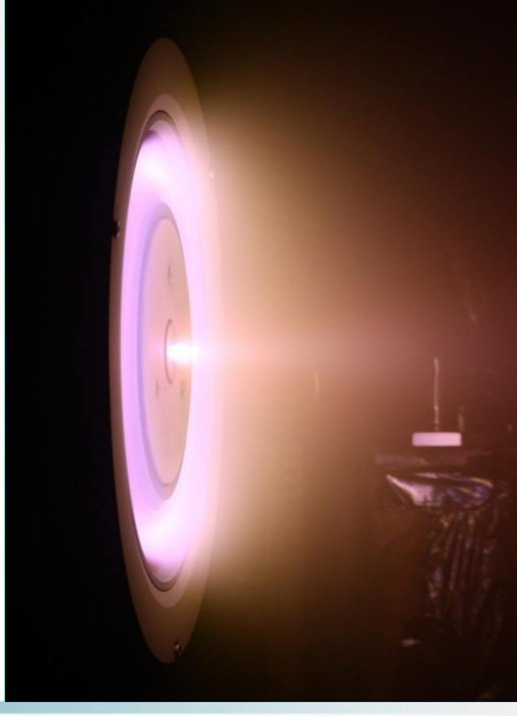


TransMIT – Gridded acceleration stage design and development

Astos Solutions – Mission scenarios analysis and optimization

RHP Technology – Material science studies for harsh environments

DEDALOS – Atmosphere definition in VLEO and in other celestial bodies

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Performed Activities:

1. **Atmosphere Definition in VLEO and Other Celestial Bodies**

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Atmospheric components of selected stellar bodies of our Solar system which are of interest to ISRU

Planet/Moon	Component to harvest
Venus, Mars	CO_2
Earth	O, O_2, N, N_2 *
Giant Planets (Gaseous & Ice)	H_2, He
Titan	N_2

** various percentages of Atmospheric Remnants (AtR), depending on the altitude (higher than the Karman line)*

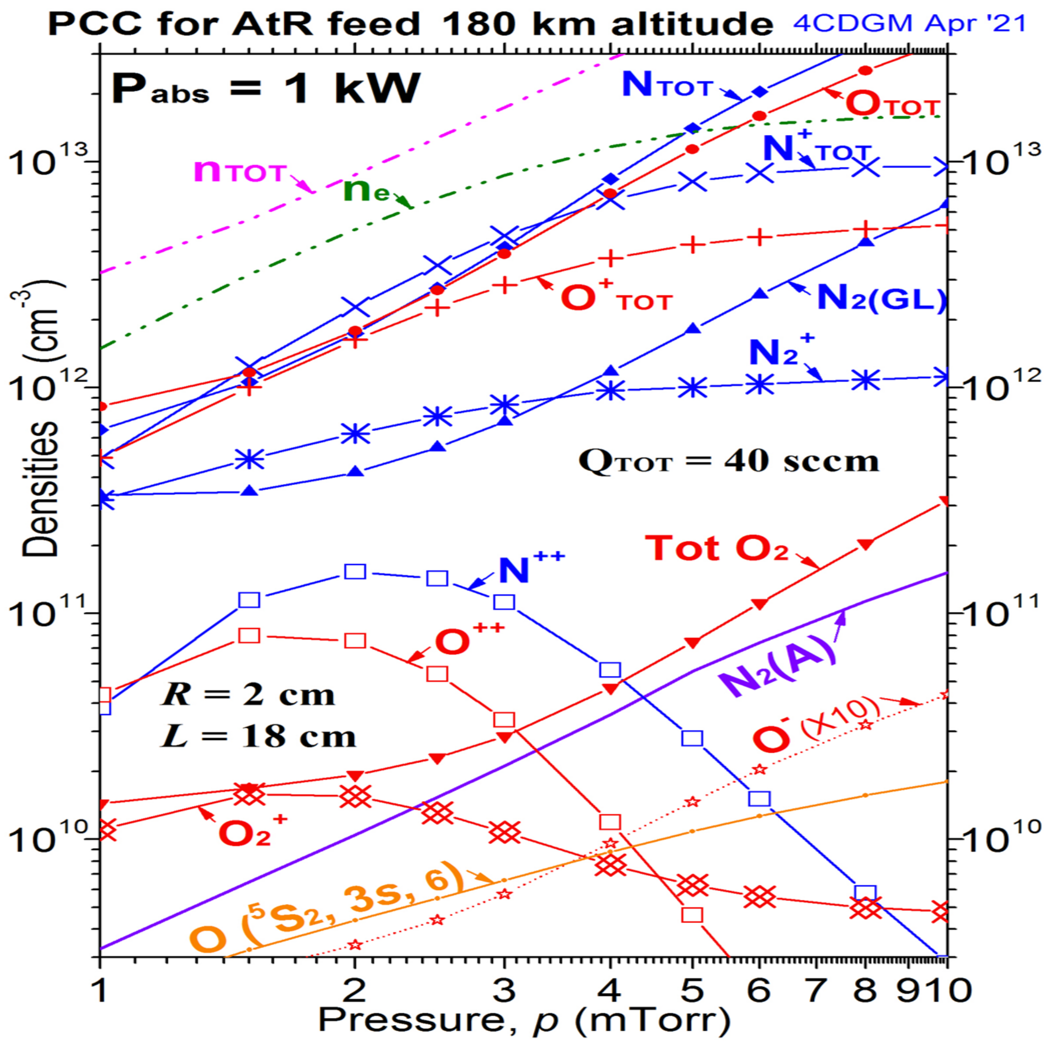


Figure 1. Plasma Components Composition (PCC) for 1 kW absorbed power, 180 km altitude

1. Atmosphere Definition in VLEO and Other Celestial Bodies

Theoretical spectra of **O** I, **O** II from **4CDGM**, **necessary for Optical Emission Spectroscopy**

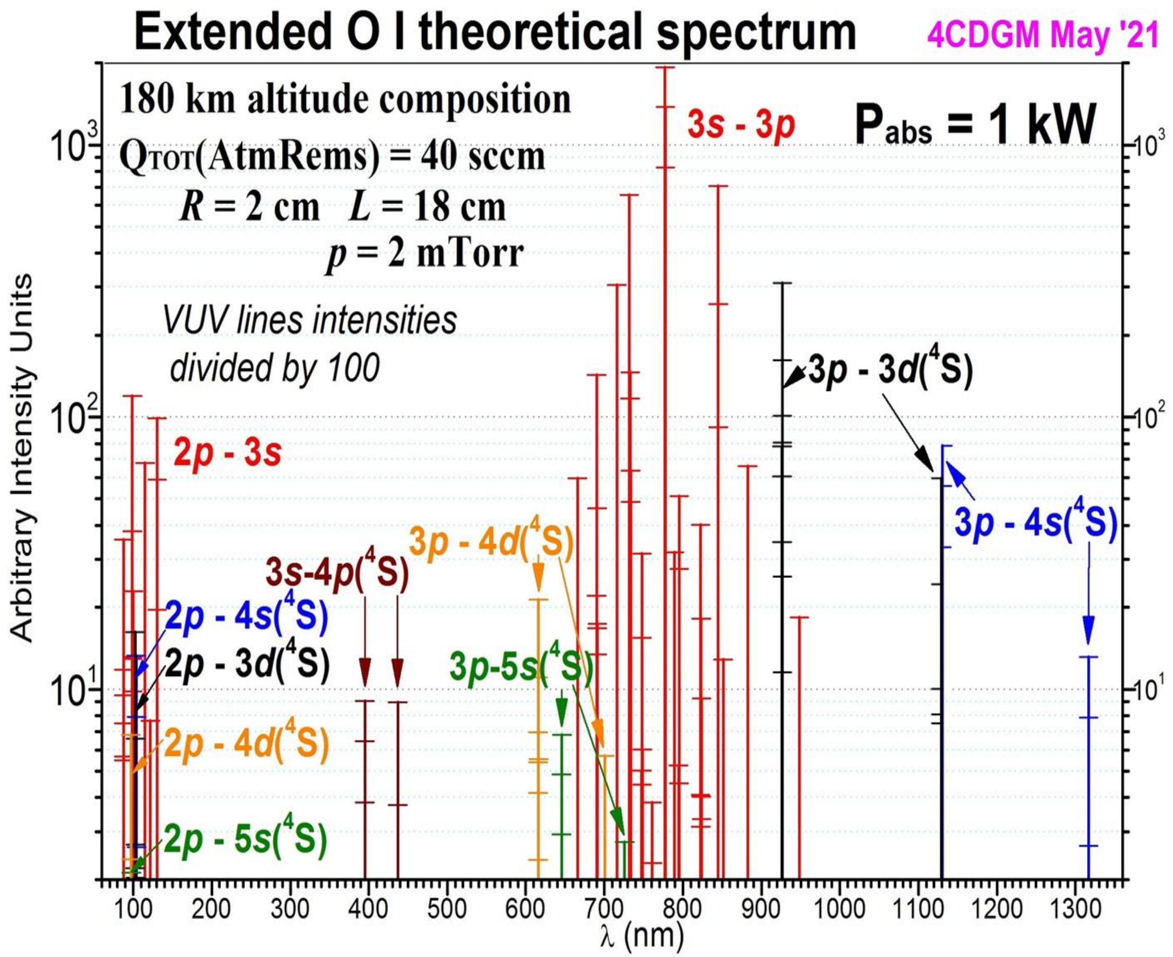


Figure 2. O I spectrum. Conditions of Fig. 1 for 2 mTorr pressure

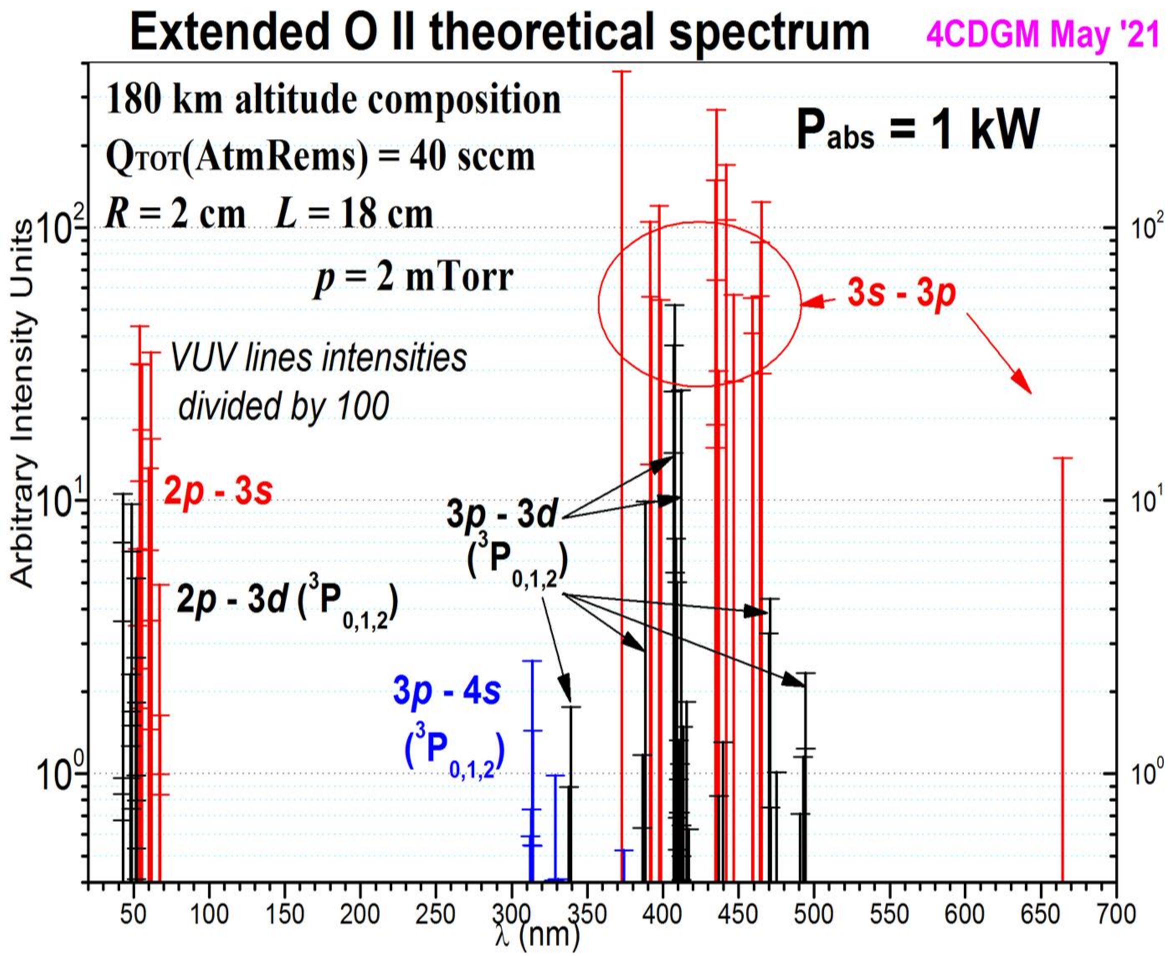
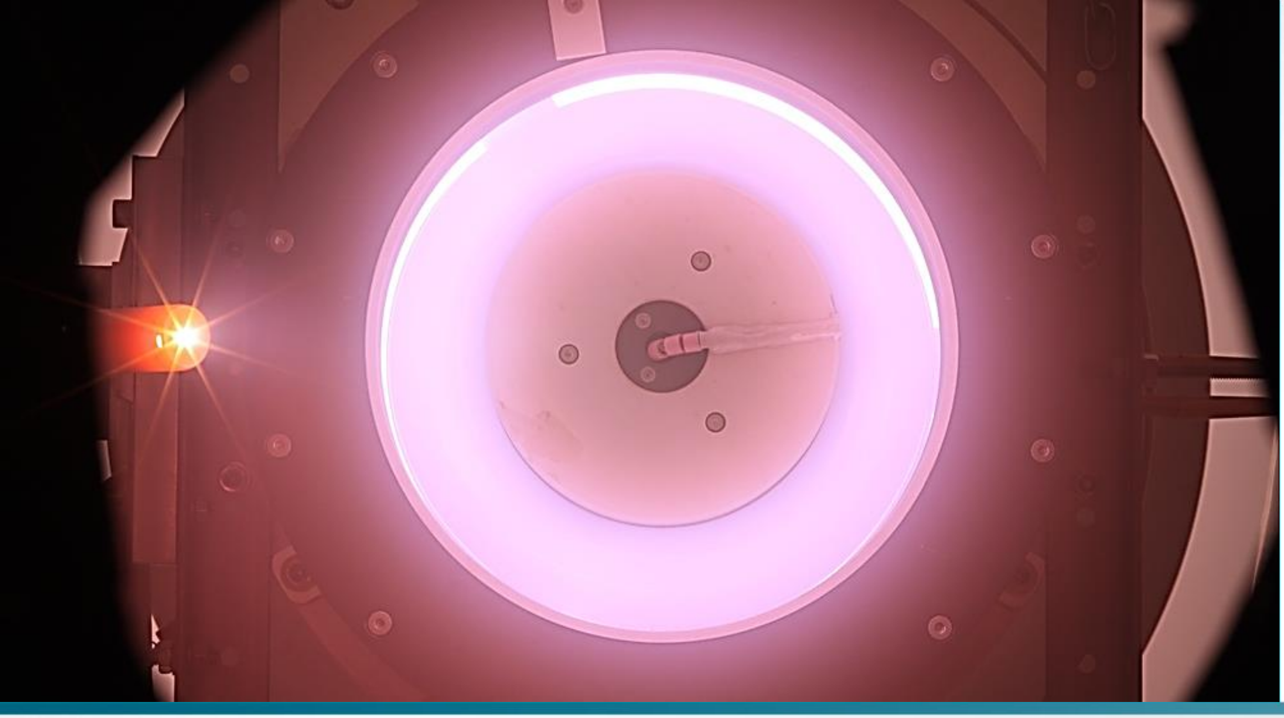
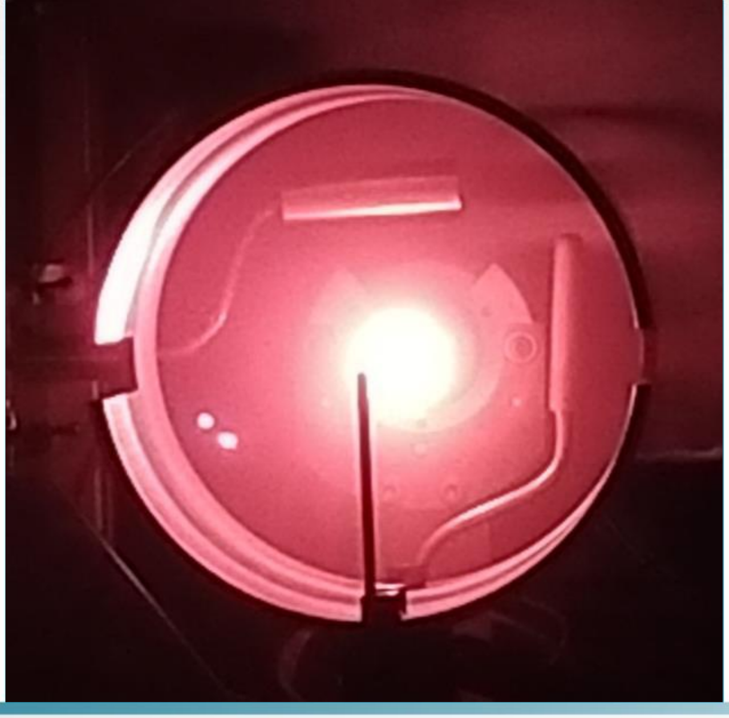
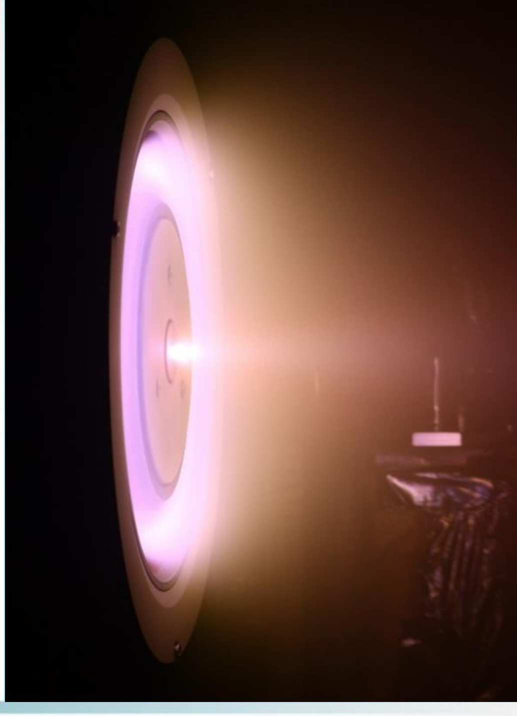


Figure 3. O II spectrum. Conditions of Fig. 1 for 2 mTorr pressure

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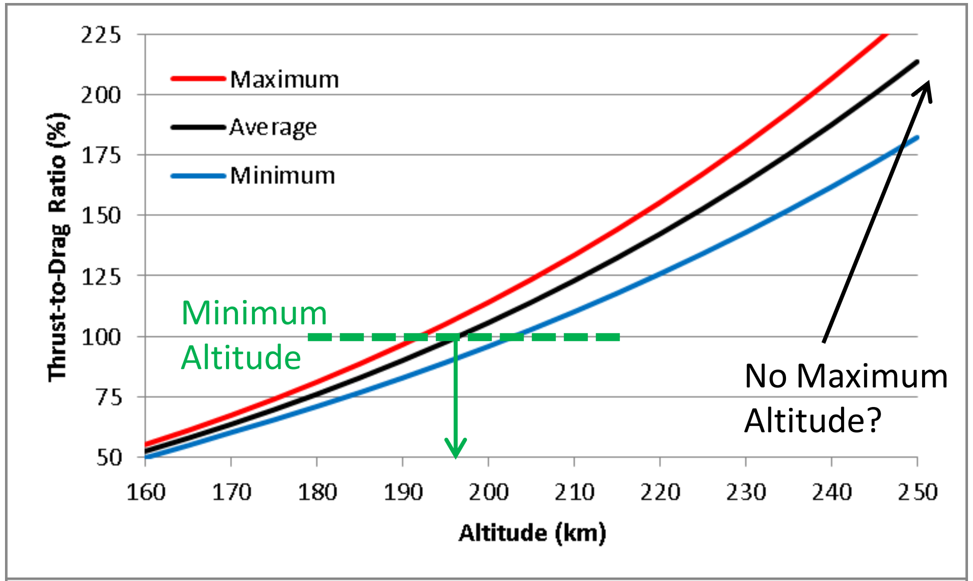
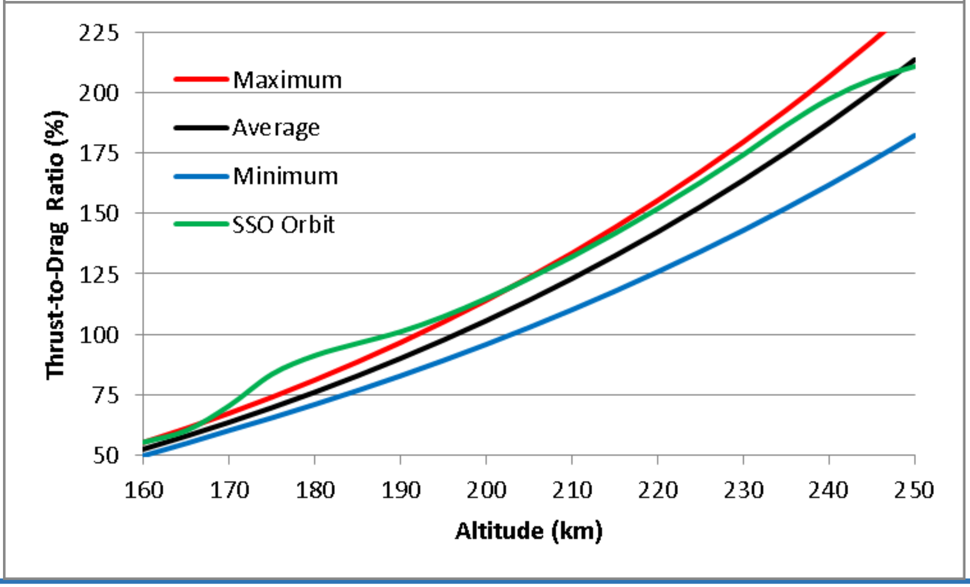
Performed Activities:

2. **Mission Scenarios and Analysis**

2. VLEO, Mission Scenarios and Analysis





Introduction

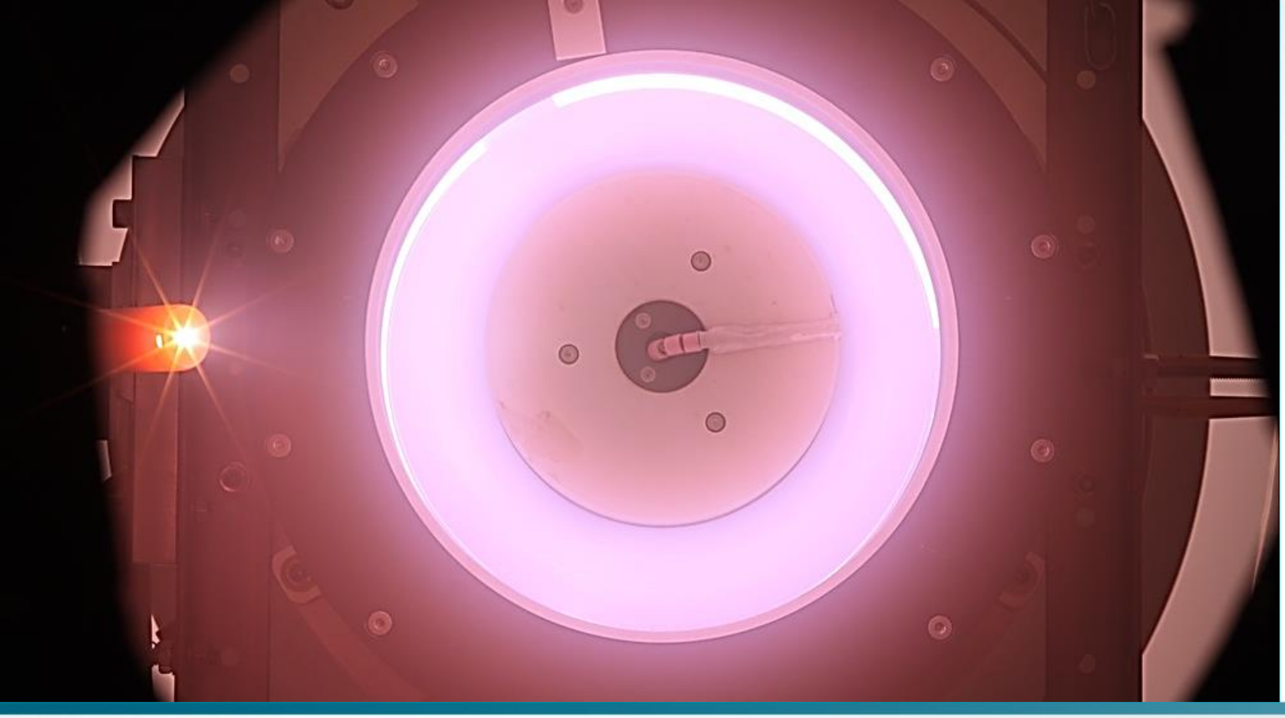
- *T/D* must be at least 1
- All results are displayed for medium solar activity (variations are due to differences in latitude/longitude)

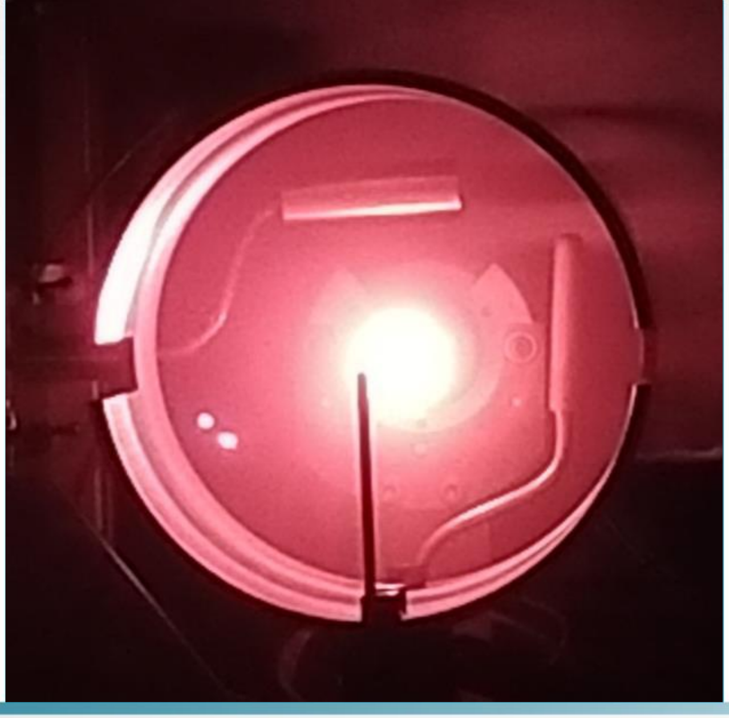
Pure Performance Data

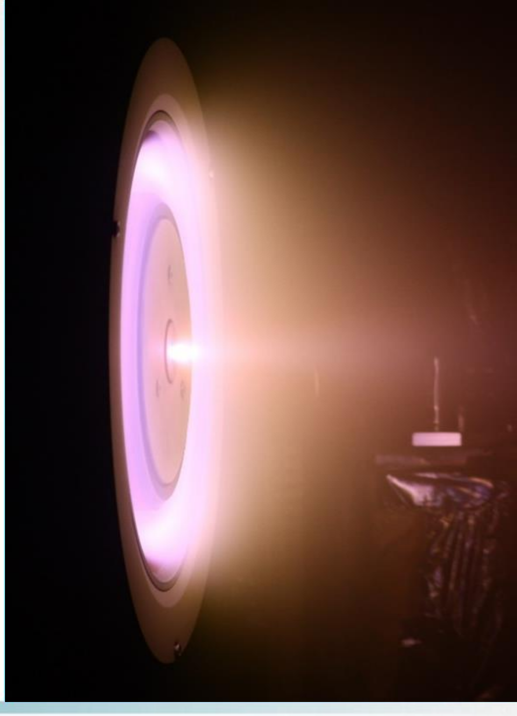
- Minimum altitude:
  - Maximum *T/D* → 192 km
  - Average *T/D* → 196 km
  - Minimum *T/D* → 203 km
- Maximum altitude > 250 km (Unlimited? Of course not…)

SSO Orbit Simulations

- Average altitude ~9 km higher than the equatorial altitude (!) → Average *T/D* of SSO is higher than average *T/D* at constant altitude
- Minimum equatorial altitude of 189 km
- Remark: results in *h* < 175 km and *h* > 230 km might be less realistic due to data extrapolation







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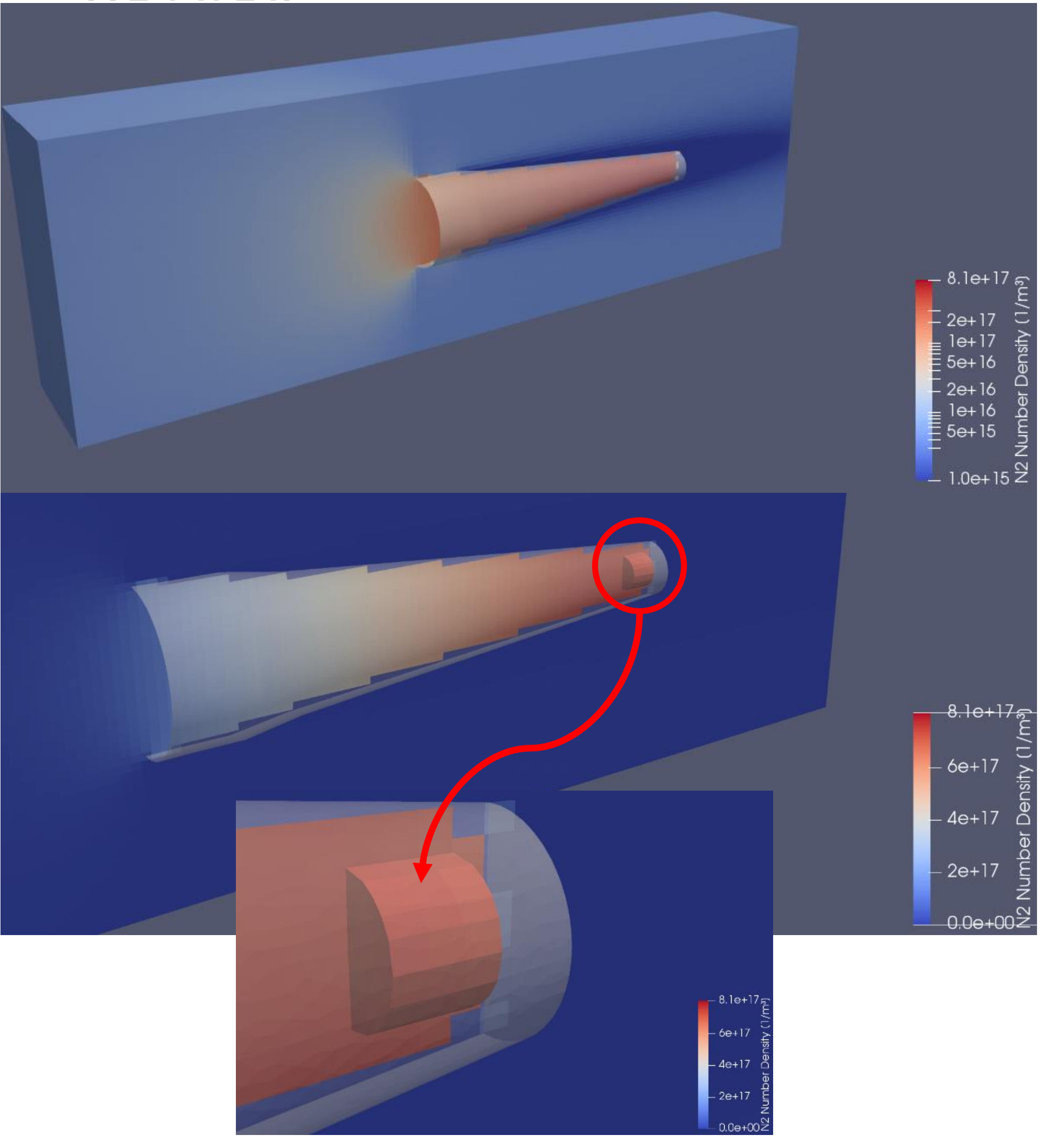
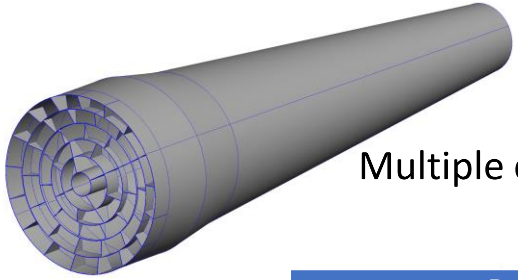
Performed Activities:

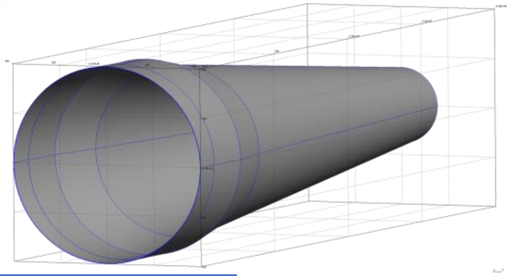
3. **Intake Optimization**

3. Intake Optimization

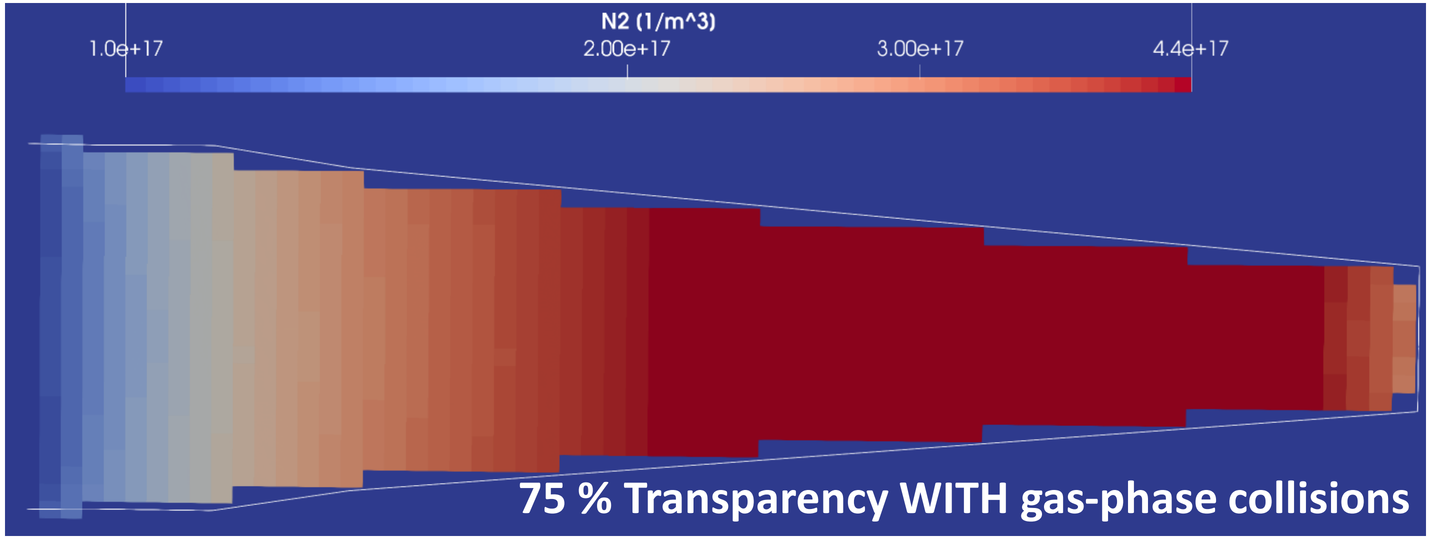




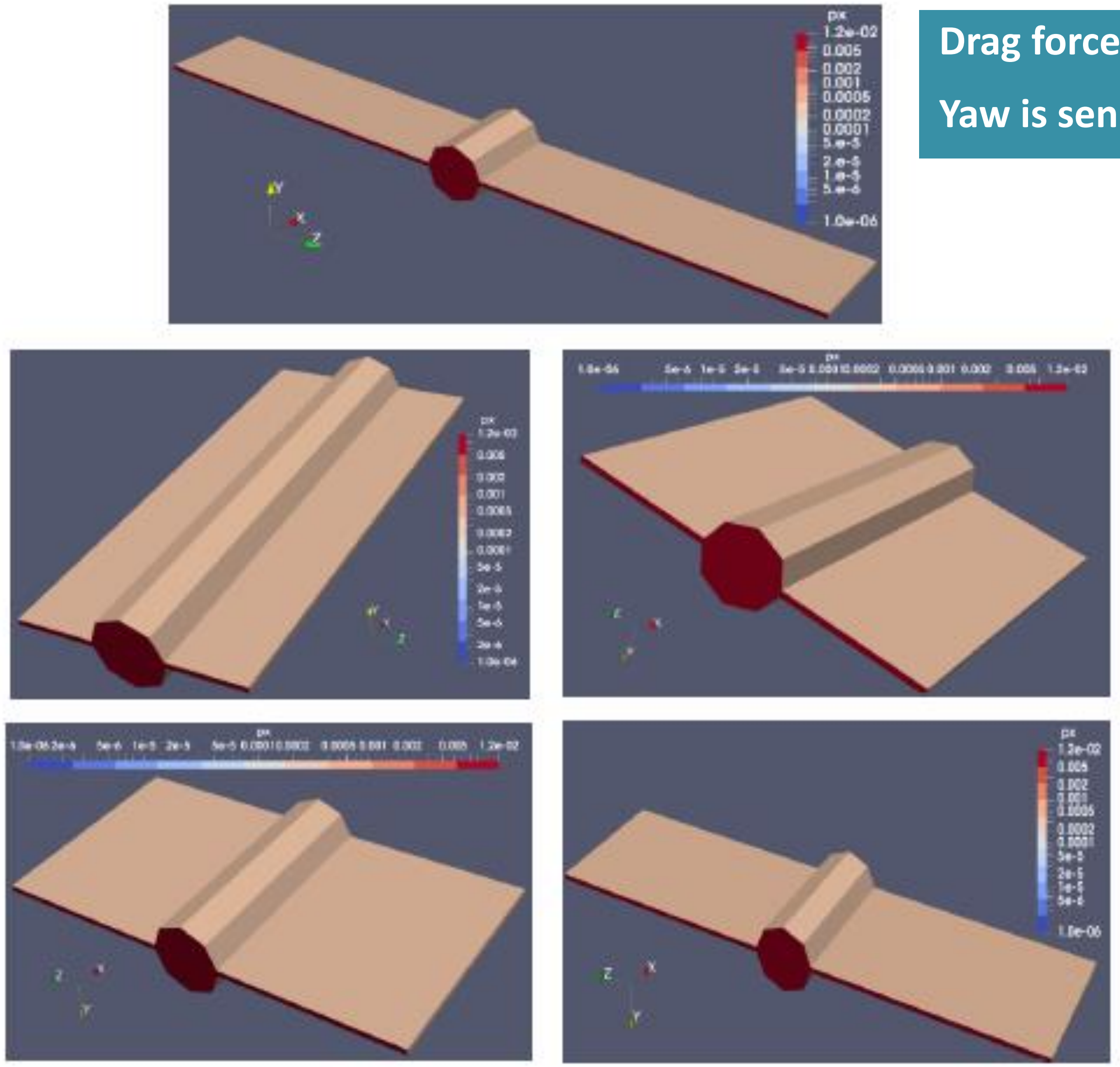
Intake options
Multiple channels vs. Single channel



Parameter	Operating Range
Mass Flow Rate to RAM-thruster	0.2 ~ 0.6 mg/s
Operative inlet number density	4e15 to 1e16 m^-3
Compression ratio	>100
Collection efficiency	>0.25
Envelope	ϕ1500mm x L 4500 mm
Mass	<40 kg
Free volume behind intake wake	>1.5 m^3



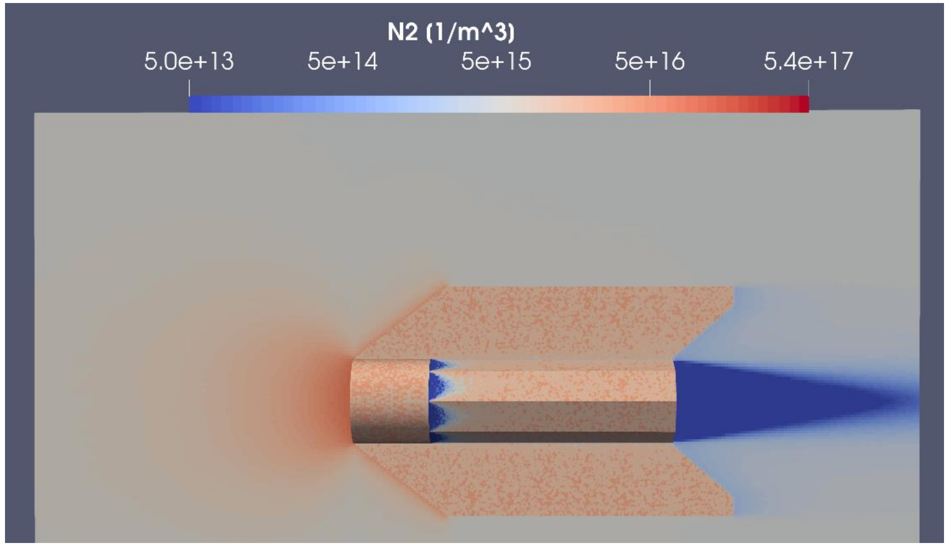
3. Intake Optimization & Platform Intake Integration



Drag force is proportional to the surface area and is not sensitive to yaw.

Yaw is sensitive to configuration.

Configuration	Drag [mN]	Drag with 3.3° Yaw [mN]	Yaw moment [mN.m]	Yaw moment with 3.3° Yaw [mN. m]
Case20	38.41	39.55	4.67E-08	7.96
Case21	39.90	40.78	1.08E-07	5.59
Case22	42.24	42.90	3.47E-07	4.01
Case23	46.05	46.53	2.54E-06	3.02
Case24	51.06	51.40	2.86E-06	2.27



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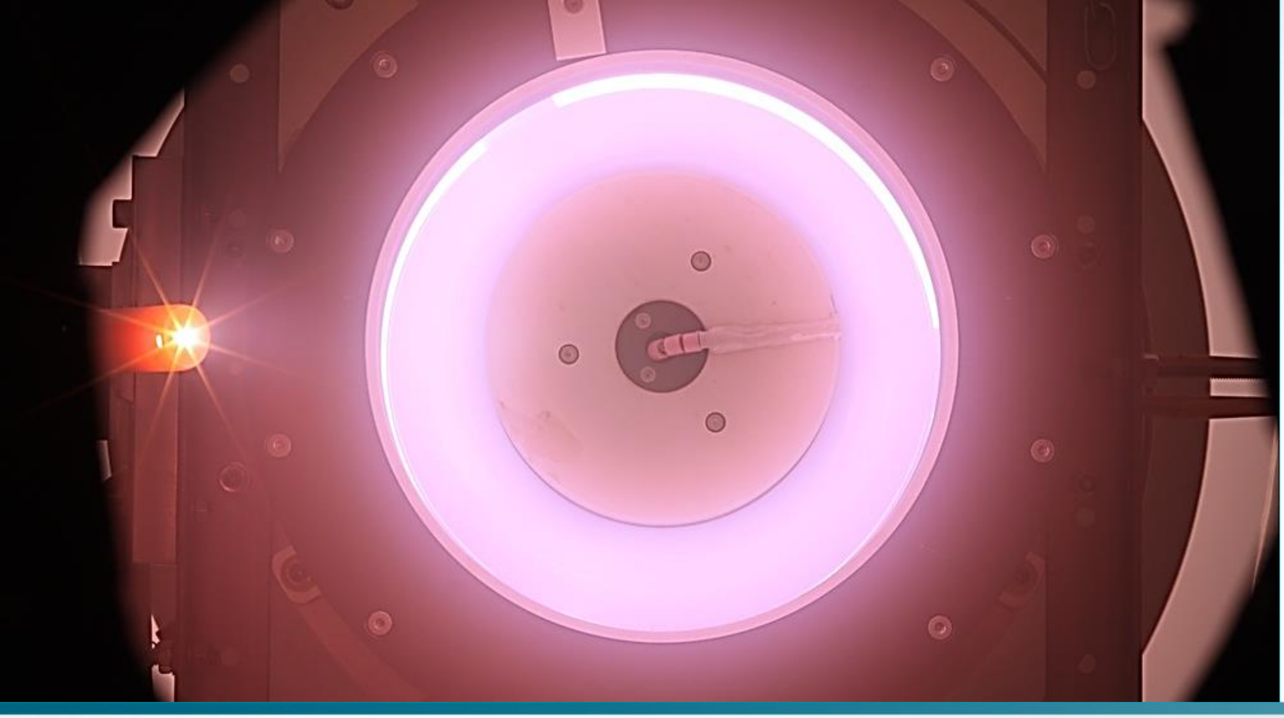
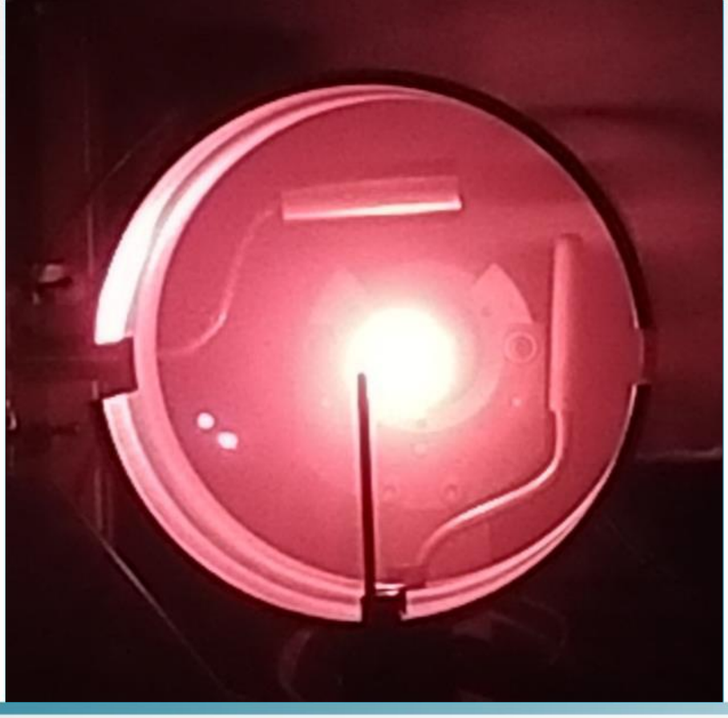
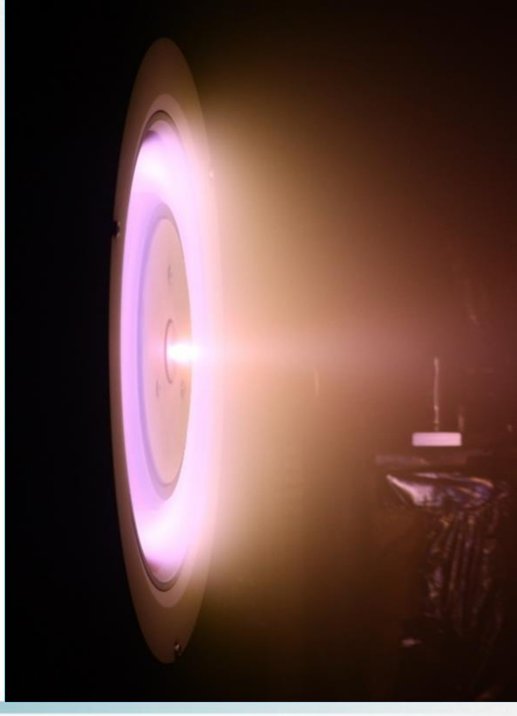
3. Intake Optimization

- The collection efficiency results have been extensively investigated, and it is with confidence it may be stated that the intake designed will **fulfill the requirement regarding the mass flow requirements.**
- It has been demonstrated that the **compression achieved inside the intake is what was targeted.**
- A first generic version of the platform model designed by SITAEL is integrated with the designed intake and DSMC calculations have been performed for the 25% and 75% transmissivities, with and without gas-phase collisions. The conclusions drawn from the intake DSMC calculations regarding the effects of transmissivities and free molecular flow assumption on the forces and intake performance remain valid.

		SPARTA DSMC							SMARTA	SPARTA	SMARTA	SPARTA	SMARTA
		Freestream		Intake exit									
		n_{N2} [1/m^{-3}]	n_O [1/m^{-3}]	n_{N2} [1/m^{-3}]	n_O [1/m^{-3}]	v_{N2}	v_O	v		Total Drag Force [mN]		mass out [mg/s]	
Thruster transparency 75%	No-collision	4.13E+15	4.13E+15	3.84E+17	2.80E+17	93	68	80	117	15.67	15.78	0.5	0.5
	Collision	4.13E+15	4.13E+15	3.75E+17	2.71E+17	91	66	78		16.1		0.46	
Thruster transparency 25%	No-collision	4.13E+15	4.13E+15	8.03E+17	5.70E+17	195	138	166	188	15.34	15.73	0.26	0.27
	Collision	4.13E+15	4.13E+15	7.51E+17	5.37E+17	182	130	156		15.93		0.24	







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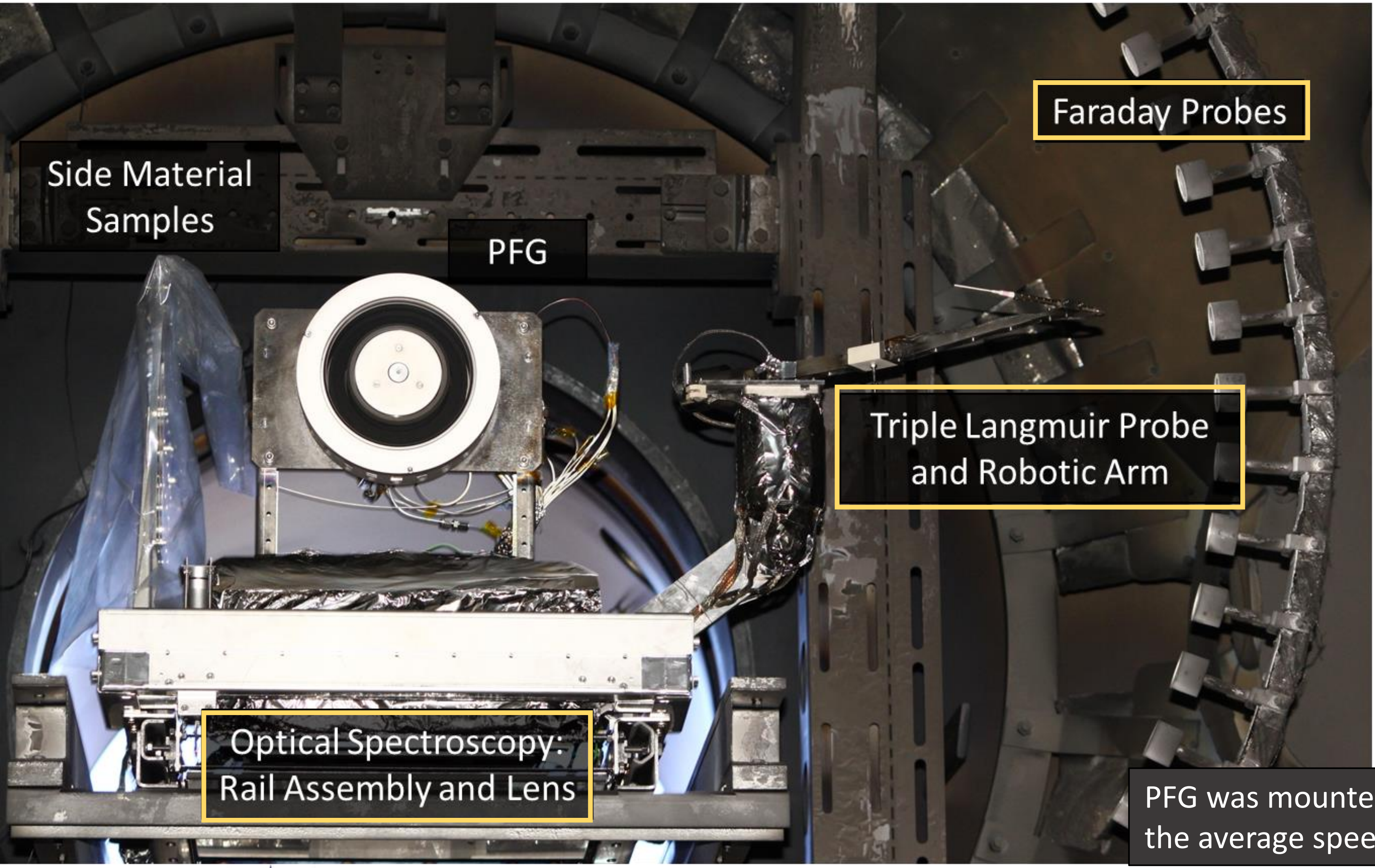
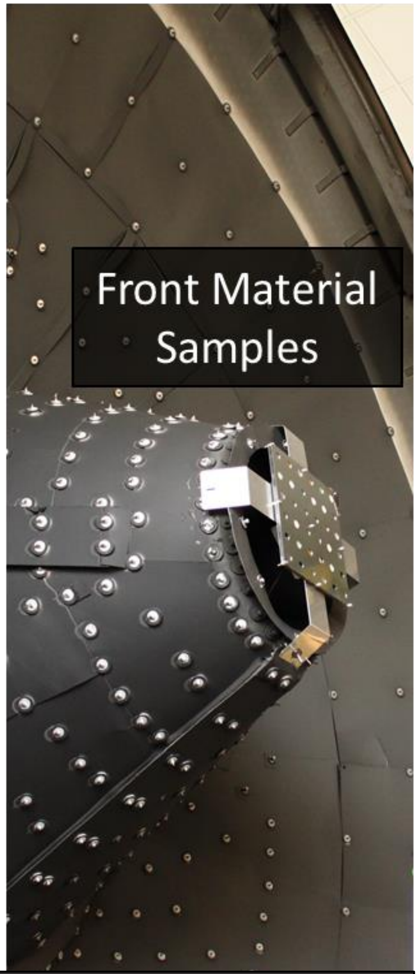
Performed Activities:

4. **Particle Flow Generator Test**

Particle Flow Generator Test

Test Facility: 200 m^3, Ultra-High Vacuum Chamber

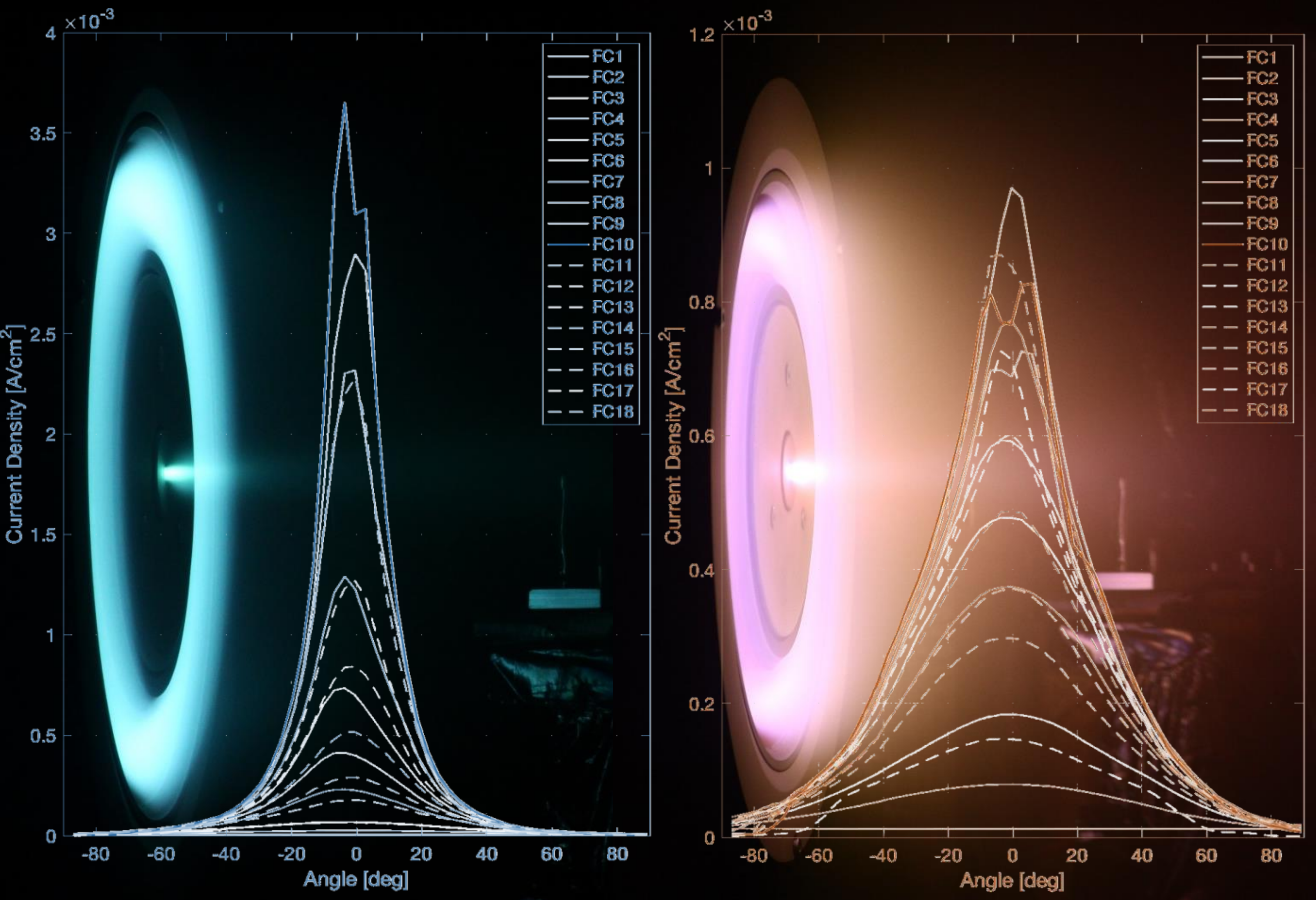




PFG was mounted on a thrust balance to indirectly measure the average speed of the ejected particles ($v = T/\dot{m}$)

Discharge Voltage: 300V
Anode MFR 10 mg/s Xe
Cathode MFR 1mg/s Xe

Discharge Voltage: 225V
Anode MFR 6 mg/s N2/O2
Cathode MFR 0.6mg/s N2



PFG, Plasma plume Distribution (Faraday probes measurement)

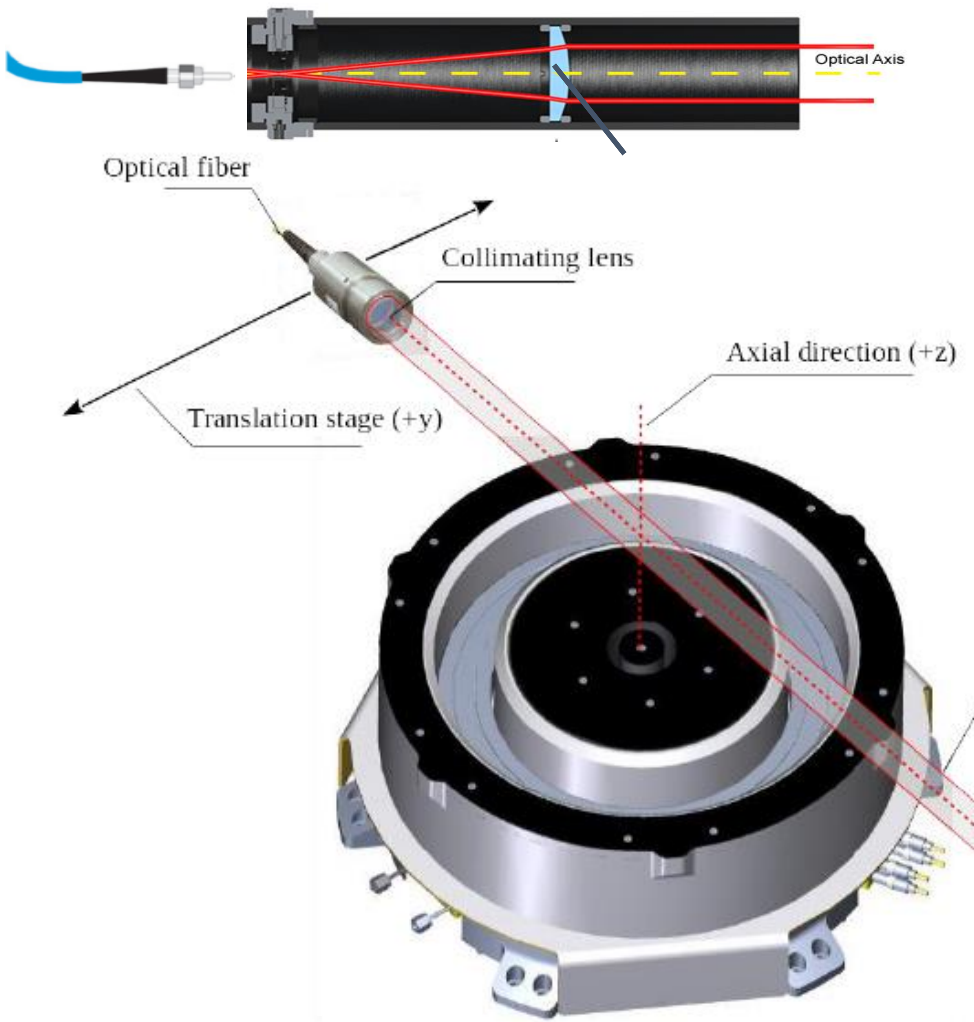
PFG-related Results:

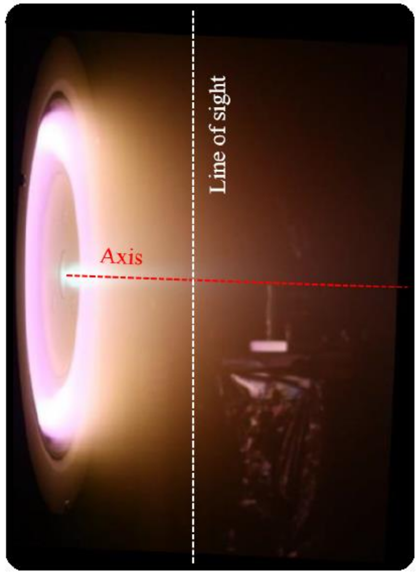
- Discharge stability with N2/O2 AMFR and N2 KMFR demonstrated in the 225V to 375V discharge voltage and 5mg/s to 7mg/s AMFR range
- Operation at 225V (Isp in 600s the 1000s range) suitable for VLEO simulation

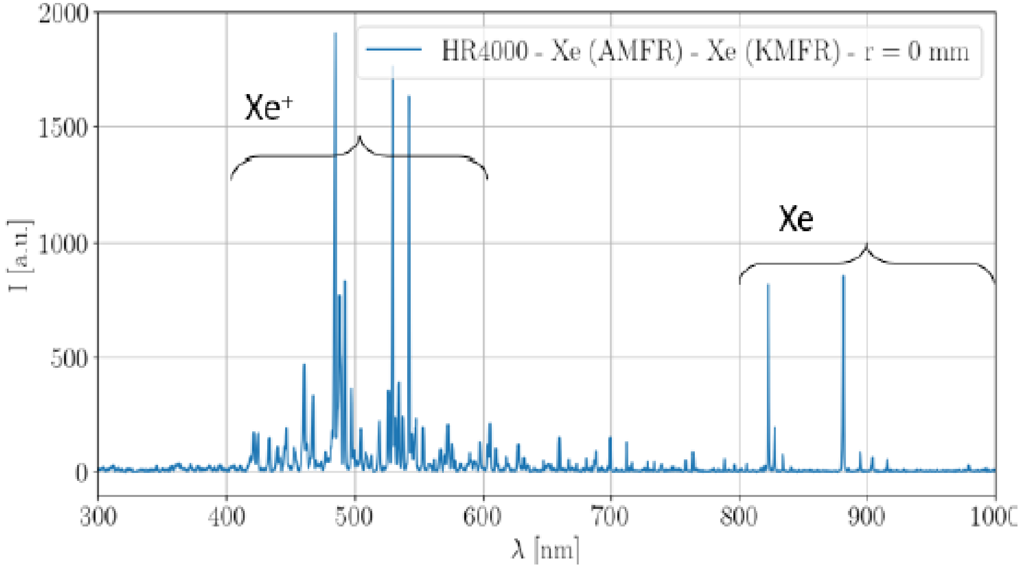
Air Breathing Propulsion-related Results:

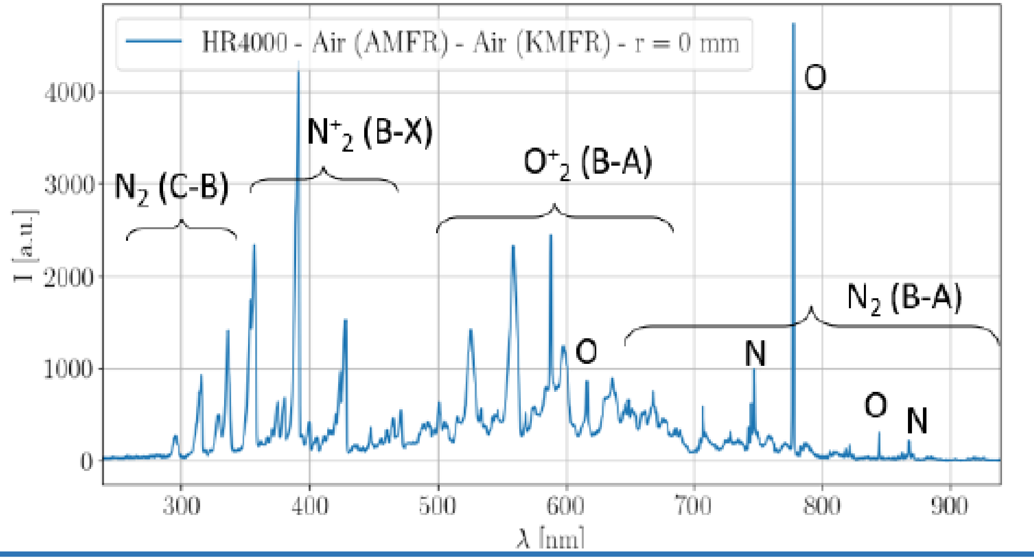
- Magnetic shielding effective with air-propellant (ceramic edges still sharp after testing)
- Anodic efficiency up to 20%

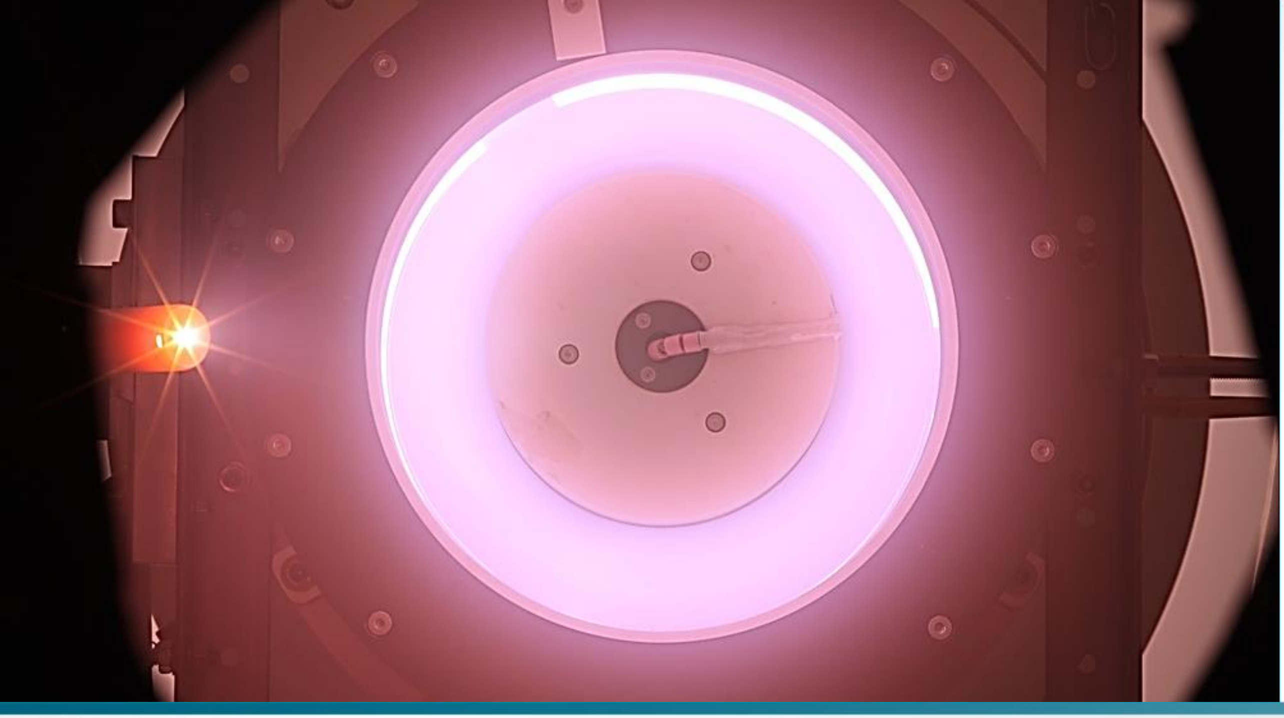
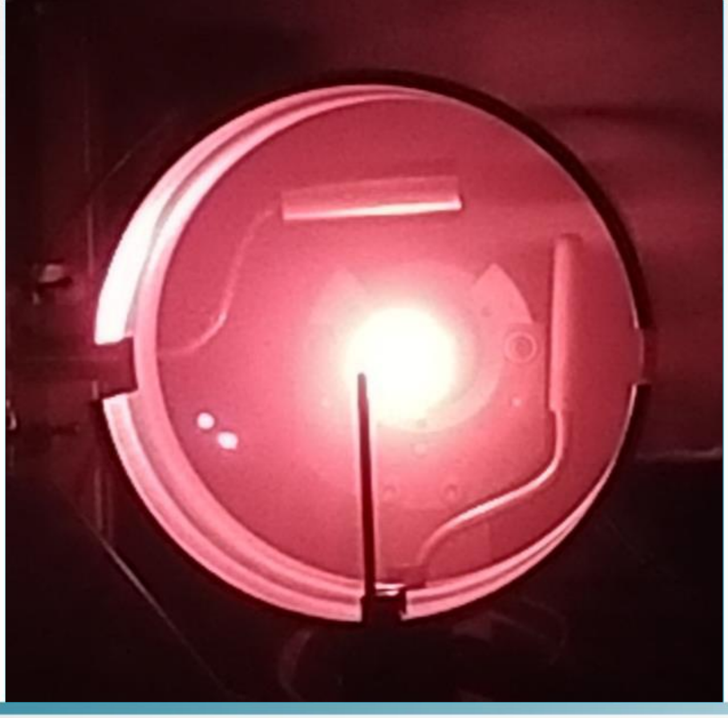
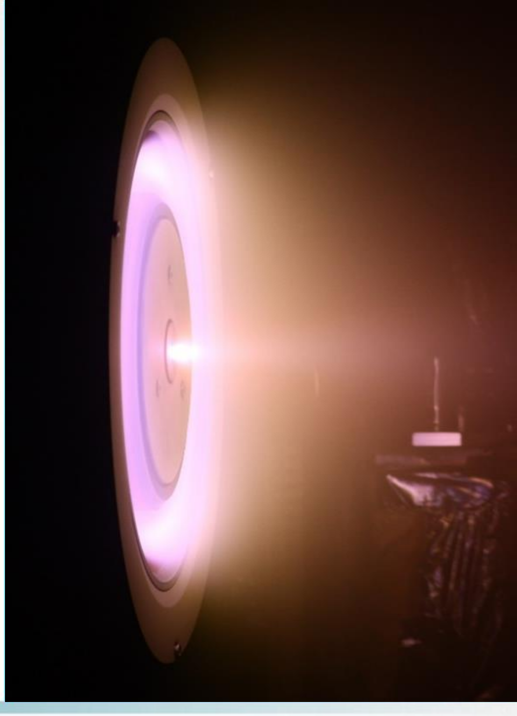
PFG characterization – non-invasive diagnostics









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Performed Activities:

5. **Effect of Atomic Oxygen on Different Materials**

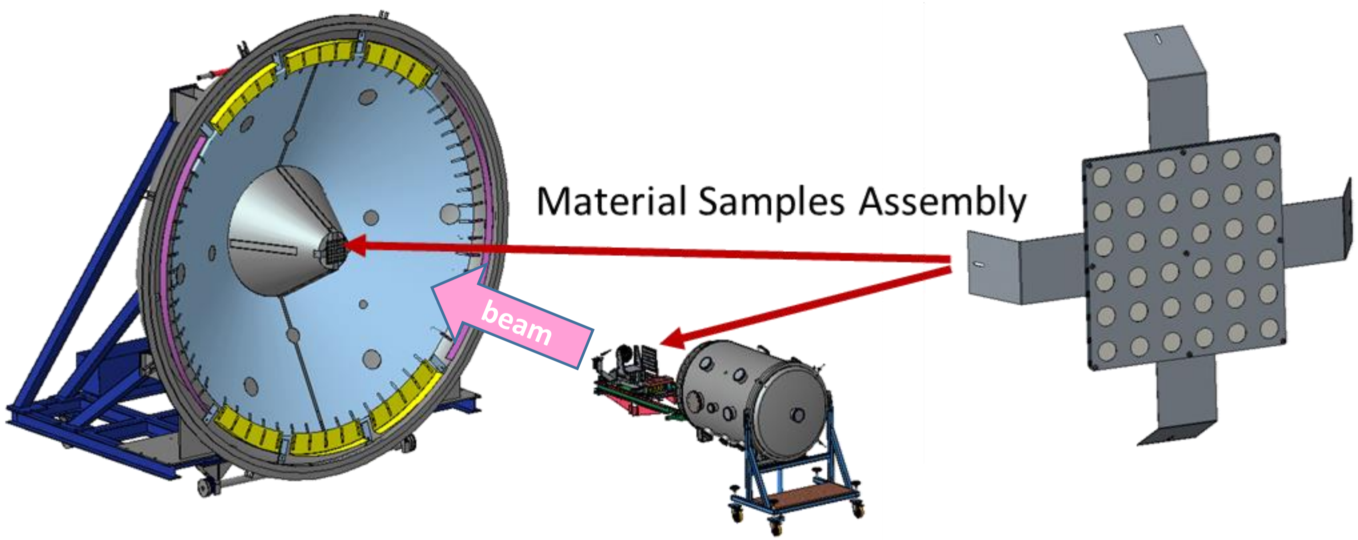
PFG - Overview of sample position (from back side) – valid for frontal and/or lateral

- Testing of materials in PFG
- Selection of materials - based on discussion with SITAEL
- Samples with dedicated geometry provided for testing

Two arrays of sample materials in the vacuum chamber:

- In front of the thruster
- On one side of the thruster

	1	2	3	4	5	6
A	SHAPAL v1 axial F/L	Al Alloy F/L	Cu-ETP	Mg alloy F/L	Cu-OF	SS F/L
B	Ti Gd5 F/L	SHAPAL v2 axial F/L	SHAPAL v2 radial F/L	W F/L	SHAPAL F/L	Al_2O_3-Y_2O_3 F ***Steel L***
C	ZrO_2-Y_2O_3 F SS L	CuCrZr F/L	TZM F/L	Mo F/L	Steel F/L	TiB_2 F/L
D	Ti Gd1 F/L	Al_2O_3 F/L	Ti Gd2 F/L	HEA5 F ***SS L***	BN F/L	HEA6 F ***SS L***
E		SHAPAL modif. Axial F/L	Pt foil F ***SS L***	Au foil F ***Steel L***	SHAPAL modif. Radial F/L	
F	SmCo demagn. F/L		MoS_2 (spacer exposed) F/L	ZrB_2-SiC F/L		SmCo magn. F/L



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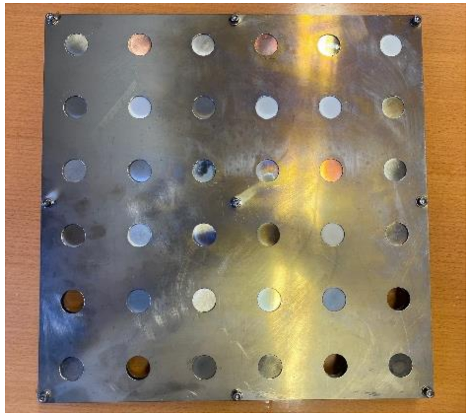
PFG - Analysis of samples exposed in PFG

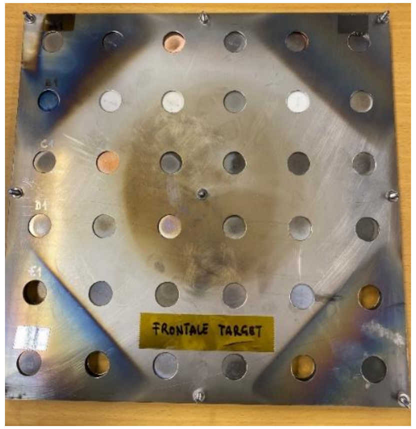
Incoming inspection

Frontal target

front side

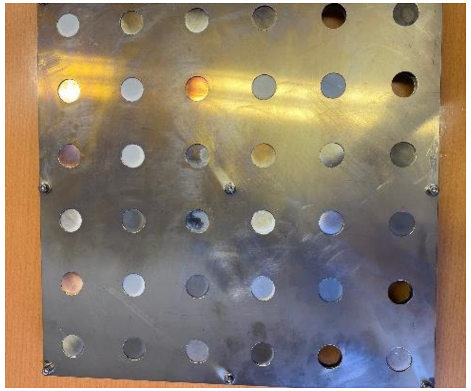


back side

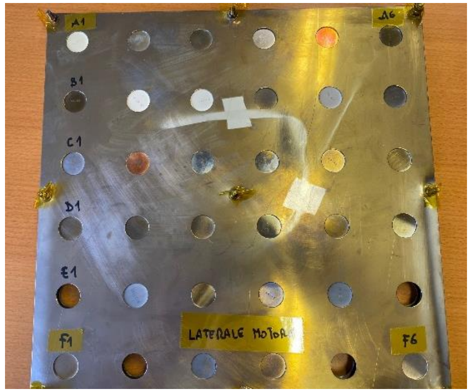


Lateral target

front side



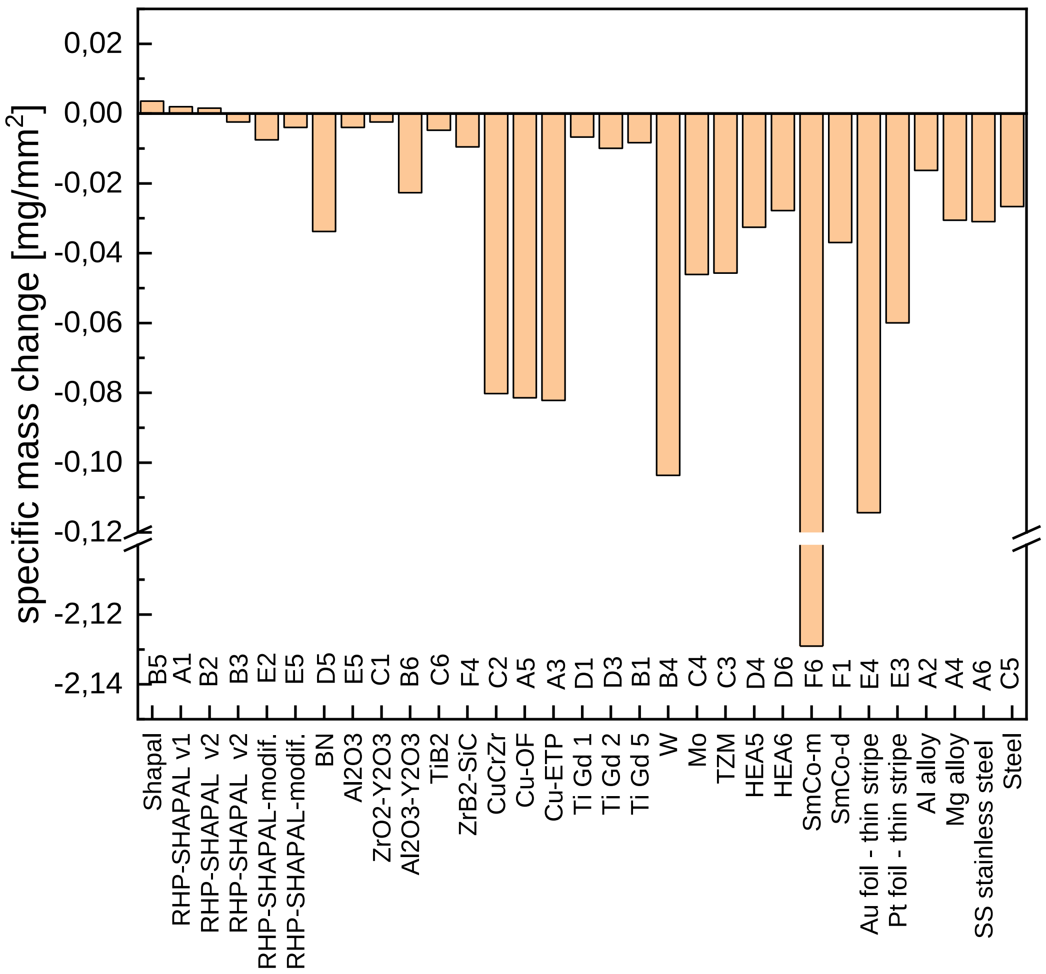
back side



Analysis:

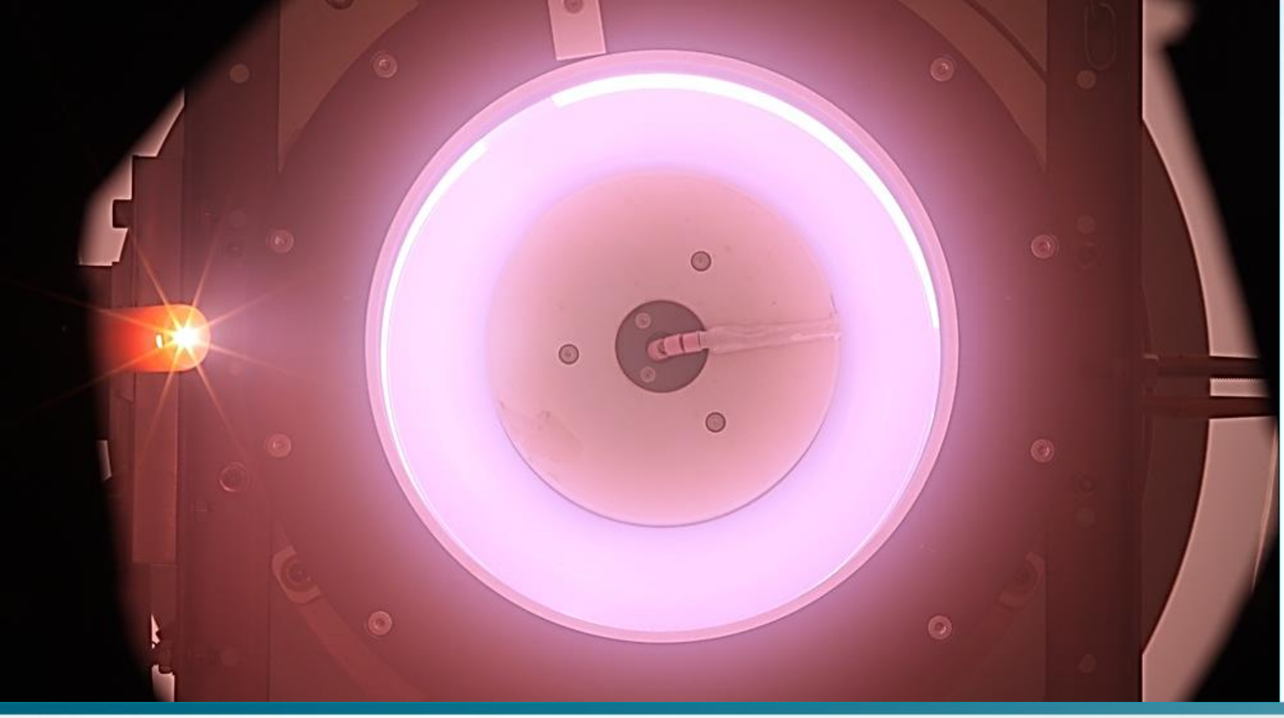
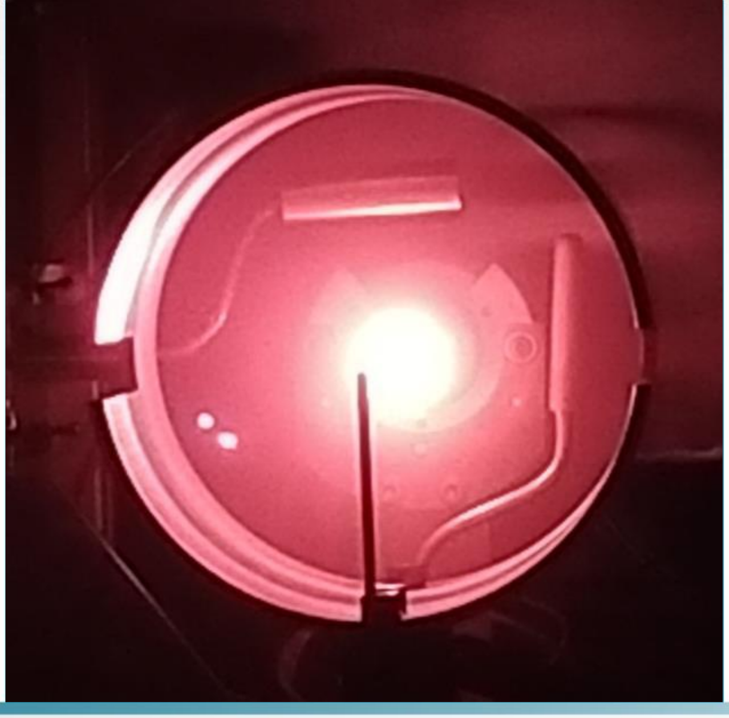
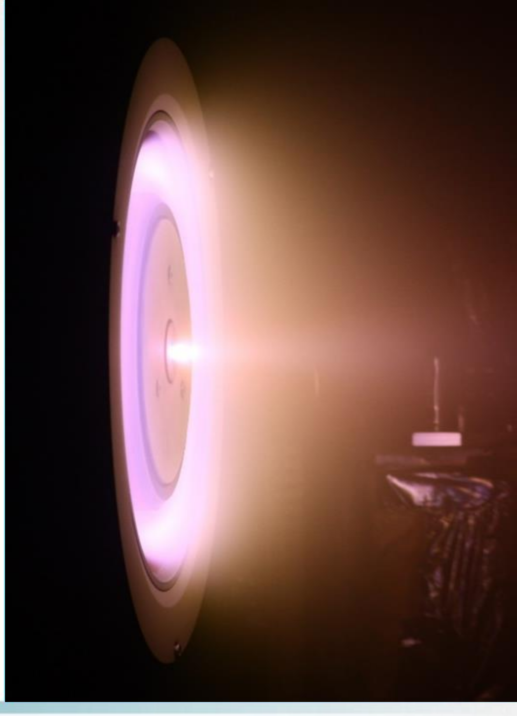
- Microstructure
- XRD
- Mass loss
- Cross-section
- SEM/EDS

PFG – Analysis of samples after exposure



Due to the different processing conditions in the PFG, either **erosion** is taking place when the samples are placed in a frontal position, or a **reaction** is taking place (between the oxygen and the surfaces) if the samples are placed in lateral position.

- Composition of gases during exposure in PFG - Xe and O_2/N_2 mixture)
- Sputtering and redeposition of neighboring samples

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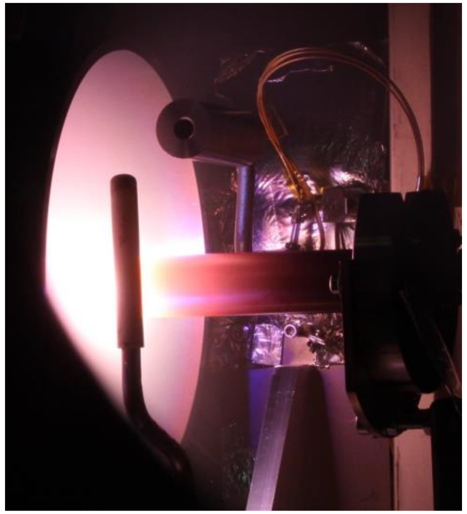
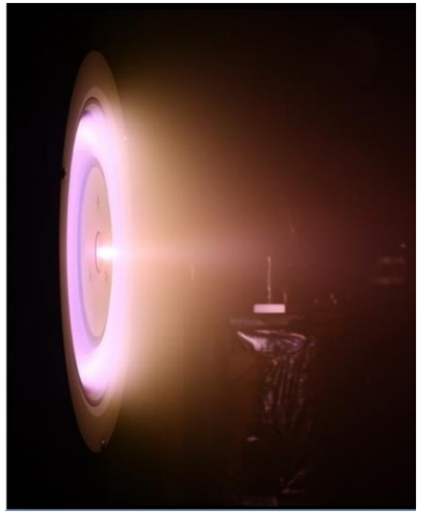
Performed Activities:

6. **Cathode Tests**

Conventional Cathode Assessment (SITAEL)

HC20h
LaB_6
Hollow
Cathode





Stand-alone tests using SITAEL's HC20h LaB_6 hollow cathode with nitrogen and nitrogen/oxygen mixture:

- Repeatable operation and ignition with **N_2**.
- **N_2** voltage values more than 1.5 times higher than those with Xe for the same molecular number density.
- No cathode performance degradation with Xe was observed before and after operation with **N_2**.
- In the case of **nitrogen/oxygen mixture** (52%/48%), the propellant transition was performed partially, with fixed Xe mass flow rate and increasing the atmospheric propellant flow rate in a keeper-anode triode mode. Cathode operation was tested up to 11.5% of **N_2/O_2**
- **N_2/O_2** significantly higher temperatures than during operation with Xe. Severe degradation of cathode components and formation of an insulating layer on the anode were observed.

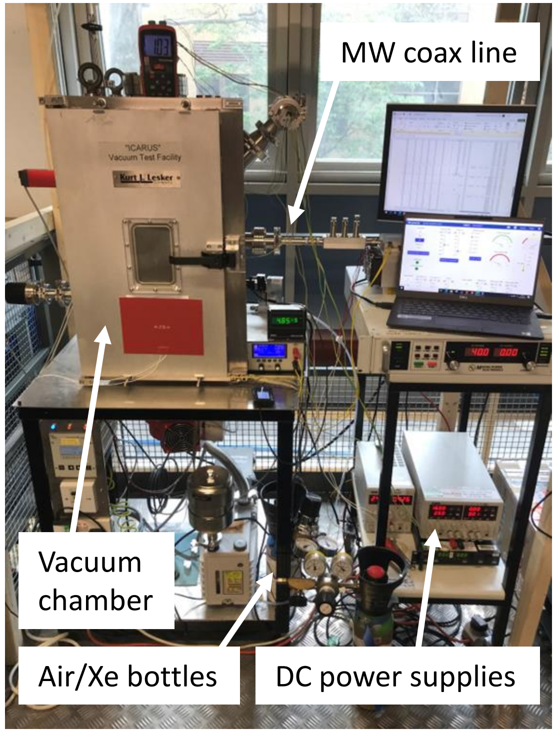
Air-breathing **TU coupling**:

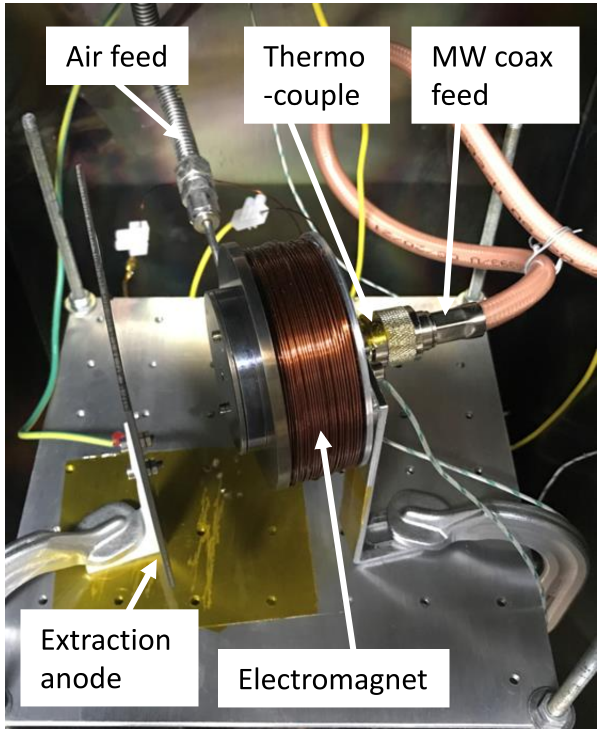
- Repeatable operation with **N_2**, higher temperatures than with Xe. Xe operating cathode resulted in higher TU performance (I_{sp}, T, η_{anodic}).

Alternative Neutraliser Design and MAIT (Surrey)

Microwave-based neutralizer laboratory model experimental development

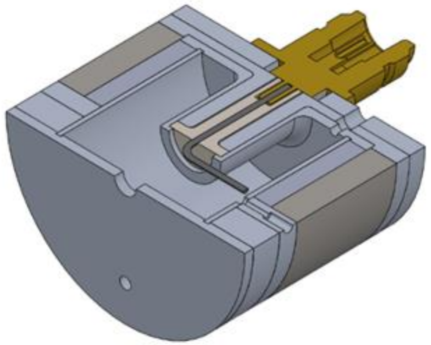
Development through iterative standalone testing at Surrey:





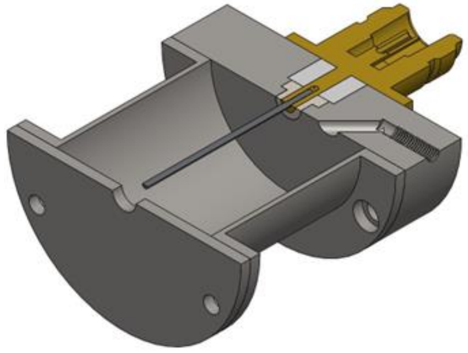
Prototype A

- Pressure test
- Material oxidation
- Antenna shape
- Magnetic field studies



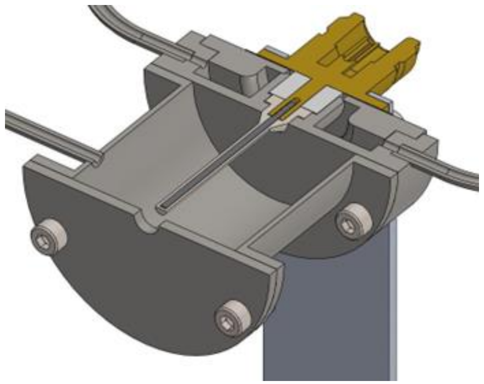
Prototype B

- Biasing effects
- Antenna isolation
- Material analysis
- Air vs Xe baseline



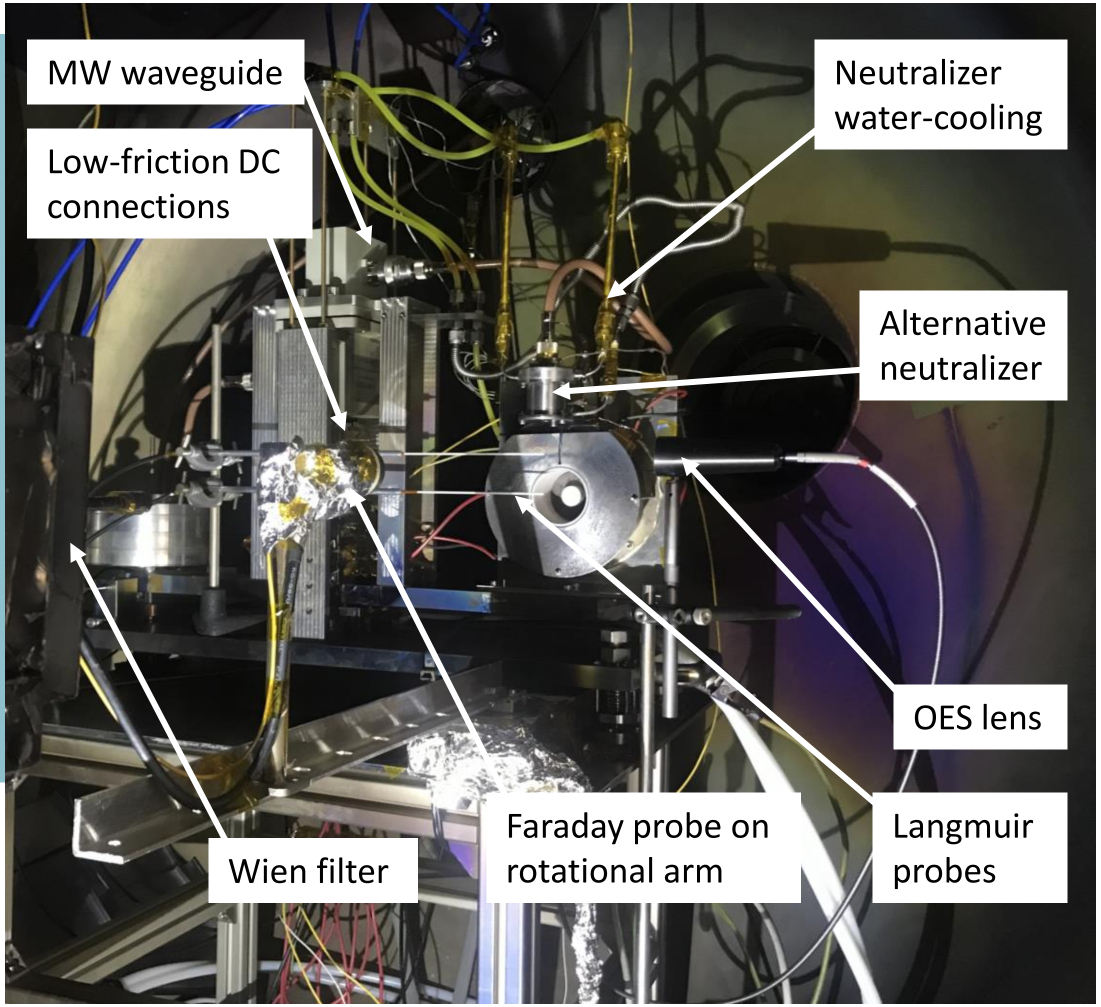
Finalised prototype

- Continuous operation
- Thruster-coupled testing

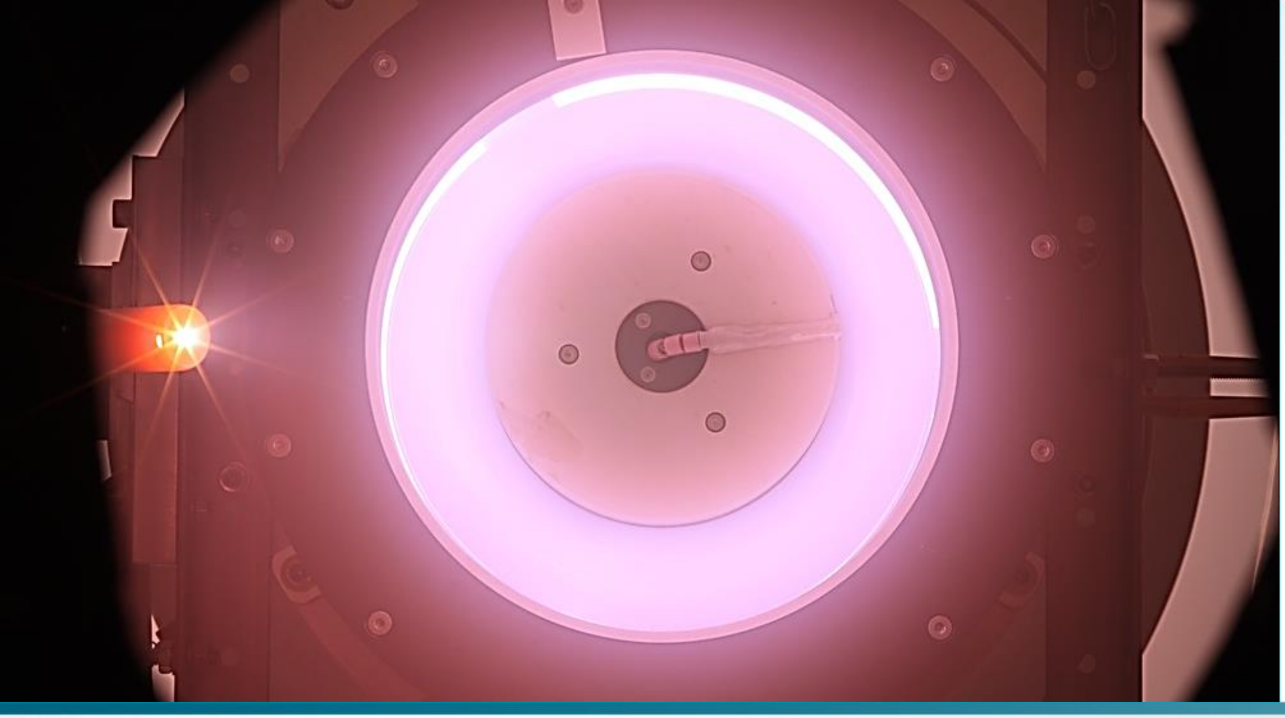
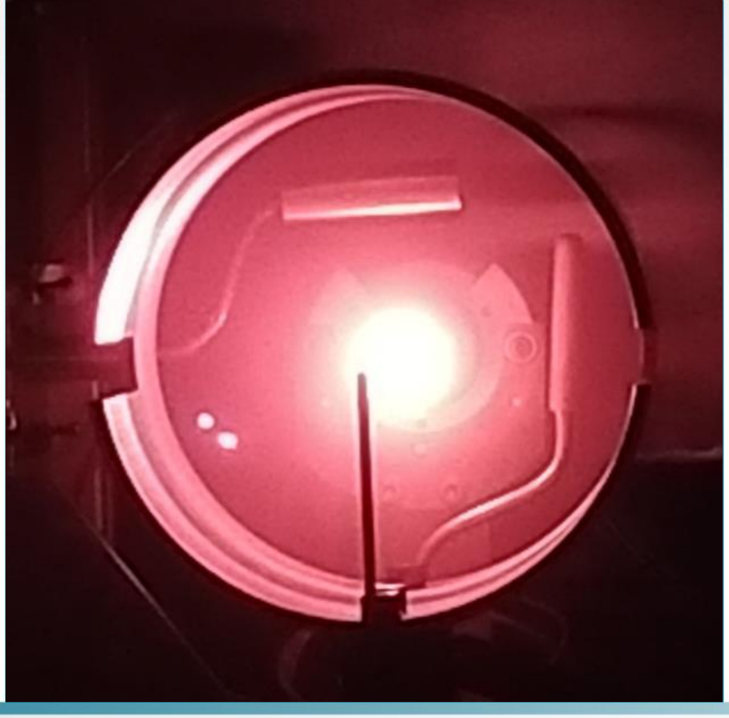
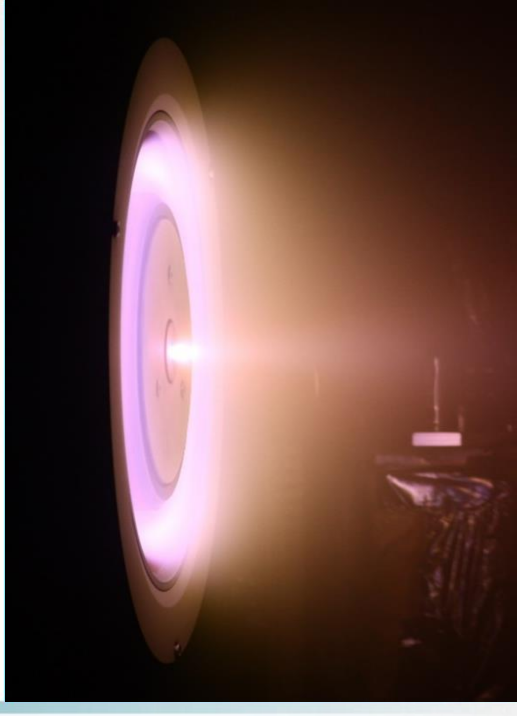


Alternative Neutraliser Design and MAIT (Surrey)

- Coupled tests with in-house **CHT-type** thruster
  - Neutralizer and thruster mounted on **rotational thrust balance** with **plasma diagnostics** at Surrey
  - Comparison of:
    i. MW neutralizer vs hollow cathode w/ Xenon
    ii. Xenon vs Air



Alternative Neutraliser Design and MAIT (Surrey)

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Performed Activities:

7. **Thruster Tests**

7. Thruster Test - Charge Separation Acceleration Stage (CSAS)

Test Item Description:

Radio Frequency Plasma Generator (RAM-EP Plasma Generator) - RPG
Cylindrical discharge chamber with a flange that is used to connect it with the CSAS,

Radio Frequency Ion Source - RIS
CSAS Demonstrator integrated on RAM-EP Plasma Generator

The test campaign will include the following tests:

- Functional test which will demonstrate repeated start-up, thrust on, stand-by modes of the Radio Frequency discharge plasma generator with CSAS attached with Xe.
- Verify the capability of the RPG with CSAS to withstand operation with the selected atmospheric propellants.
- To characterize the CSAS in the predicted range (7 mN to 20 mN)

7. Thruster Test - Charge Separation Acceleration Stage (CSAS)

Test Facility: R2D2 Bundeswehr University Munich

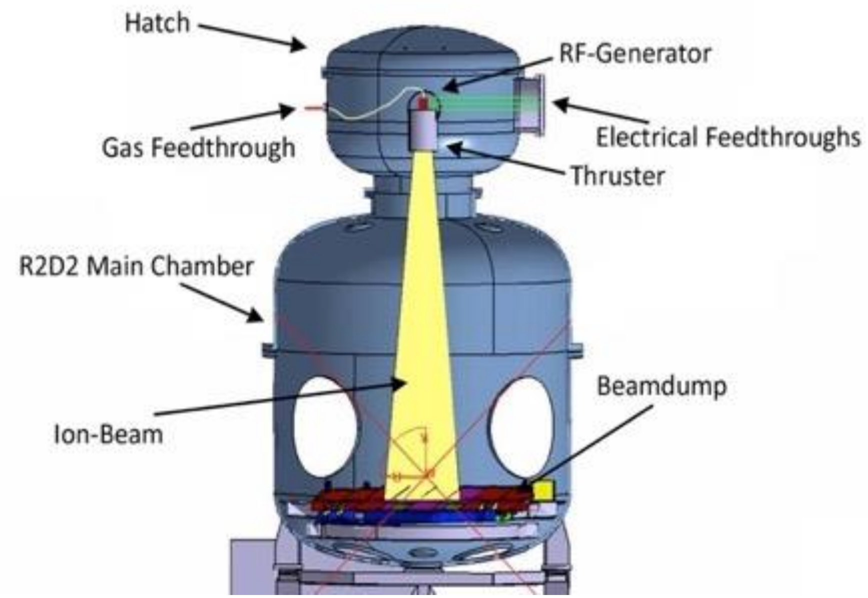
R2D2 has a main chamber volume of 4.5m^3.

It consists of a test chamber and a hatch, that are separated by a pneumatic high vacuum isolation gate valve.

- The test chamber - diameter about 1.9 m and length of about 4 m.
- The hatch - dimensions of about 0.75 m in diameter and length.

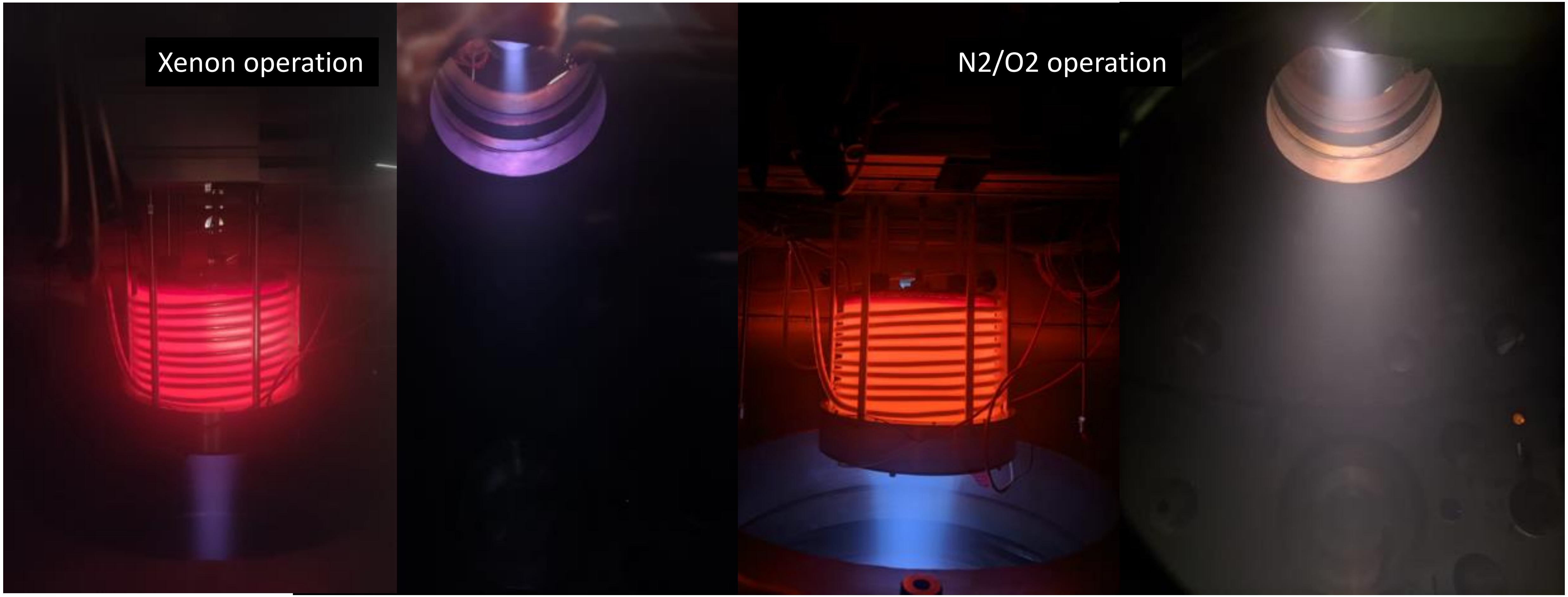
Pumping speed is around 25,000 l/s by the mean of 2 cryo-panels.

1,5 kW power beam dump located at the rear end of the main chamber.



Vertical firing of the thruster eliminate some ground effects but does not allow thruster balance use, but RF ion thrusters show good reliability of indirect thrust measurements

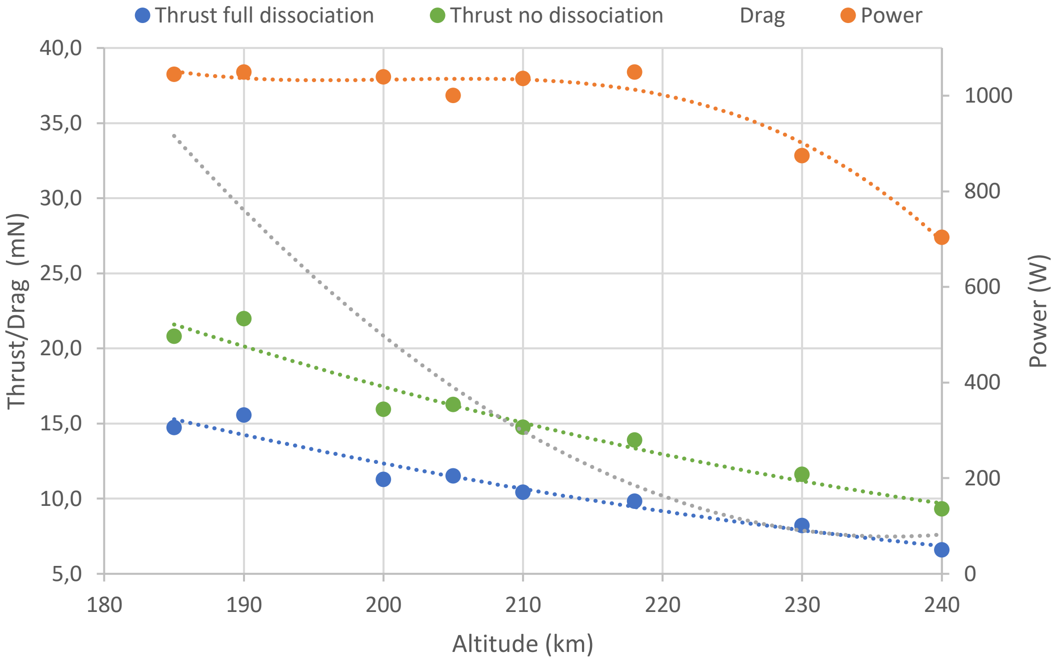
7. Thruster Test - Charge Separation Acceleration Stage (CSAS)



7. Thruster Test - Charge Separation Acceleration Stage (CSAS)

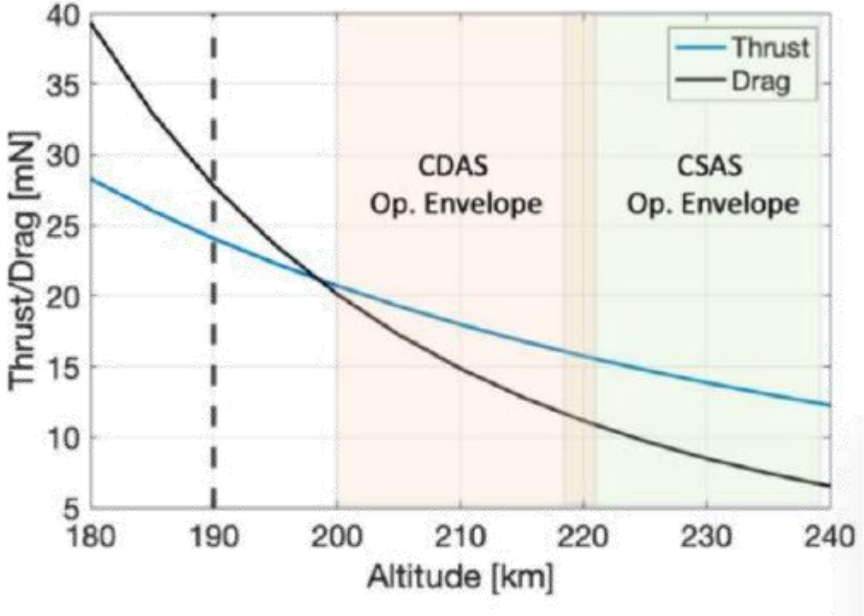
- Performance measured for target envelope under 1000 W, full extended target thrust range is reached as per requirements document but system limited at low altitudes to compensate actual drag
- High power operation was performed (higher than 1000 W) successfully
- Could the power availability to the system be extended to 2 kW for CSAS, the drag compensation at any point of VLEO would become possible. This technology would become very appealing if more efficient power sources would be available at the market

CSAS measured performances



CSAS Vs. CDAS Performance

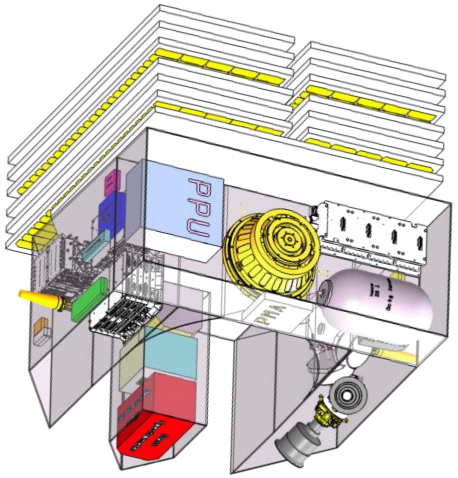
CDAS = Closed Drift Acceleration Stage

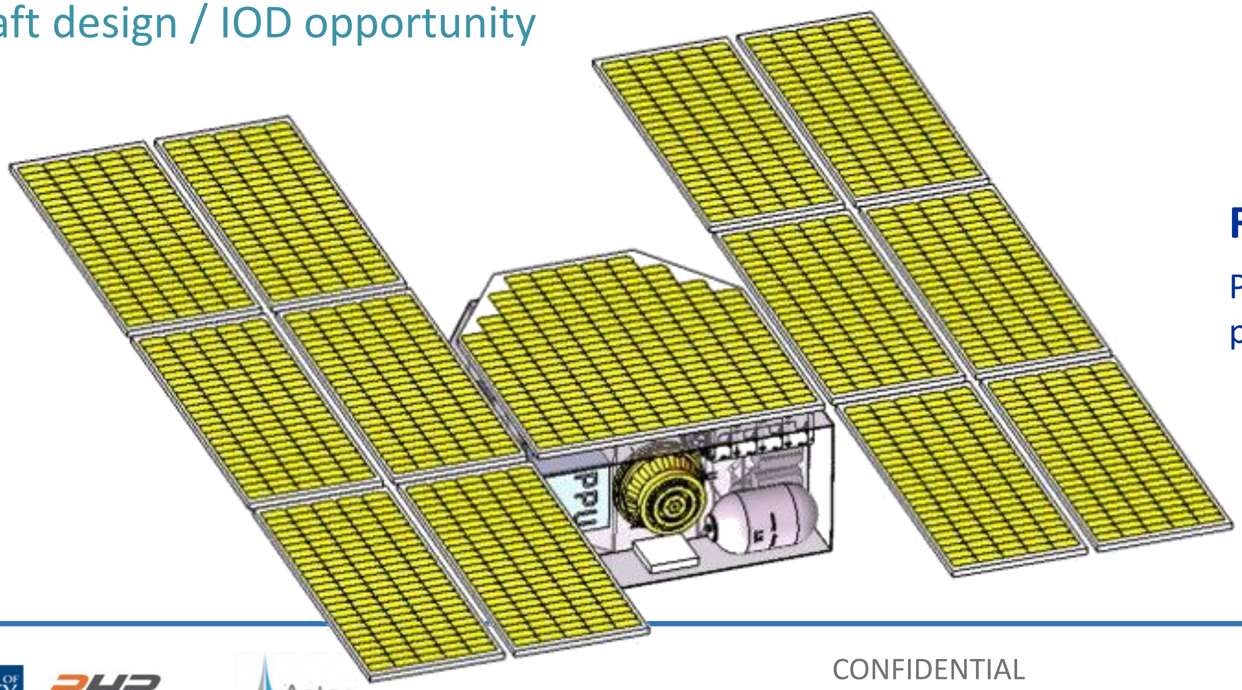


Conclusions and Next Steps

- Significant steps forward in dimostrating the feasibility of the RAMEP concept
- Extensive test campaigns on the Particle Flow Generator and on the CSAS thruster concept
- Advanced diagnostics (spectroscopy)
- Investigation of different materials behaviour in an ‘atmospheric plasma beam’
- Intake analysis, mission analysis and atmospheric model to foster a future S/C integration of a RAMEP thruster

- Way Forward: Air-breathing spacecraft design / IOD opportunity





RED Programme (ESA)

Preliminary design of a platform operating in VLEO

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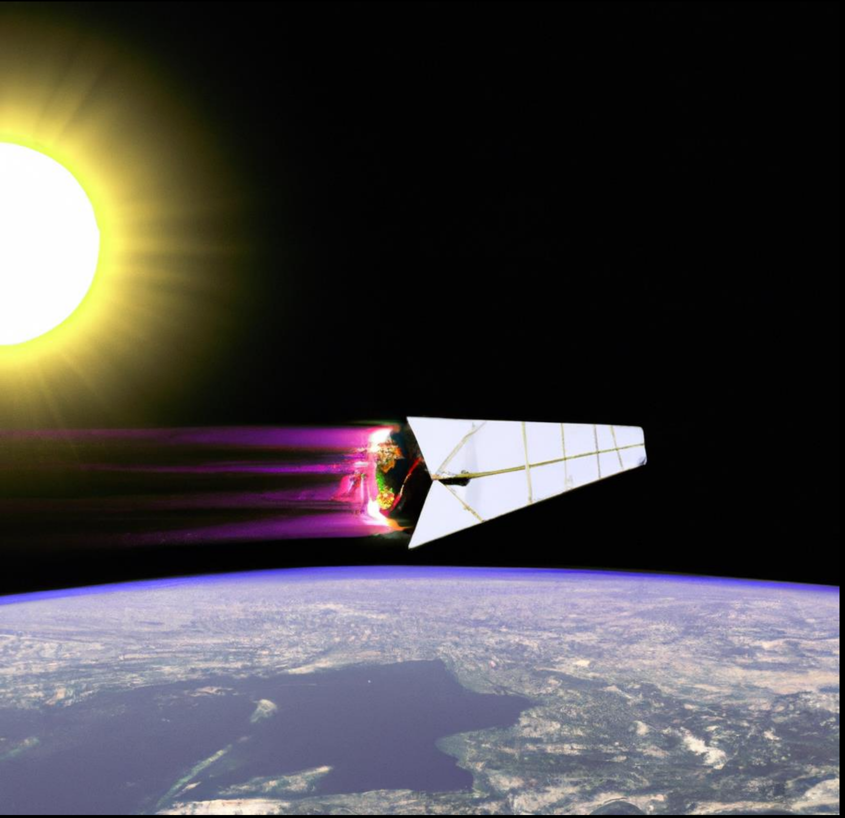
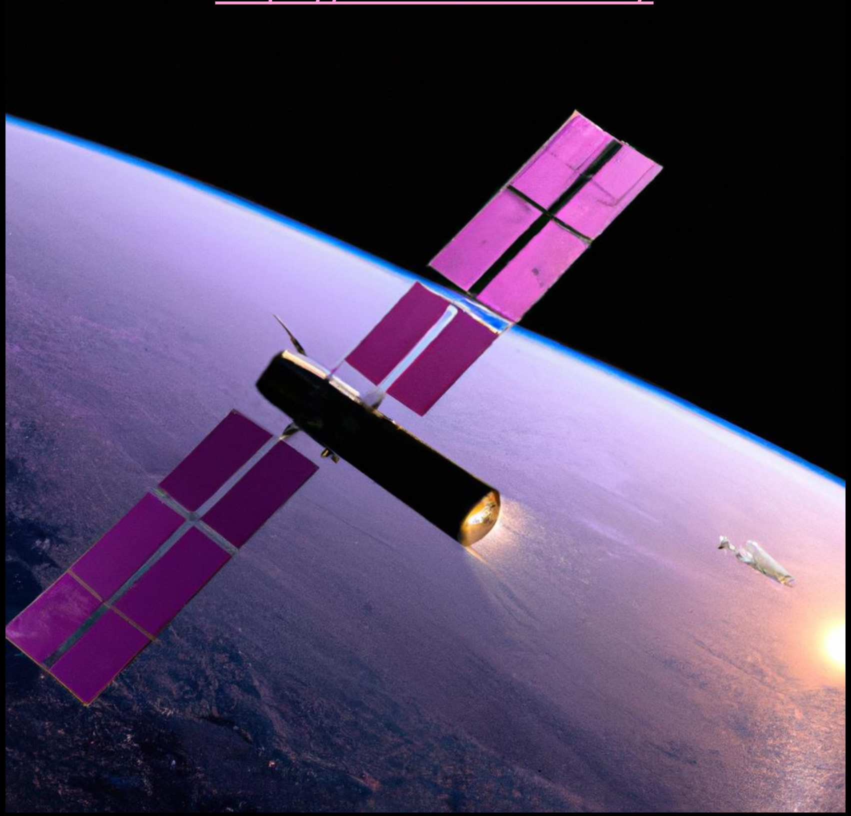
https://aether-h2020.eu/





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