

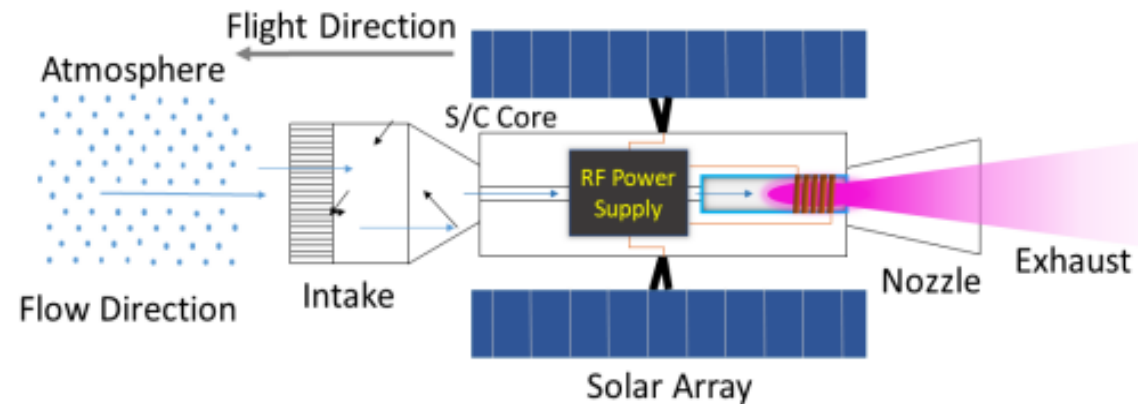
Experimental characterization of electrodeless plasma thrusters for very low Earth Orbit applications

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PhD Aerospace Engineering UC3M
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2nd and 3rd June 2026

Introduction to ABEP

■ Air-Breathing Electric Propulsion (ABEP)



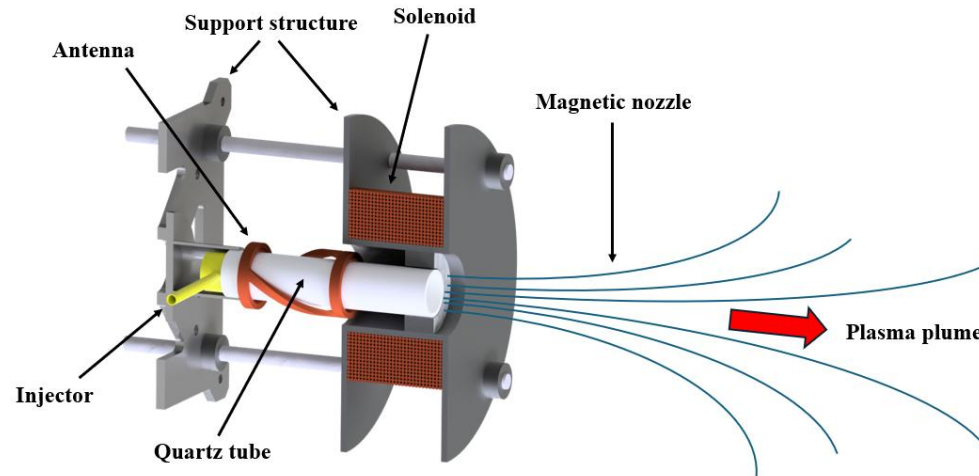
Romano, F. et al. (2017). Performance Evaluation of a Novel Inductive Atmosphere-Breathing EP System.

- It is a hot topic in the electric propulsion community.
- Thruster technology, intake, mission analysis, particle-surface interactions, business-cases, etc...
- In-orbit demonstration missions expected in the coming years.

Institution	Thr. type	Propellant	P [kW]	T/P [mN/kW]	$I_{sp} [\times 10^2 s]$
TsNIMASH	HET	Air/Xe	-	-	-
SAFRAN, Giessen Uni., SITAEL	RIT	N ₂ /O ₂	0.2-0.6	7-14	5-64
	HET		0.5-1.4	-	-
SITAEL	HET	N ₂ /O ₂	1.2-5.2	~25	6-16
Busek	HET	N ₂ /O ₂ /Ar	1-5.5	15-25	10-27
Stanford Uni. Uni. of Surrey	HET	Air/N ₂ /Xe	0.4-0.7	-	-
Stanford Uni. Poli. di Torino	HET	N ₂	0.5-0.8	27-44	10-11
Moscow state Tech. Uni.	HET	N ₂ /O ₂	0.3-1.4	16-21	-
Beijing Inst. of Control Eng.	MCFT	N ₂	0.4-1.3	15-18	6-13
Uni. of Michigan	HHT	N ₂	~1.75	21	8-9
TsAGI	RIT	N ₂ /O ₂	< 0.8	< 26	-
IRS	IPT	N ₂ /O ₂	-	-	-
Australian National Uni.	Helicon	N ₂	0.25	-	-
Pennsylvania State Uni.	MET	N ₂ , O ₂	1-1.6	-	2-4
Uni. of Tokyo IRS	PPT	Air	-	-	1-7
Russian Academy of Sciences	MPD	Air	-	-	-

T. Andreussi, E. Ferrato, V. Giannetti, A review of air-breathing electric propulsion: from mission studies to technology verification, *Journal of Electric Propulsion* 1 (2022) 31.

■ Helicon Plasma Thrusters



Advantages of HPT over HT

- No need for cathode or neutralizer.
- Less complex PPU.
- Less sensitive to erosion problems.
- Very versatile. Identified as a candidate for alternative propellants since the 2000's.

Disadvantages of HPT over HT

- Less mature technology.
- Lower efficiencies, poor propellant utilization...
- The physics are poorly understood.

Publications	P_{rf} (kW)	F (mN)	I_{sp} (s)	F/P_{rf} (mN/kW)	η_{rf} (%)	Gas
1-Takahashi et al., APL2011 (Takahashi et al. 2011a)	0.9	3	510	3.3	0.83	Ar
2-Pottinger et al., JPD2011 (Pottinger et al. 2011)	0.65	2.8	286	4.3	0.6	Kr
3-Takahashi et al., PRL2011 (Takahashi et al. 2011b)	0.8	6	816	7.5	3.0	Ar
4-Charles et al., APL2012 (Charles et al. 2012)	0.8	5	680	6.3	2.1	Ar
5-Takahashi et al., PRL2013 (Takahashi et al. 2013a)	1	11	1559	11.0	8.4	Ar
6-Shabshelowitz and Gallimore, JPP2013 (Shabshelowitz and Gallimore 2013)	1.5	11	160	7.33	0.58	Ar
7-Williams and Walker, JPP2013 (Williams and Walker 2013)	0.6	6	136	10	0.67	Ar
8-Takahashi et al., JPD2013 (Takahashi et al. 2013b)	2	15	2126	7.5	7.8	Ar
9-Charles et al. APL2013 (Charles et al. 2013)	0.9	6	696	6.7	2.3	Xe
10-Harle et al. PSST2013 (Harle et al. 2013)	0.4	1.1	187	2.75	0.25	Ar
11-Takahashi et al. PSST2014 (Takahashi et al. 2014)	2	20	2721	10	13.3	Ar
12-Takahashi et al. PSST2015 (Takahashi et al. 2015)	6	58	2818	9.7	13.3	Ar
13-Kuwahara et al. JPP2017 (Kuwahara et al. 2017)	3	40	459	13.3	3.0	Xe
14-Oshio et al. IEPC2017 (Oshio et al. 2017)	1	6	510	6.0	1.5	Ar
15-Siddiqui et al. IEPC2017 (Siddiqui et al. 2017)	0.1	5	146	50	3.6	Xe
16-Trezzolani et al. IEPC2017 (Trezzolani et al. 2017a)	0.15	1.4	714	9.33	3.3	Xe
17-Trezzolani et al. IEPC2017 (Trezzolani et al. 2017b)	0.07	0.85	867	12.1	5.2	Xe
18-Takahashi et al. Fig. 22 (Takahashi and Ando 2018)	6	67	3256	11.2	17.8	Ar

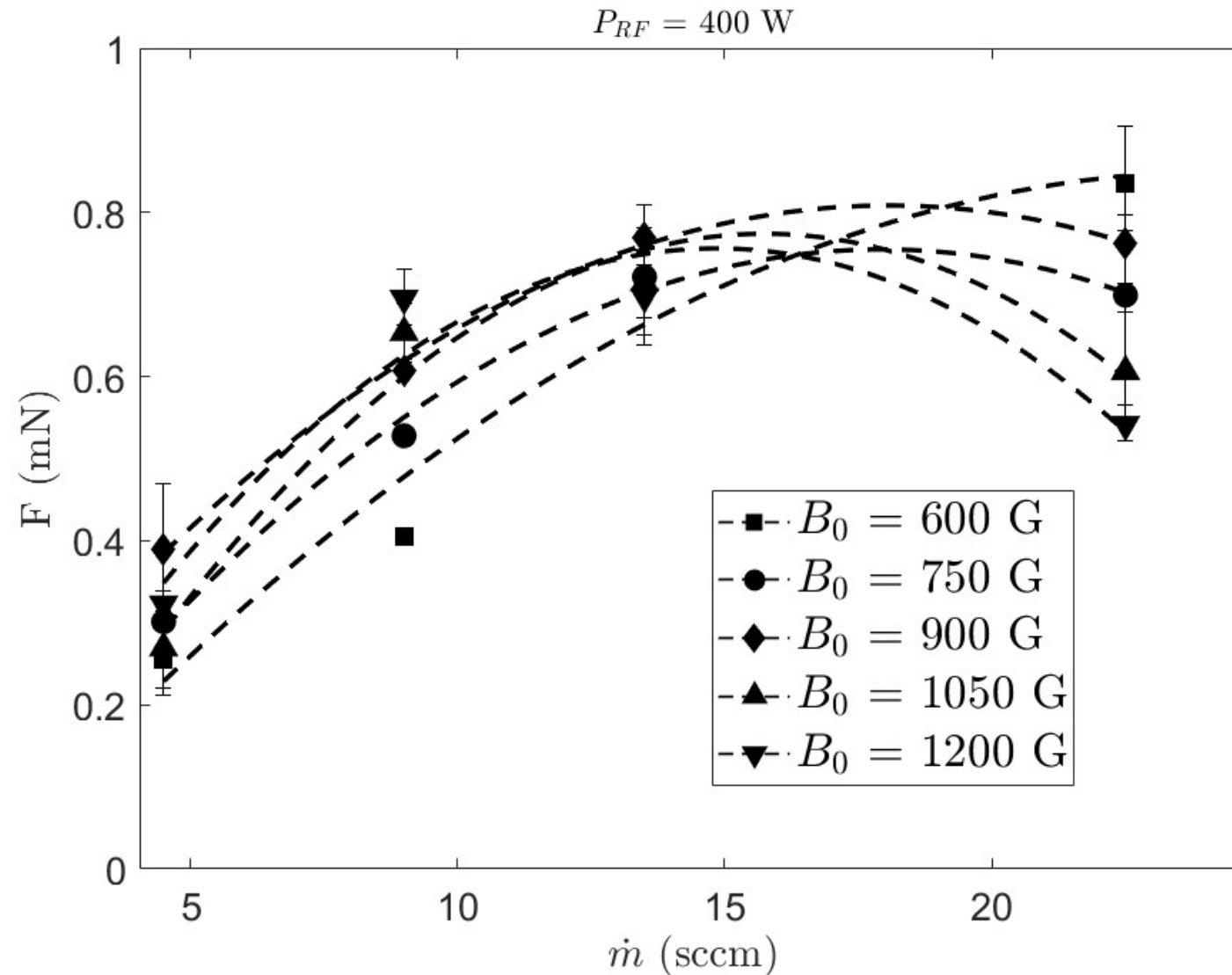
K. Takahashi, Helicon-type radiofrequency plasma thrusters and magnetic plasma nozzles, Reviews of Modern Plasma Physics 3 (2019) 3.

Objectives

- Experimental analysis of alternative propellants in a **plasma thruster breadboard model**.
 - Characterization of the HPT operated with Air and Air-Kr mixtures.
- Experimental analysis of alternative propellants in a **plasma source breadboard model**.
 - Controlled RF discharges with air mixtures for ABEP validation, and ABEP-Kr assisted validation.
 - Design and improvement of plasma diagnostics for Air / Kr RF plasma.



**Design modifications
and ABEP-oriented
optimization**



MAIN TAKEAWAYS

- Thrust below 1 mN.
- Above $\sim 13.5 \text{ sccmAir}$, the thrust saturates.
- Above $\sim 13.5 \text{ sccmAir}$, increasing the magnetic field penalizes the thrust.

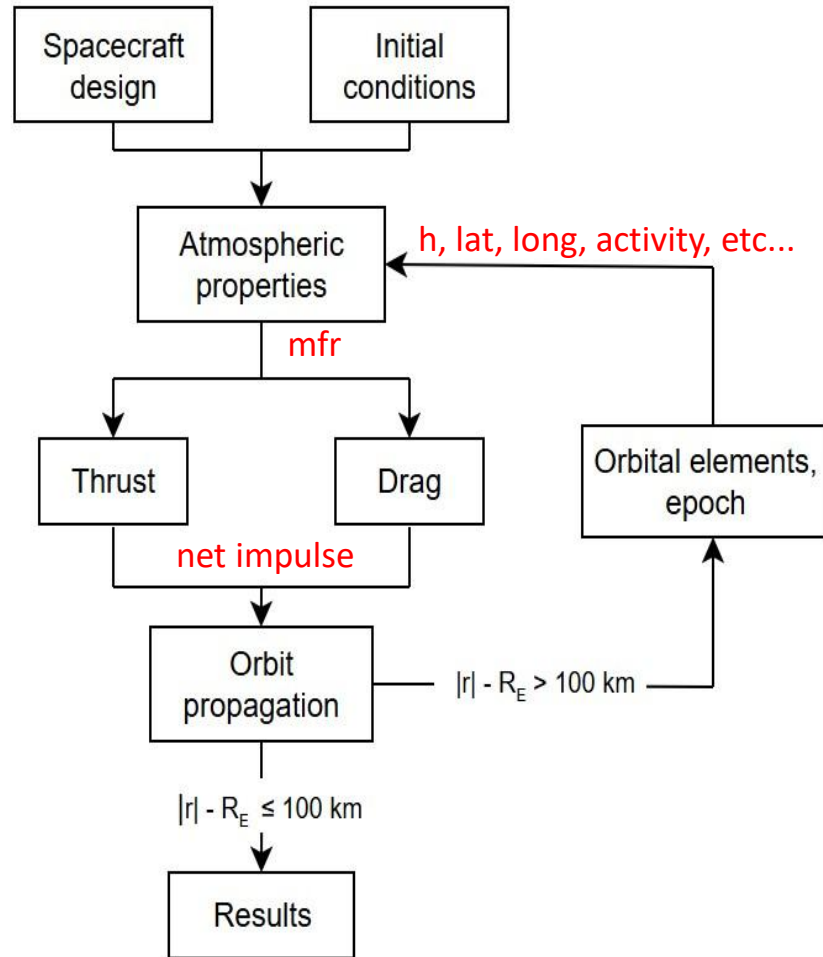
TWO QUESTIONS ARISE

- Does this performance allow for a feasible in-orbit demonstration at VLEO?
- Are the operation conditions of the HPT representative of the VLEO environment?

MAIN PROBLEMS

- Ignition requires a greater mass flow rate than typical VLEO atmospheric flow rate.
- Uncertainties regarding the plume composition limit the understanding of the performance.

Does this performance allow for a feasible IOD at VLEO?



ORBIT PROPAGATION MODEL

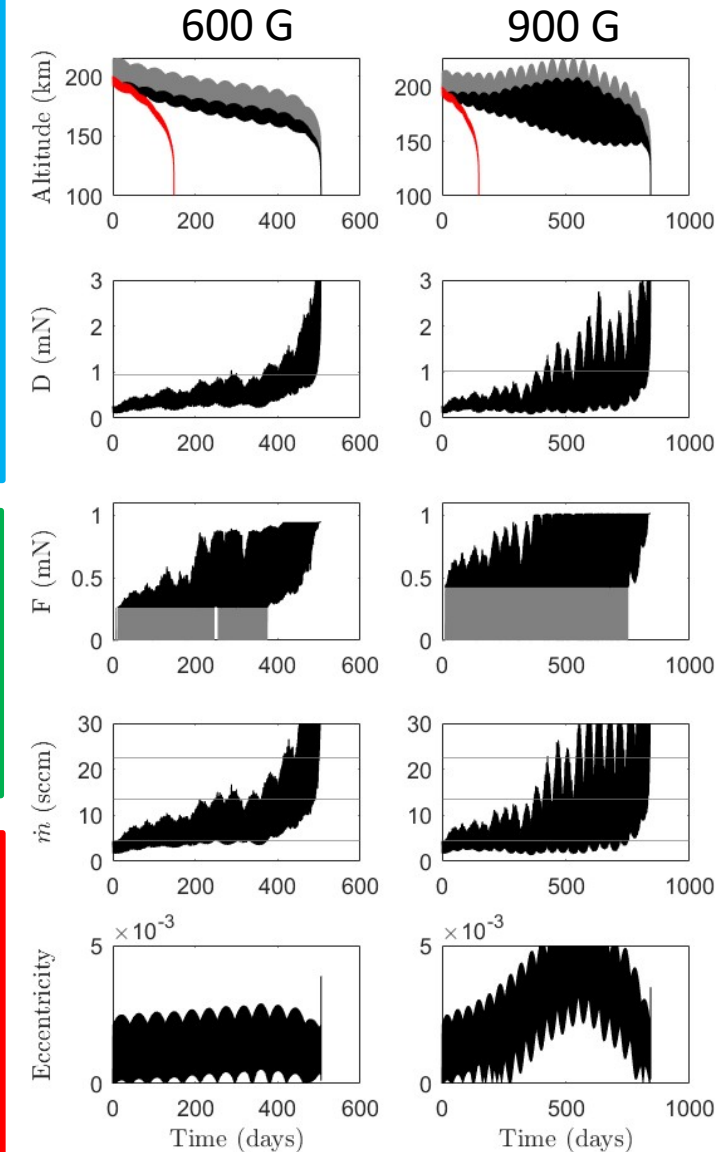
- NRLMSISE-00 atmospheric model.
- Simple analytical intake model.
- Drag computed using particle-surface interaction models.
- Thrust, drag and intake performance are computed in every step.
- J_2 , atmospheric drag, non-sphericity, etc..
- Different thruster control laws.

POSITIVE RESULTS

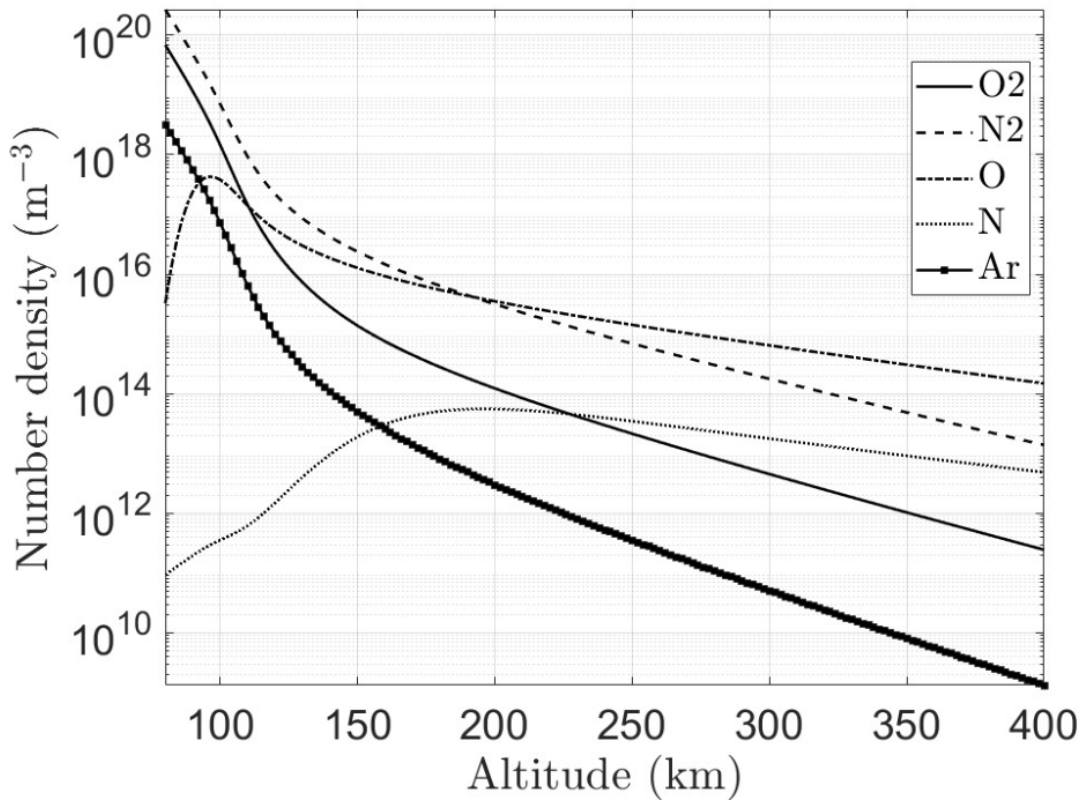
- Satellite lifetime can be expanded.
- The model confirms our predictions regarding the relation between thrust saturation and orbit de-stabilization.

MAIN PROBLEMS

- The application requires highly optimistic (but theoretically feasible) spacecraft and intake surface properties.
- Still assumes that the performance with Air is representative of all gas mixtures.

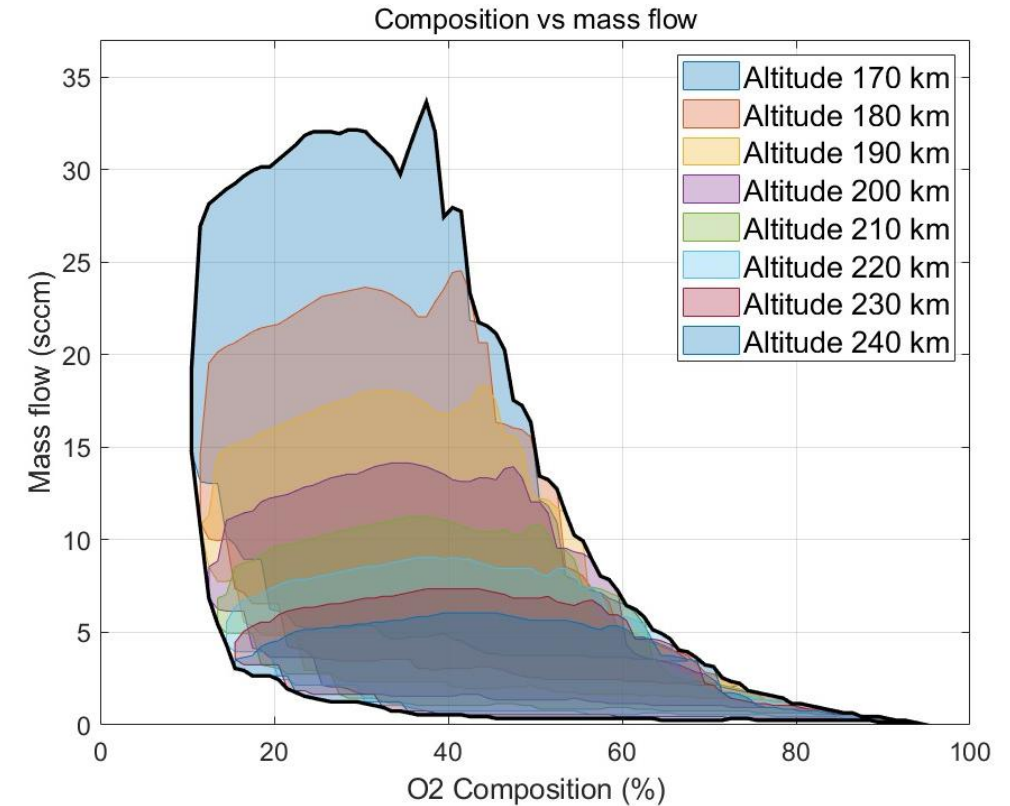


Are the operation conditions representative of an IOD at VLEO?



- Day of the year
- Hour of the day
- Geodetic altitude
- Latitude
- Longitude
- Local Apparent Solar Time
- Solar activity

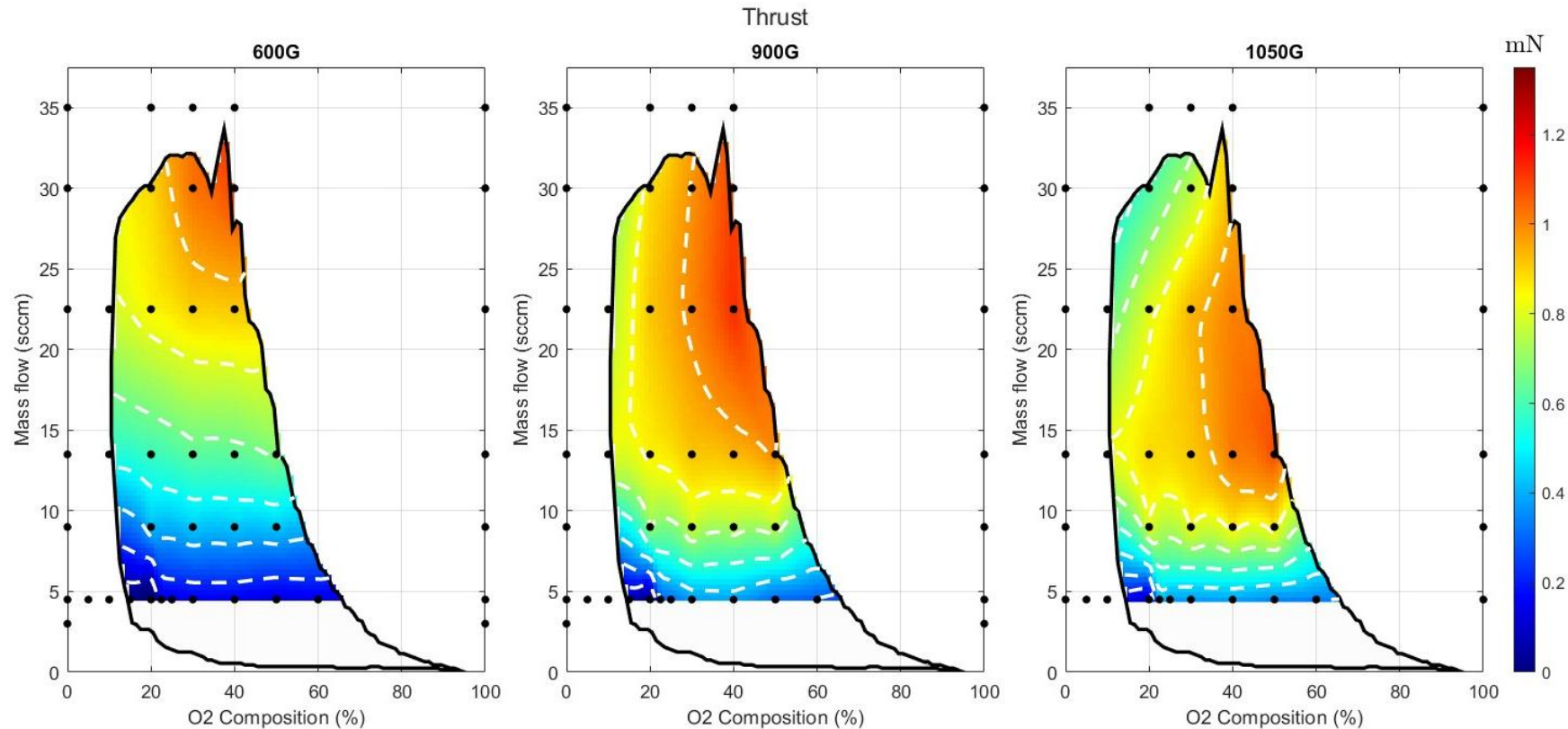
“Brute-force” analysis
~1.2 million cases



MAIN HYPOTHESES

- Assumes a given intake size and performance from the literature.
- Assumes that the atomic species recombine in the intake mainly due to surface chemistry (associative wall recombination).

Are the operation conditions representative of an IOD at VLEO?



MAIN TAKEAWAYS

- First campaign's Air results are representative of the 20% O₂ case.
- High mass flows require low magnetic fields, and viceversa.
- Oxygen enhances the performance.
- The problems are the same as with Air.
- Testing with Air can be an easy way to obtain the trends, but not the actual performance.

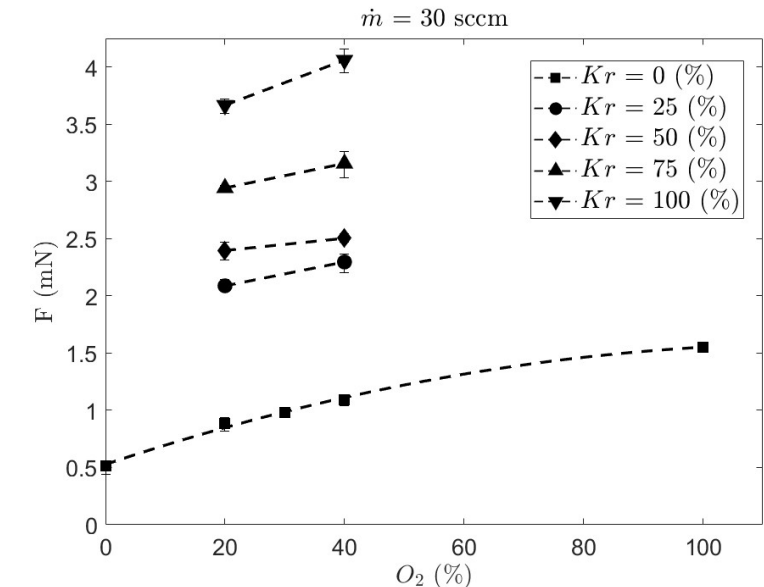
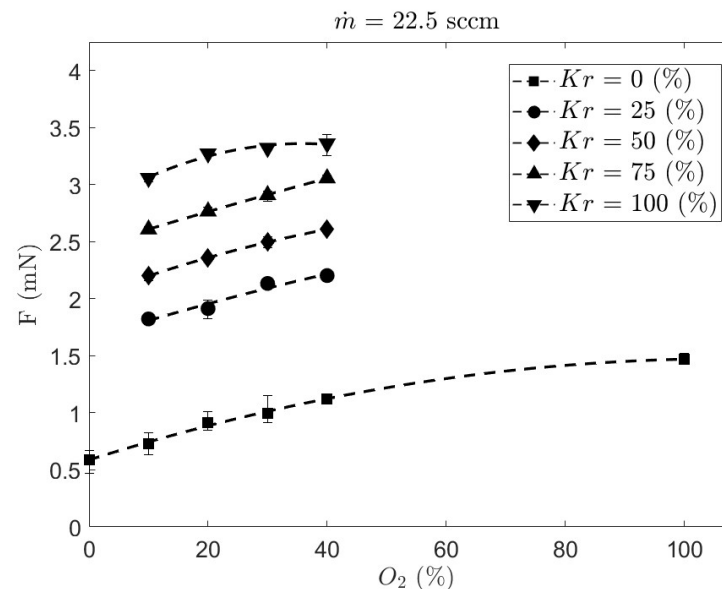
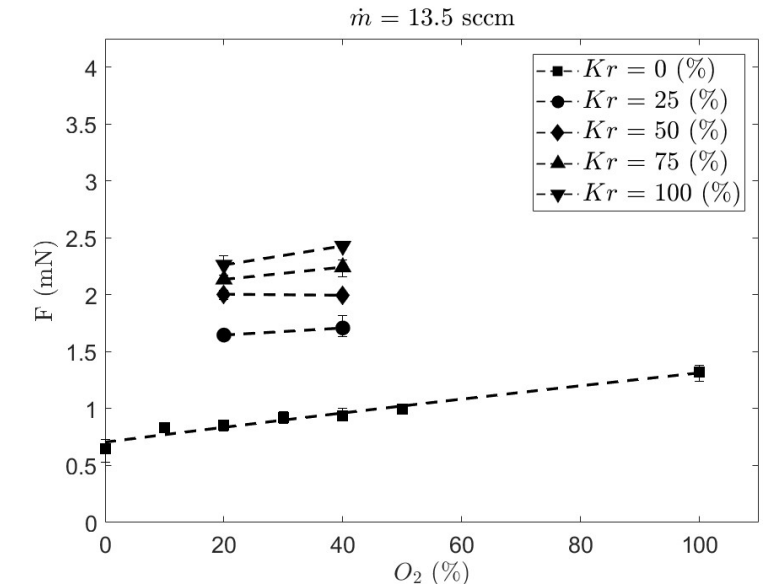
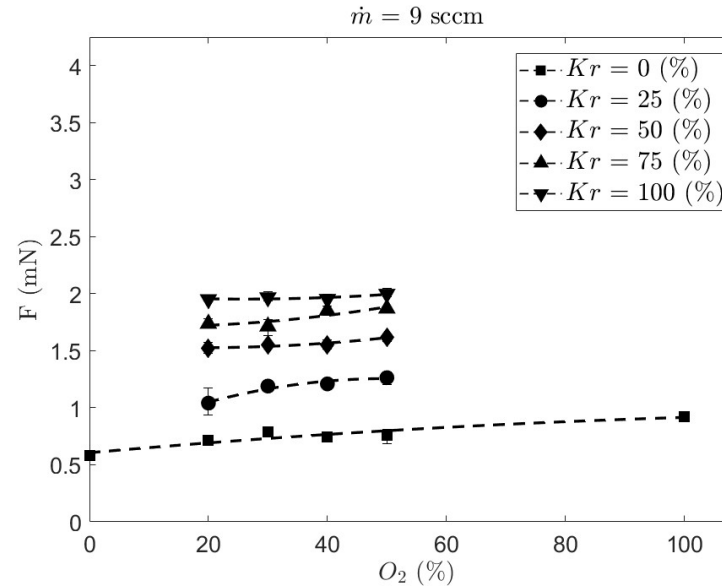
Ignition requires a greater mass flow rate than the operation condition

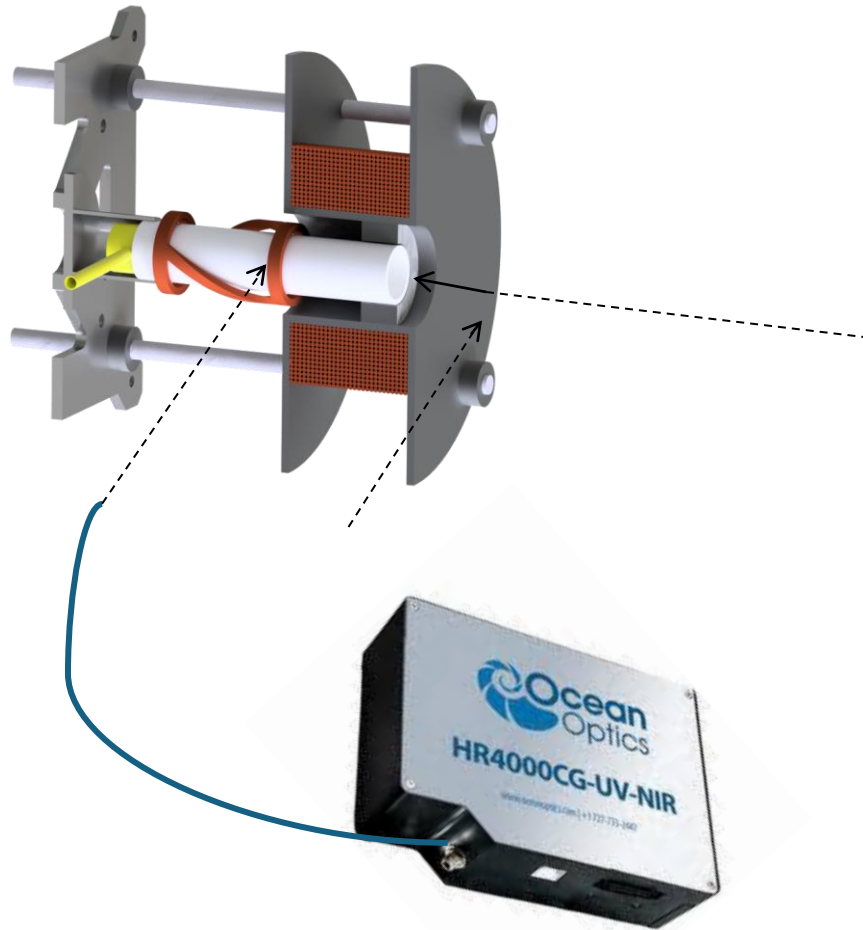
MAIN IDEA -> ADD KRYPTON

- Different alternatives were considered:
 - Add small percentages to dope the discharge (physics studies approach).
 - Add constant value to increase the mass flow (engineering/operation approach).
 - **Add 25-50-75-100% of the air flow (intermediate approach).**

MAIN TAKEAWAYS

- Performance seems to indicate that Kr and N₂-O₂ are decoupled.
- The source pressure to ignite the HPT is the same (~15 mbar) but that can be reached at a lower N₂-O₂ flow.
- Thrust is greatly enhanced. Could be a good option to produce thrust when the ABEP does not counter the drag.





OPTICAL EMISSION SPECTROSCOPY

- Optical non-intrusive diagnostic that allows to detect the different species inside the plasma.
- 200-1100 nm, with 0.75 nm resolution.
- Before/after the acceleration region and the integrated line-of-sight of the source and plume.

WHY DO WE NEED IT?

- Uncertainty in the average ion mass greatly influence the propellant utilization efficiency based on FP.
- N and O have very similar masses so ExB probe measurements might be difficult to analyze.
- Global Models rely on unknown phenomenological coefficients.

MAIN USES

- Identify species.
- Qualitatively compare different operation conditions.
- Compute electron temperature.

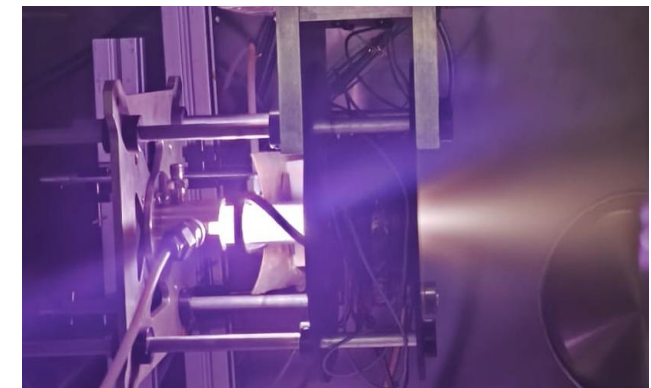
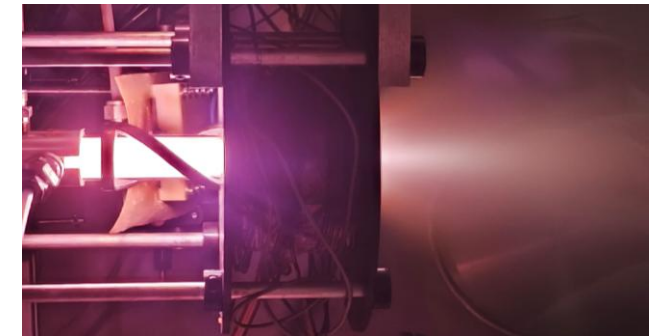
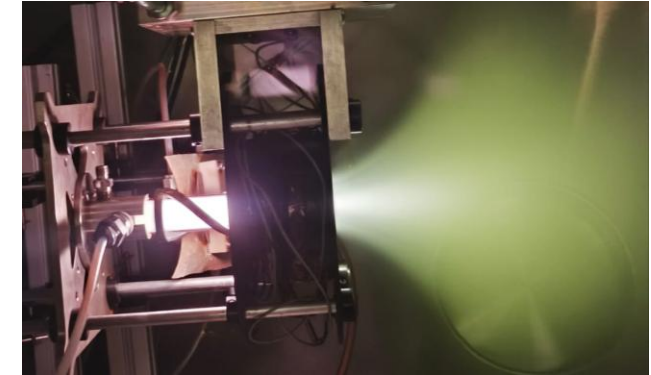
Conclusions & Future work

■ Conclusions:

- We have tackled the main open questions and problems of last year's results.
- An orbit propagation model has been developed and coupled to the experimental results to assess the prototype's performance feasibility.
- The results dataset has been expanded with more HPT operation conditions and a larger sensor suite.

■ Future work:

- Complete the campaign and post-process the data.
- Modify the orbit propagation model to include the new data in terms of propellant composition and possible Krypton propellant tanks.
- ExB probe measurements could be interesting.
- Research stay TBD.
- HPT design modification with lessons learnt.
- B-dot probe post-processing and consolidation.



- Journal Papers:

- Internal review, coming soon...

- Conference Papers/Presentations

- A. Rabuñal-Gayo, M. Inchingolo, and J. Navarro Cavallé, Air-Breathing Helicon Plasma Thruster Performance and Plume Characterization by Means of Direct Thrust Measurements and Other Standardized Diagnostics (Imperial College London, London, 2025).
 - Navarro-Cavallé, J., Rabuñal-Gayo, A., Bayón, B., Perrotin, T., & Inchingolo, M. (2025). Experimental characterization of magnetized plasma beams in RF-based Air Breathing Electric Propulsion. Presented at the Spanish Fluid Mechanics Conference (SMFC25), Málaga, Spain, 24-27 June 2025.
 - Navarro-Cavallé, J., Inchingolo, M., & Rabuñal-Gayo, A. (2025). Magnetic field pattern identification in a RF plasma thruster plume expansion. Presented at the XL Simposio Nacional de la Unión Científica Internacional de Radio, Tarragona, Spain, 3-5 September 2025.

- International Workshops:

- 2025 Electrodeless Plasma Thrusters Worksop, "Performance characteristics of an HPT for air-breathing electric propulsion", Madrid, Spain, 03-04 July 2025.
 - Plasma Diagnostics for Electric Propulsion Systems, "Design, calibration and testing of a b-dot probe for Helicon Plasma Thrusters", Giessen, Germany, 18-20 August 2025.

- Dissemination activities:
 - European Researchers' Night (G-Night) - Create and launch your own rocket!
 - Madrid's Science and Innovation Week 2025 - Create and launch your own rocket!
- Teaching activities:
 - Practical lessons on “Space Propulsion”, from the MiSE.
 - The Conquest of Space

Thank you!
Questions?

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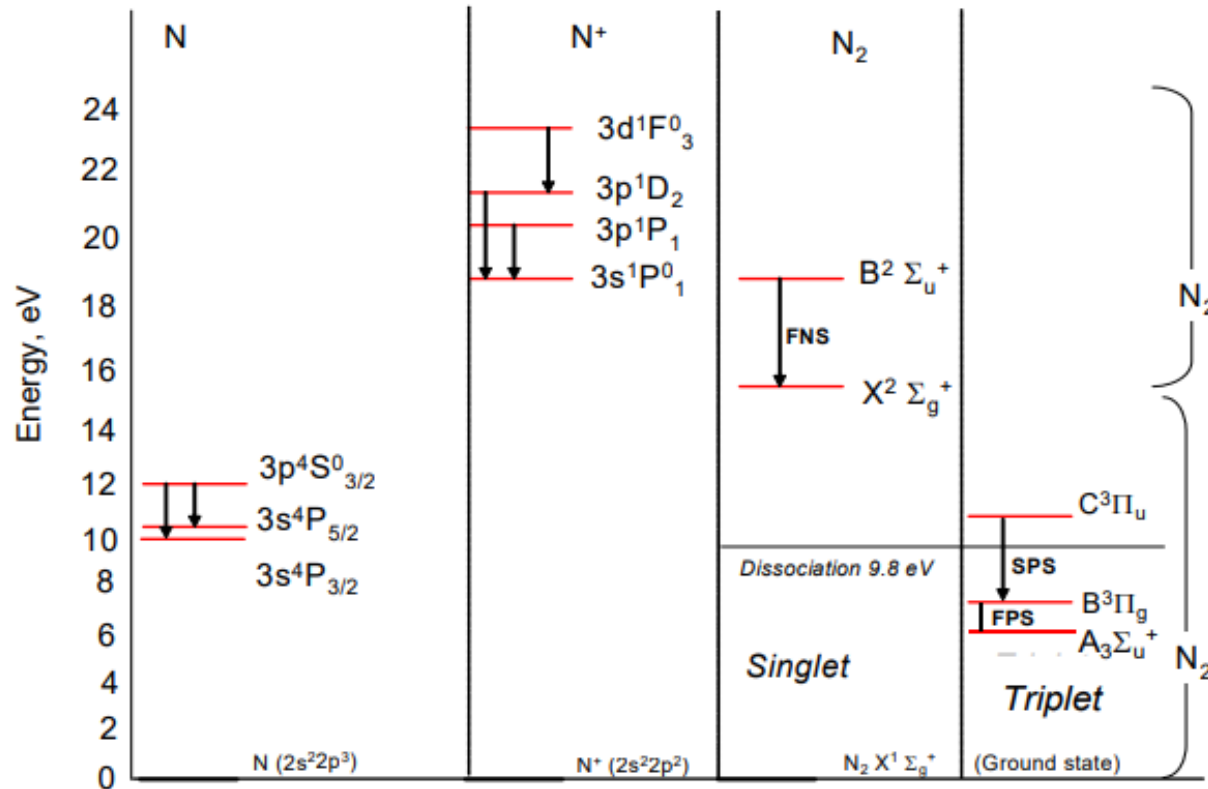


Diagram illustrating the Bohr model of an atom and the process of a quantum jump.

The diagram shows three states of an atom, represented by a central nucleus and concentric dashed orbits labeled i and j .

- Top Left:** The atom is in a ground state with an electron (red dot) in orbit i .
- Top Right:** An arrow labeled "Energy" points to this state, where the electron has moved to orbit j .
- Bottom Left:** An arrow labeled "Quantum jump" points to this state, where the electron has returned to orbit i .

A green wavy arrow points from the electron in the bottom-left state to the equation:

$$\lambda = \frac{hc}{\Delta E}$$

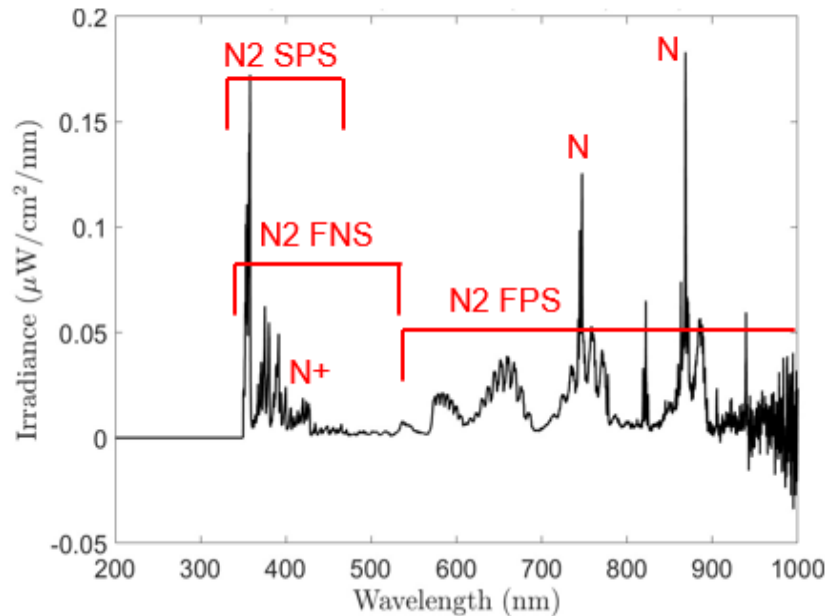
$$\lambda = \frac{hc}{\Delta E}$$

$$E(v, J) = E_{el} + \hbar\omega_e \left(v + \frac{1}{2}\right) - \hbar\omega_e x_e \left(v + \frac{1}{2}\right)^2 + BJ(J+1)$$

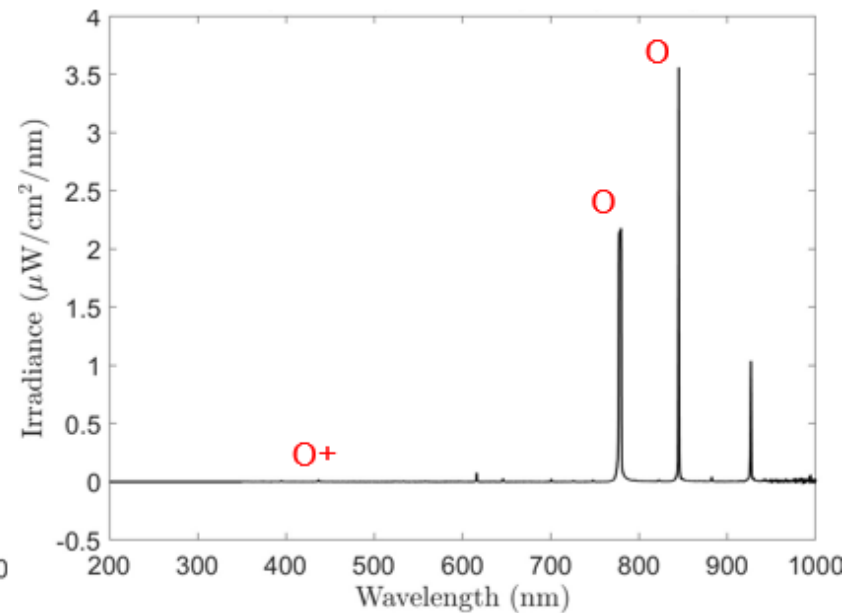
Rotational term

Reference spectra for different gases

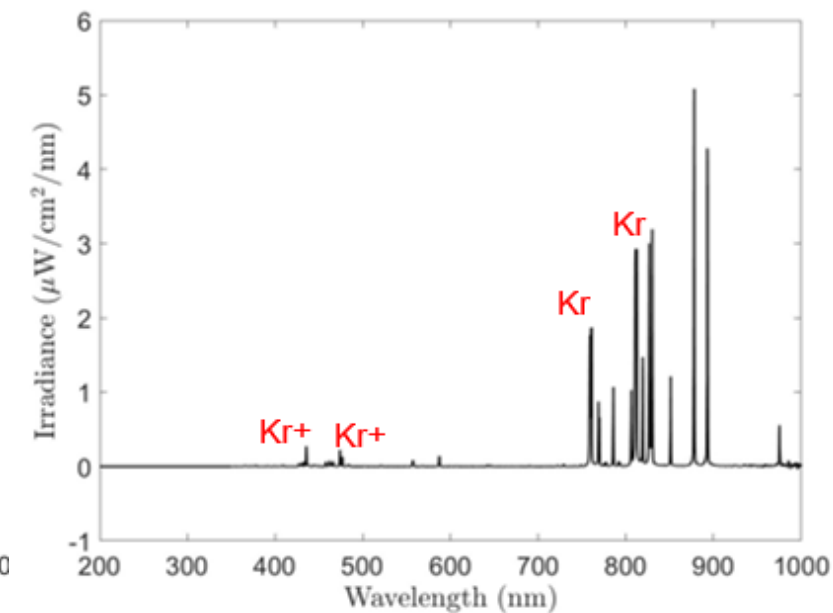
NITROGEN



OXYGEN



KRYPTON



- Very rich spectrum.
- Many overlapping bands and systems.
- Relatively low SNR.
- All relevant species are identified at least once.

- Absolutely dominated by neutral O.
- Molecular species are difficult to observe (dominant metastable states, high dissociation).
- Good SNR.

- Still work in progress.
- All the lines have been identified as Kr or Kr+.
- Feasible to be fully characterized.
- High SNR.