ANALYSIS OF IONIZATION IN AIR-BREATHING PLASMA THRUSTER

Anmol Taploo, Li Lin, and Michael Keidar

Micro Propulsion and Nanotechnology Laboratory

George Washington University

Washington DC 20052, USA

Graduate Summer School' 21

Princeton University

https://mpnl.seas.gwu.edu/

INDEX

RESEARCH AT MPNL AND
AIR BREATHING PLASMA THRUSTERS (ABPT)

OBJECTIVES

STUDY OF AIR IONIZATION USING CHEMICAL KINETICS SIMULATION

ABPT PERFORMANCE CALCULATIONS

FUTURE WORK

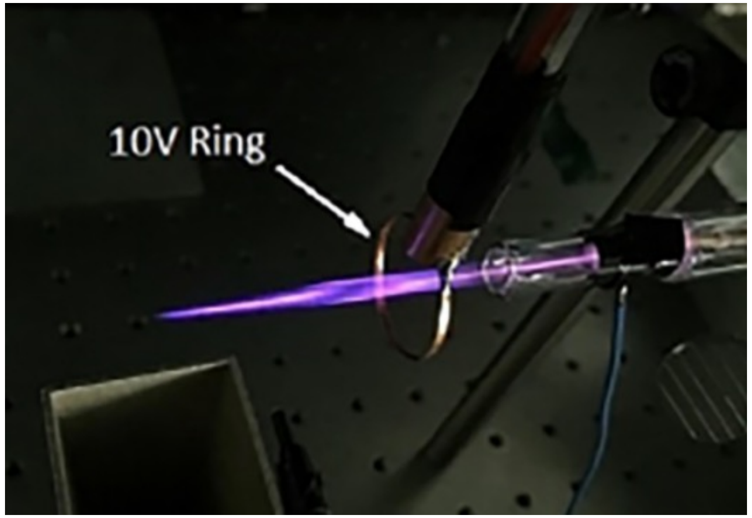
MPNL PLASMA MEDICINE RESEARCH

(A) : Copper ring used in Cold Atmosphere Plasma (CAP) to control the chemistry and optical emission.

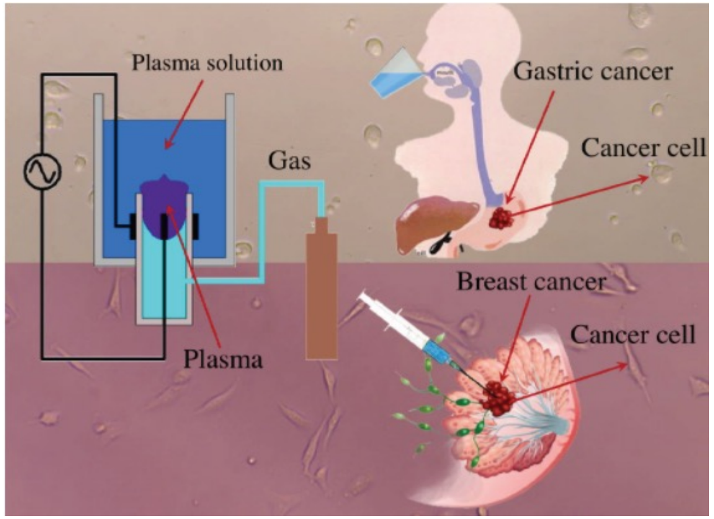
(B) : Proposed CAP-activated water as a non-invasive method for gastric and breast cancer treatment.

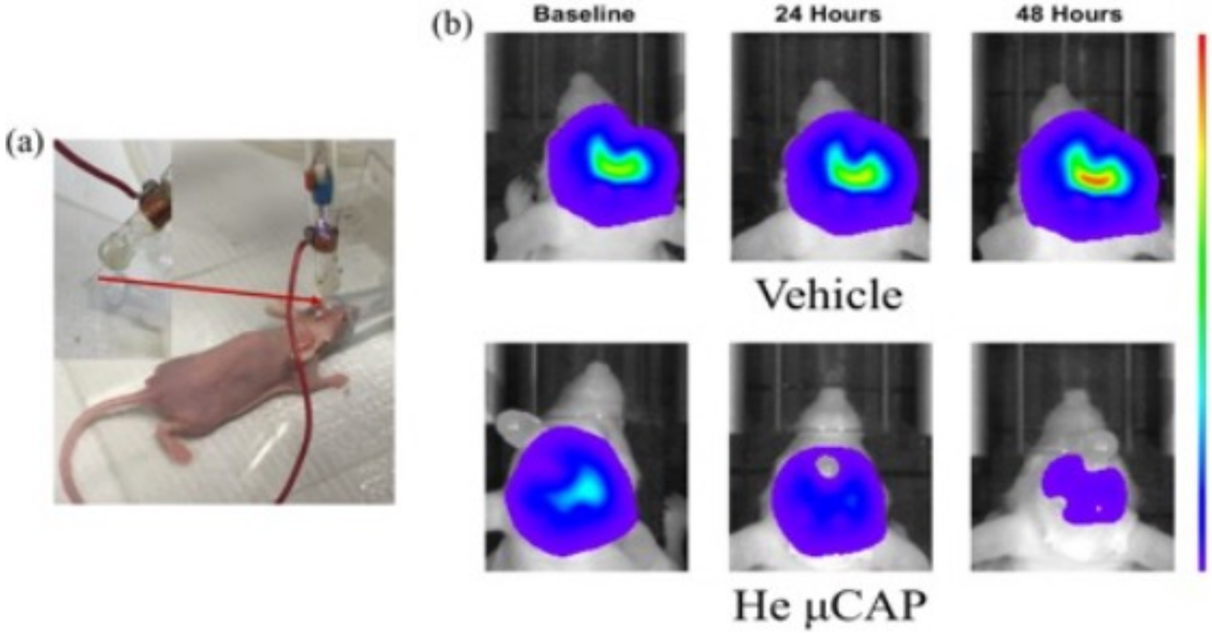
(C) : μCAP devise developed to target glioblastoma tumors via intracranial endoscopic tube.

(A)



(B)



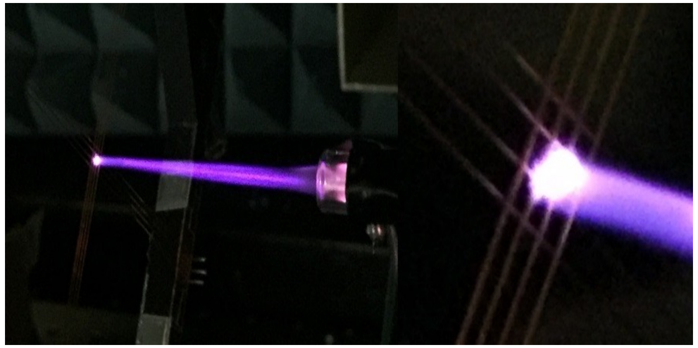


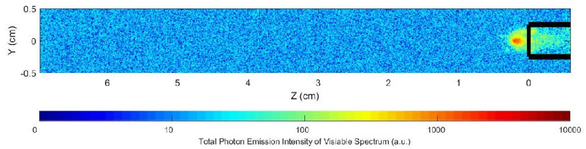
(C)

https://mpnl.seas.gwu.edu

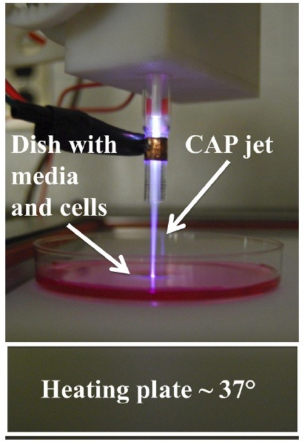
SUMMARY: PLASMAS FOR MEDICINE

Cold atmospheric plasmas



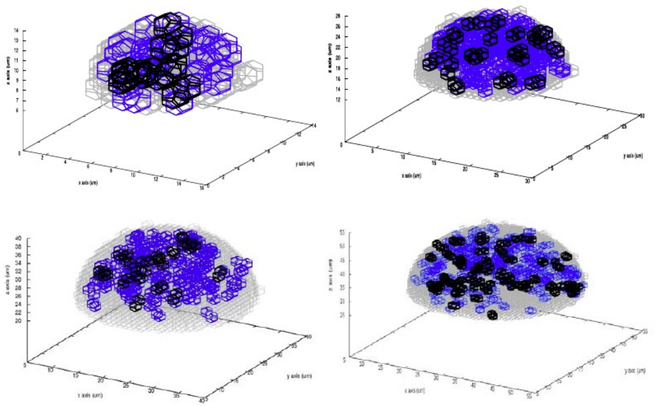


In vitro

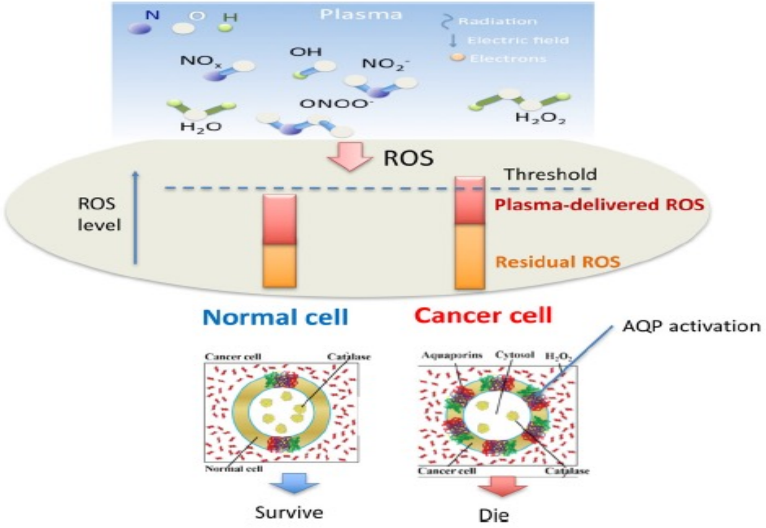


In vivo

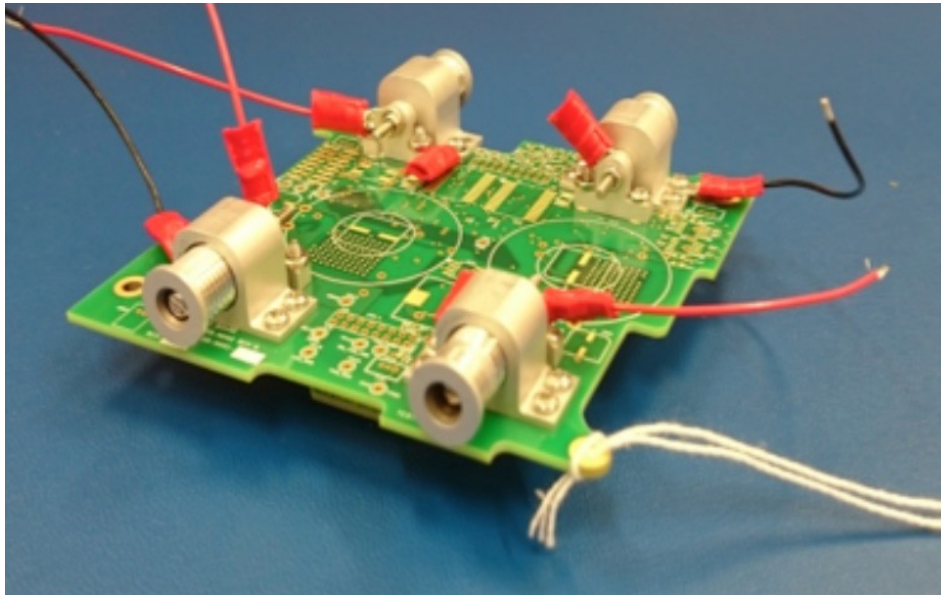
Simulation of plasma interaction with solid tumor



Mechanism

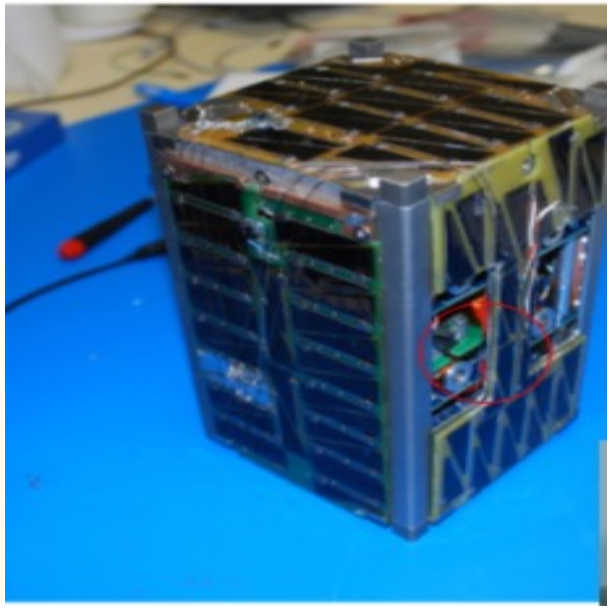


MPNL – PROPULSION RESEARCH



MpNL BUILT THRUSTERS FOR NASA AMES PHONESAT EXPERIMENT
https://www.nasa.gov/centers/ames/cct/office/cif/2013/arc_thruster.html

mCAT (GWU/NASA)
https://svs.gsfc.nasa.gov/vis/a010000/a012000/a012025/FactSheet_v12.pdf



BRICSat-P Thrusters
https://gwtoday.gwu.edu/gw-researchers%E2%80%99-plasma-thruster-reaches-space

Various thruster systems including high thrust to power micro-thrusters

MPNL PROPULSION RESEARCH-CONTD.

- Projects in Propulsion:
- High thrust to power ratio micro-thrusters,
- Discharge ignition phenomena in plasma micro-thrusters,
- Multi-stage micro-propulsion
- Linear-drive micro-cathode thrusters
- **Air Breathing Plasma thruster (My PhD Research)**
- MPD thruster

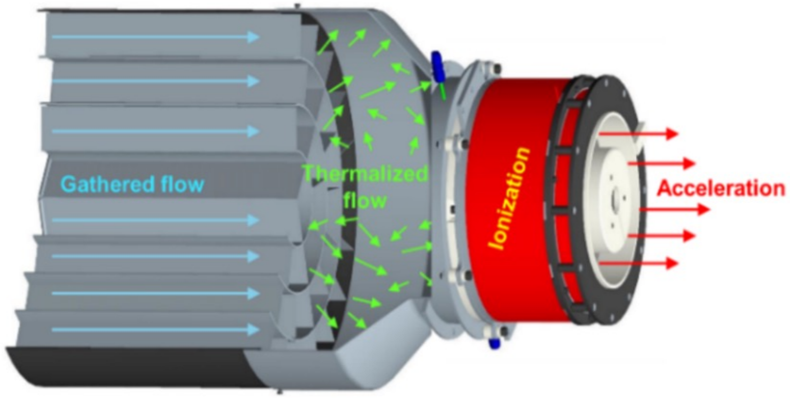
ABPT

ABPT uses incoming air propellant that is ionized and then consequently accelerated to produce thrust.

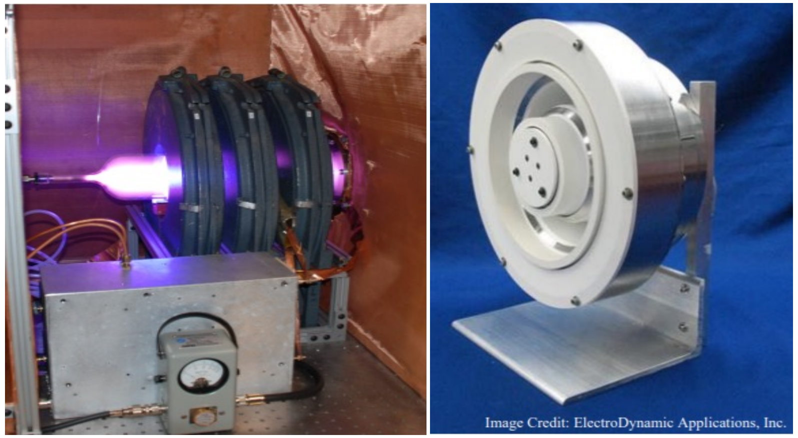
Typically thrust level (90 mN-90 N) required to cancel drag (60 mN-60 N) substantial at low altitudes[1-9].

Advantage: Increased satellite resolution, weight reduction, and low launch cost and burning up on reentry to prevent the formation of space debris.

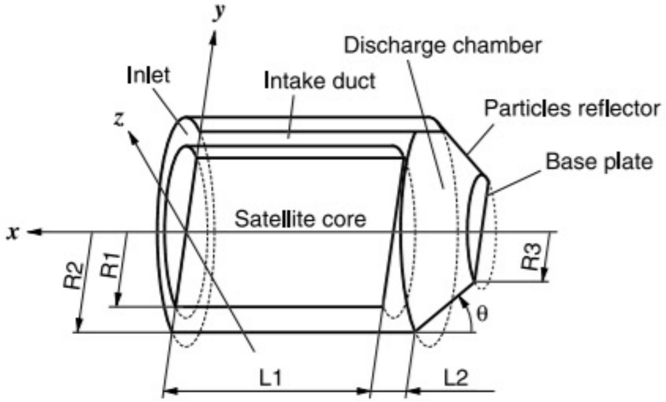
Existing Tested Designs and models in ABPT field



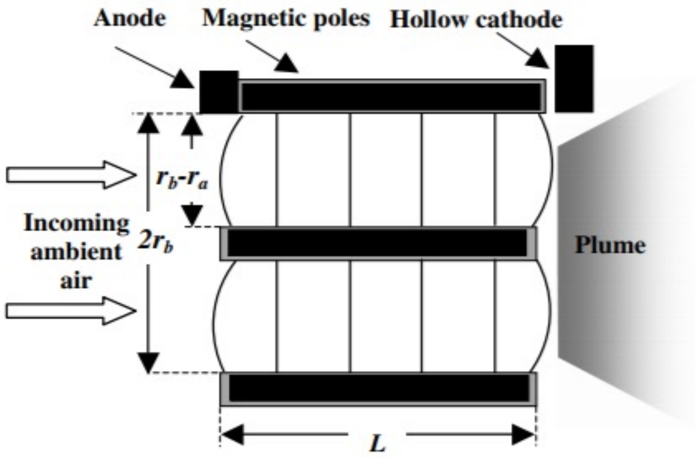
Ferrato et. al. SITAEL RAM-EP[1]



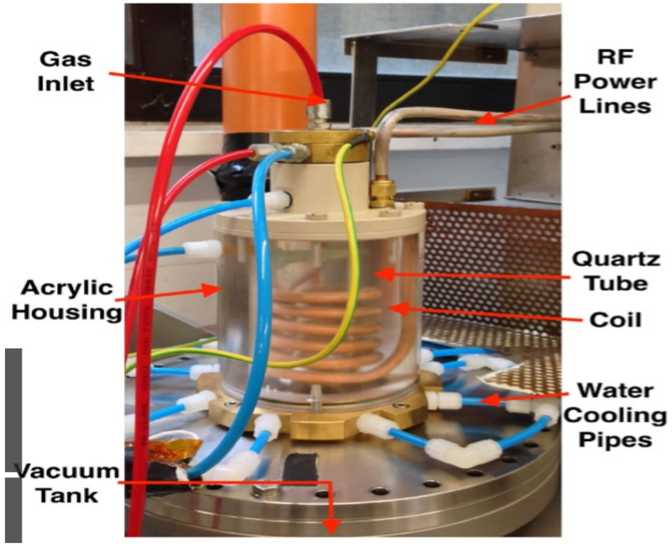
Adam Shabshelowitz [5] RPT and HHT thruster



Fujita's model [8]



Pekker and Keidar [6]



Romano et. al IPT [9]

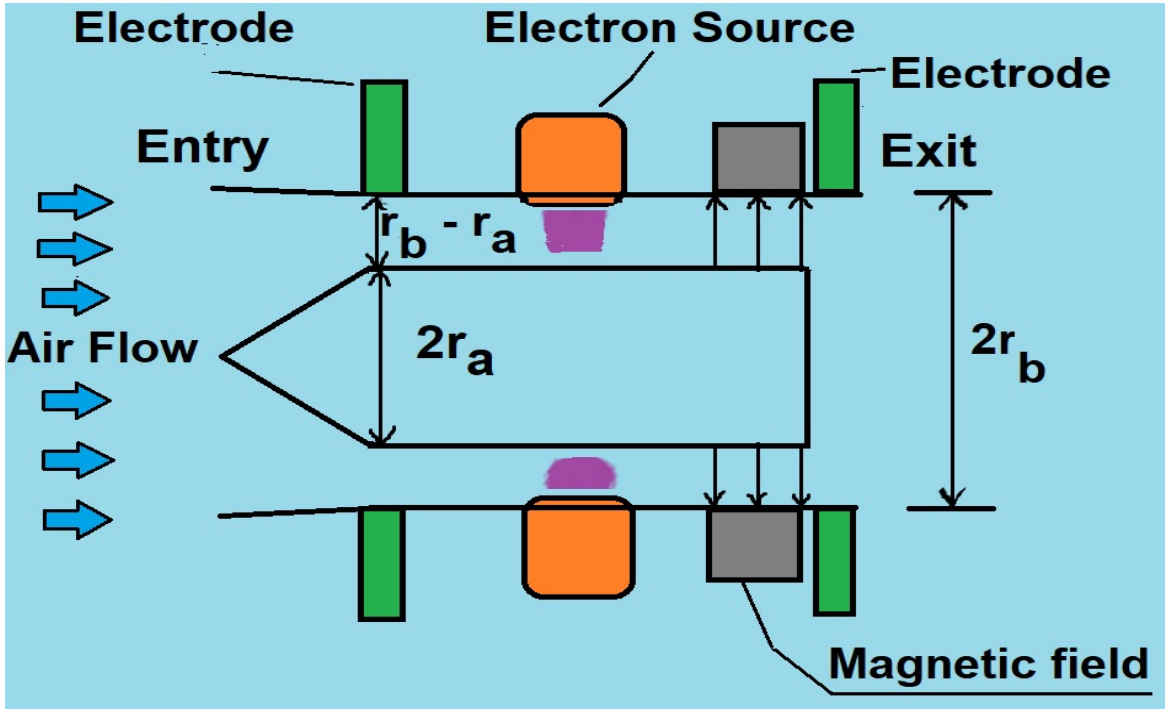
PROBLEMS TO SOLVE

- Cathode Neutralizer in ABPT
- Corrosion due to atomic oxygen in ABPT
- Drag introduced due to collimator designs on ABPT
- Power requirements
- Orbital debris

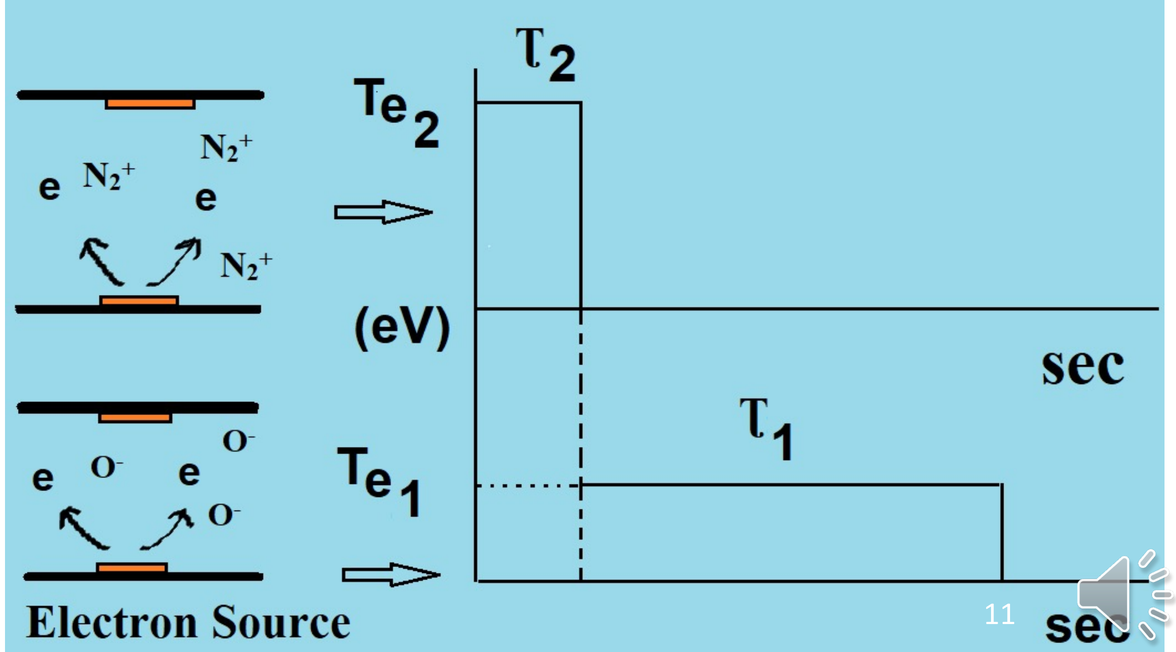
OBJECTIVES

Study	Study the ionization inside an ABPT using Chemical Kinetics Simulation:
Explore	Explore self-neutralization by operating in high-low electron energy mode.
Perform	Perform ABPT performance calculations to find thrust conditions to compensate drag in very low earth orbits.

Hall Thruster type configuration



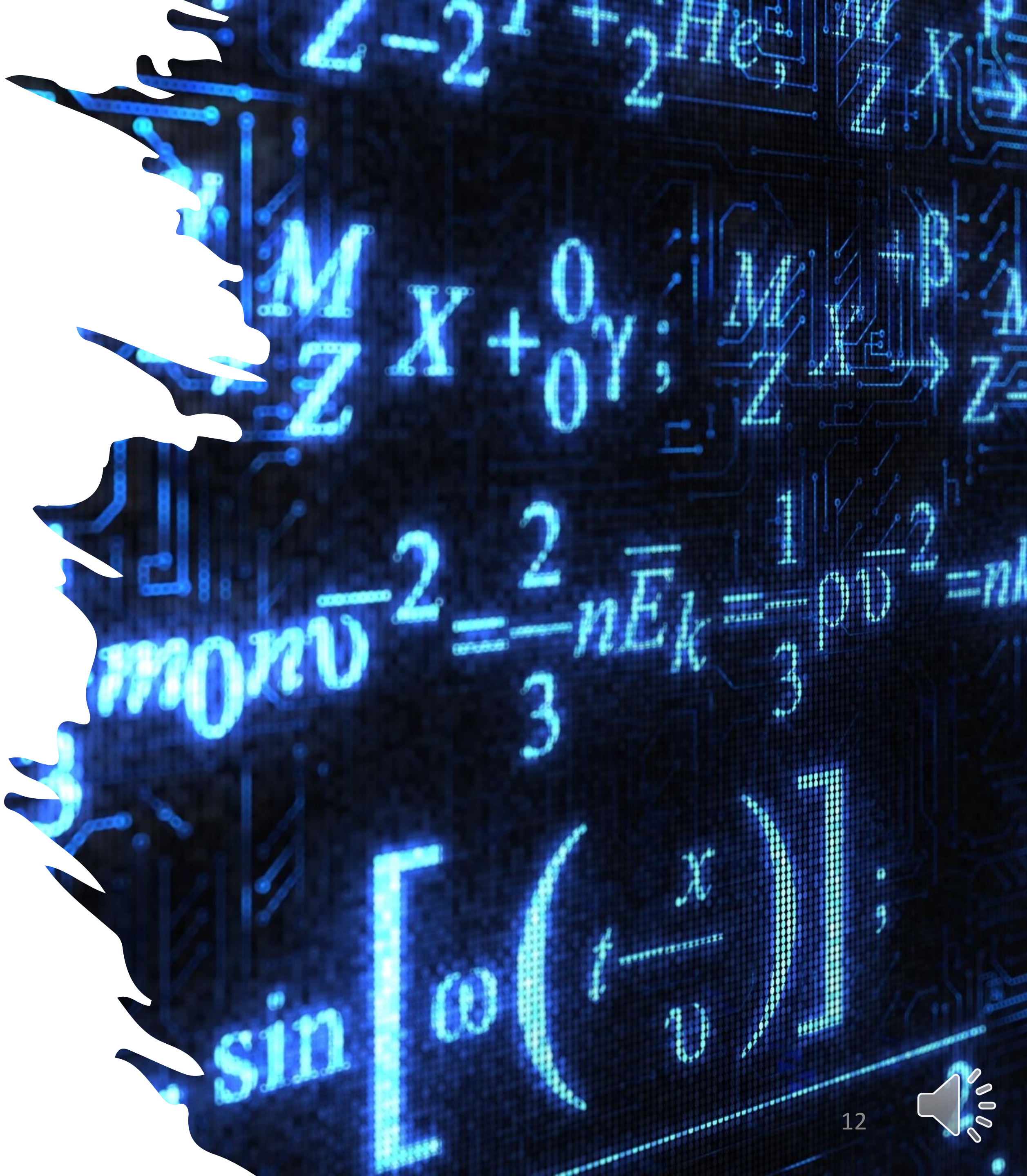
Low-high electron energy modes with the operation times



Equations used:

- $\frac{dn_a}{dt} = \sum_b k_b \left(T_e, T_g\right) \prod_c n_{b,c}$ - Chemical Kinetics Eq.
- $Q = e\, n_i\, u_e \tau$ - Charge Density
- $T = M\pi \left(r_b^2 - r_a^2\right) V_o n_i$ -Thrust
- $D = M_a n_{gas}\, \pi \left(r_b^2 - r_a^2\right) V_o^{\,2}$ - Drag
- $P_{average} = \varphi\left[\, (I_i)_{high}\, \tau_1 + (I_i)_{low}\, \tau_2 \,\right] / \left(\tau_1 + \tau_2\right)$

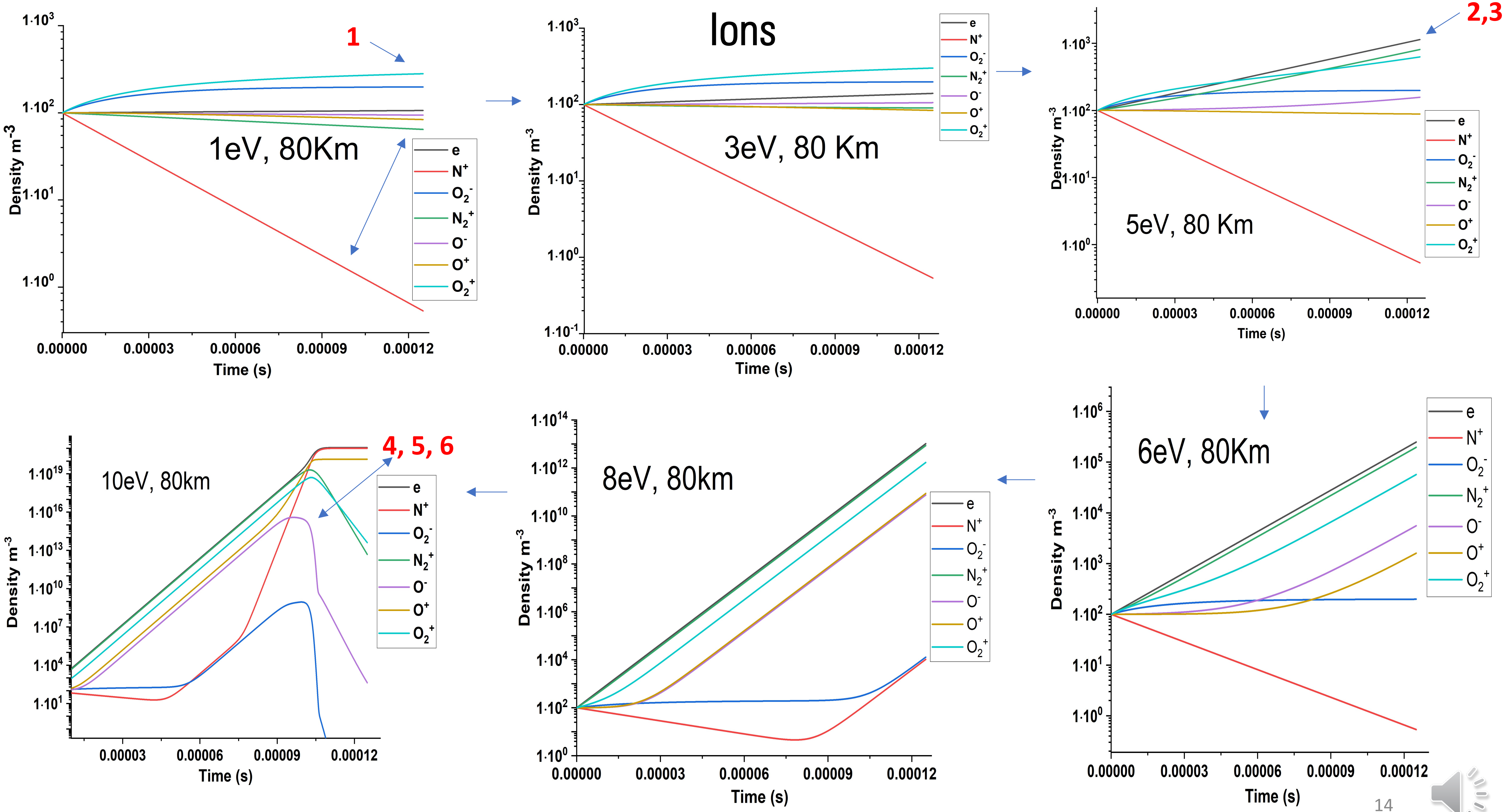
  -Average Power
- $I_i = n_i\, e\, V_0\, \pi \left(r_b^2 - r_a^2\right)$- Ion current



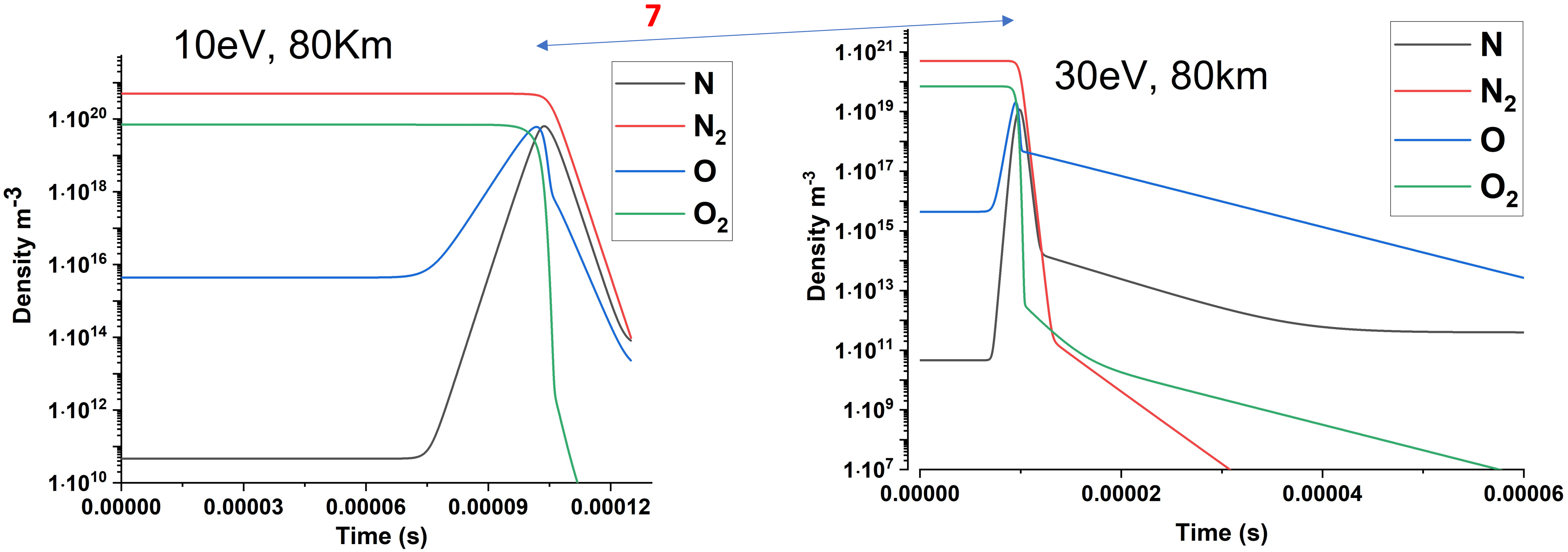
STUDY OF AIR IONIZATION USING CHEMICAL KINETICS SIMULATION

80 TO 110 KM ALTITUDE

Ions


1
1eV, 80Km
3eV, 80 Km
2,3
5eV, 80 Km
6eV, 80Km
8eV, 80km
10eV, 80km
4, 5, 6
e
N^+
O_2^-
N_2^+
O^-
O^+
O_2^+
Density m^{-3}
Time (s)
0.00000
0.00003
0.00006
0.00009
0.00012

Neutrals



https://mpnl.seas.gwu.edu

TOP KEY POINTS

$N_2^+ + O_2 = O_2^+ + N_2$ & $N^+ + O_2 = O_2^+ + N$ cause increase in O_2^+ and decrease in N_2^+ and N^+ (1, 3 eV).

Electron detachment causes increase in e density relative to O_2^+ (5eV)

Ionization dominates $k_{reaction\ rate} = f\ (T_e)$

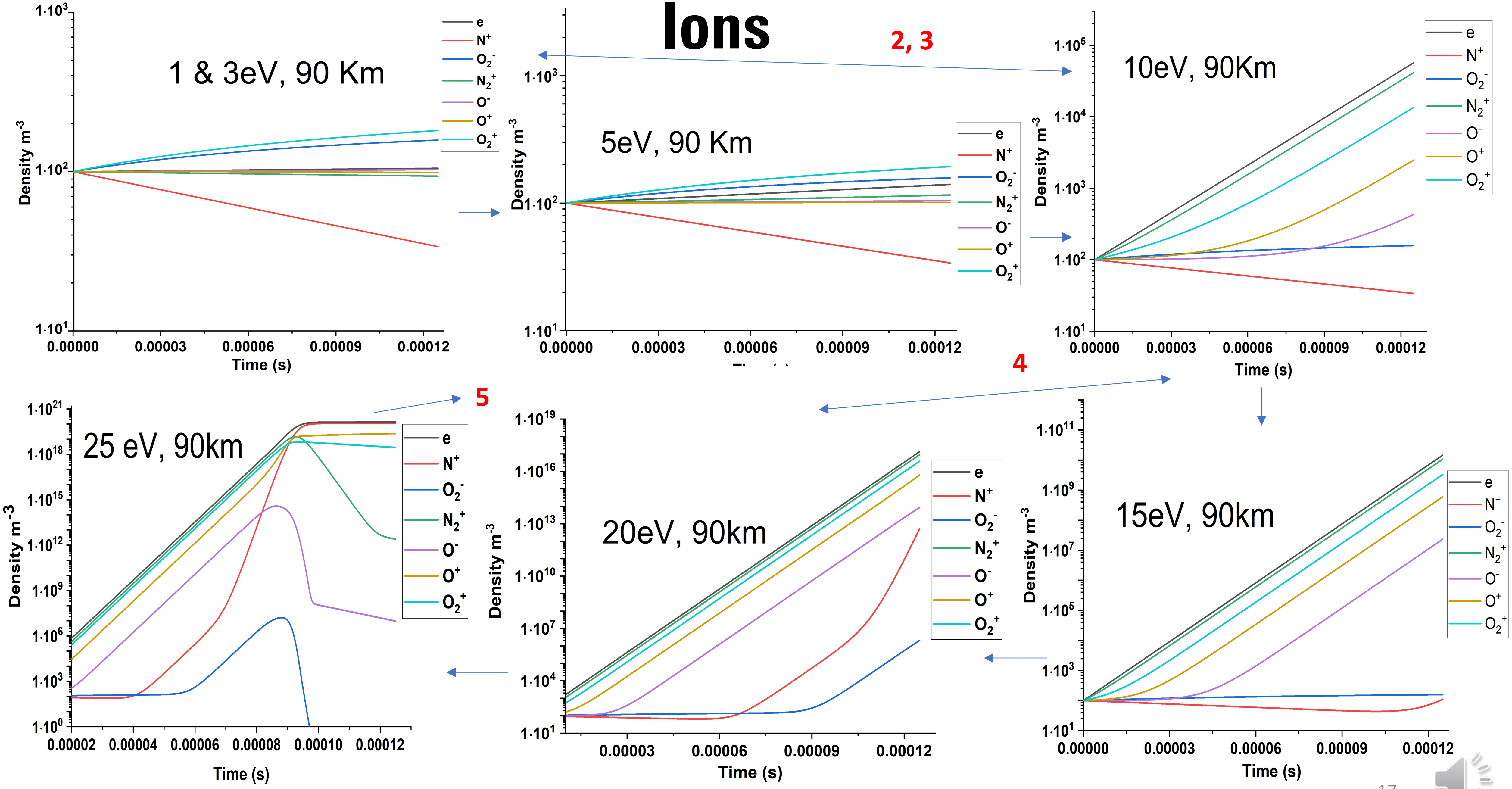
$Ions_{positive}$ > $Ions_{negative}$ (Charge balance)

Peaks indicate ionization, attachments and recombination

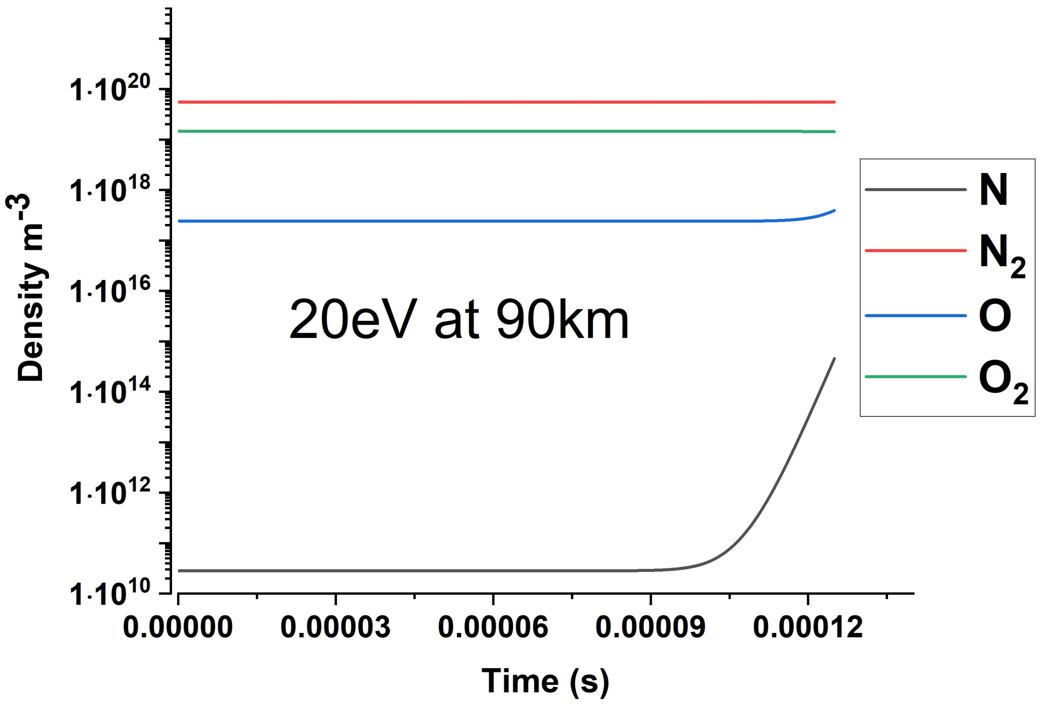
Final plasma e, N^+ and O^+ ions.

Neutral depletion peaks around species evolution peaks.

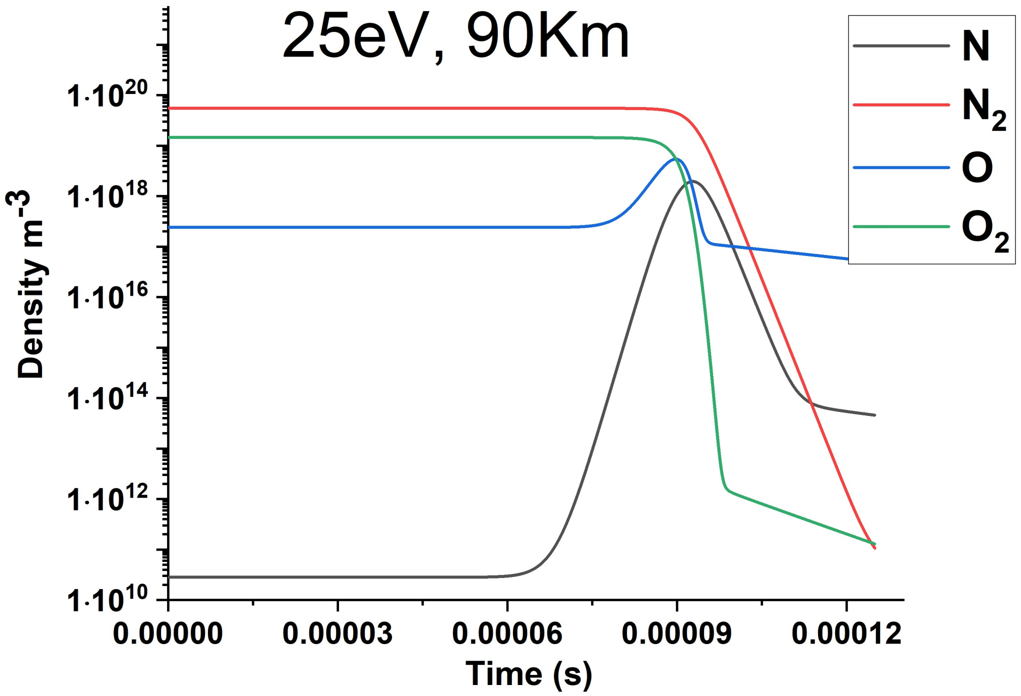
Ions


1 & 3eV, 90 Km
5eV, 90 Km
10eV, 90Km
15eV, 90km
20eV, 90km
25 eV, 90km
2, 3
4
5
Density m^{-3}
Time (s)
e
N^+
O_2^-
N_2^+
O^-
O^+
O_2^+
$1{\cdot}10^{1}$
$1{\cdot}10^{2}$
$1{\cdot}10^{3}$
$1{\cdot}10^{4}$
$1{\cdot}10^{5}$
$1{\cdot}10^{0}$
$1{\cdot}10^{3}$
$1{\cdot}10^{6}$
$1{\cdot}10^{9}$
$1{\cdot}10^{12}$
$1{\cdot}10^{15}$
$1{\cdot}10^{18}$
$1{\cdot}10^{21}$
$1{\cdot}10^{4}$
$1{\cdot}10^{7}$
$1{\cdot}10^{10}$
$1{\cdot}10^{13}$
$1{\cdot}10^{16}$
$1{\cdot}10^{19}$
$1{\cdot}10^{5}$
$1{\cdot}10^{7}$
$1{\cdot}10^{9}$
$1{\cdot}10^{11}$
0.00000
0.00002
0.00003
0.00004
0.00006
0.00008
0.00009
0.00010
0.00012

Neutrals



20eV at 90km
N
N_2
O
O_2
Density m^{-3}
Time (s)
$1\cdot10^{20}$
$1\cdot10^{18}$
$1\cdot10^{16}$
$1\cdot10^{14}$
$1\cdot10^{12}$
$1\cdot10^{10}$
0.00000
0.00003
0.00006
0.00009
0.00012



25eV, 90Km
N
N_2
O
O_2
Density m^{-3}
Time (s)
$1\cdot10^{20}$
$1\cdot10^{18}$
$1\cdot10^{16}$
$1\cdot10^{14}$
$1\cdot10^{12}$
$1\cdot10^{10}$
0.00000
0.00003
0.00006
0.00009
0.00012

TOP KEY POINTS

For 100-110 km, larger than 1m engine length required to reach peaks.

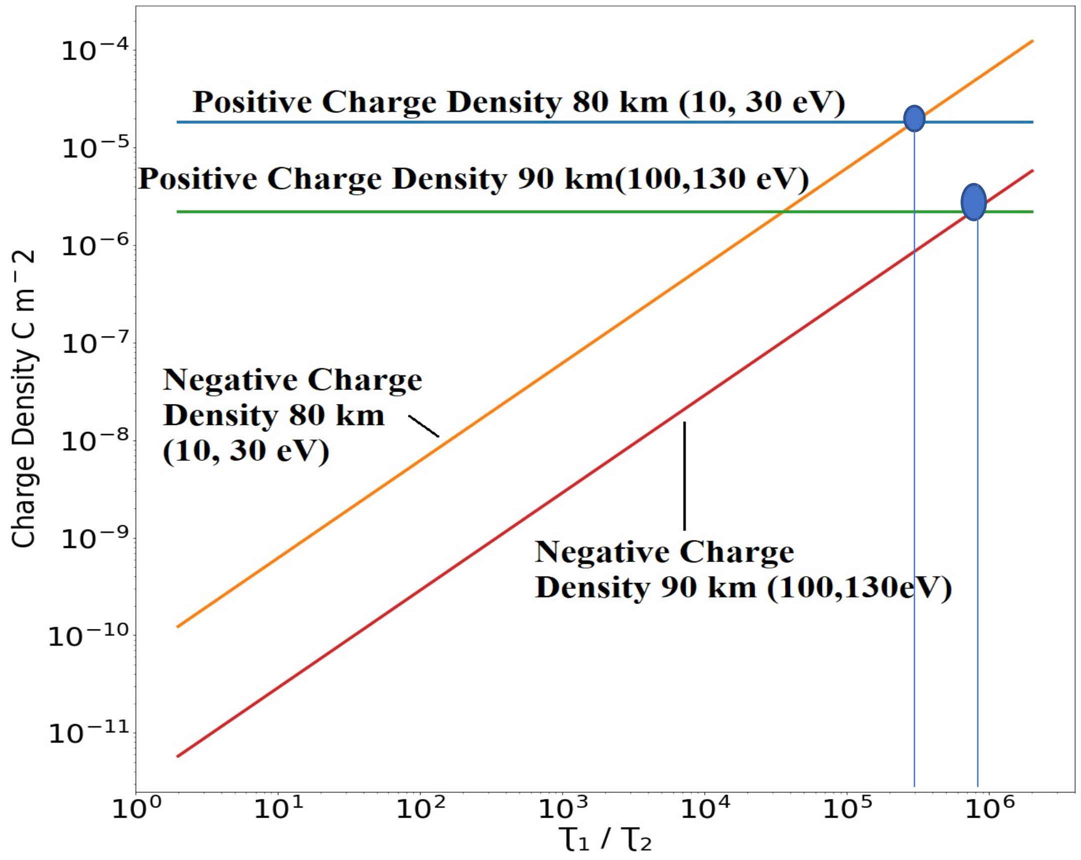
1, 3 and 5 eV similar trend like 80 Km altitude (1, 3eV).

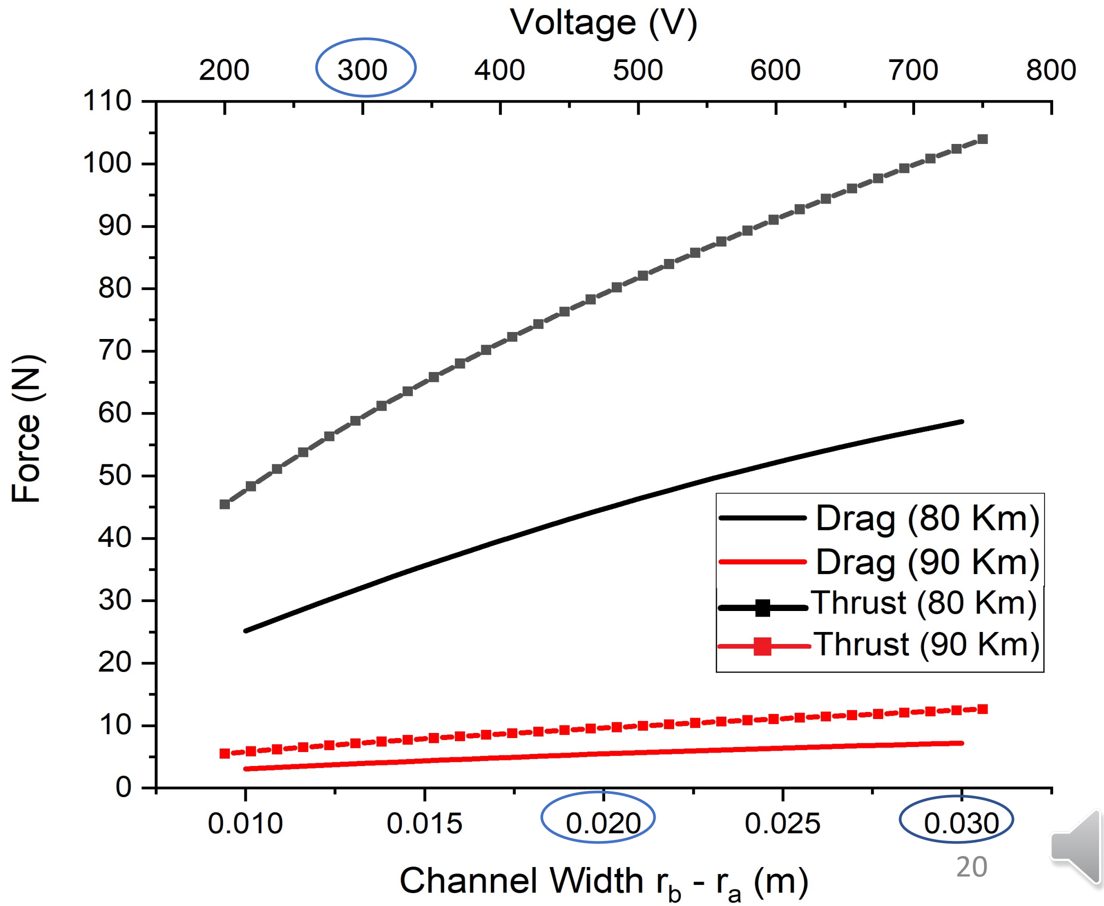
High O density (90 Km), O^+ + O + air => O_2^+ + air and e + O + O_2=> O + O_2^- , caused high O_2^+ and O_2^- density.

Ionization dominate beyond 10 eV (15-20 eV great increment of e density)

Final plasma e, N^+ and O^+ ions.

ABPT Performance Calculations





Calculated Results

Parameters	80 km	90 km
Thrust	59 N	7.2 N
Drag	58 N (r_b and r_a: 0.05, 0.02m)	7.18 N (r_b and r_a: 0.05, 0.03m)
Power	1.37 MW (full ionization)	166 kW (full ionization)
Thrust/ Power	43 mN/kW	43.4 mN/kW

- Above results obtained for 300 V discharge Voltage
- With relaxation in ionization degree (electron/neutral density), power can be greatly reduced.
- Power can be Laser beam transmitted to the satellite [6, 12]
- Calculated the maximum possible drag whereas only lateral surfaces will experience drag.

Future Work

- To validate the obtained results and prediction of ionization, an experimental approach would be crucial.
- Develop methods to increase the ionization degree for 100 km and above altitudes.
- Analysis for electron current measurement would be required to estimate the total power supplied. [13]
- Characterize electron sources and final ABPT design using Rayleigh Microwave scattering, Optical emission spectroscopy, Langmuir probes and Thrust measurements (indirect and direct).
- Reduced power analysis for ABPT.

References

1. Ferrato, Giannetti, Piragino, Andrenucci and Andreussi, Development Roadmap of SITAEL's RAM-EP System, (2019). http://electricrocket.org/2019/886.pdf

2. Neil Wallace, Jameson, Saunders, Fehringer, Edwards and Floberghagen, The GOCE Ion Propulsion Assembly – Lessons Learnt from the First 22 Months of Flight Operations, (2011). http://electricrocket.org/IEPC/IEPC-2011-327.pdf

3. D. Di Cara, A. Santovincenzo, B.C. Dominguez, M. Arcioni, A. Caldwell, I. Roma, Roma, RAM Electric Propulsion for Low Earth Orbit Operation: an ESA Study, (2007). http://electricrocket.org/IEPC/IEPC-2007-162.pdf

4. K. Diamant, A 2-stage cylindrical Hall thruster for air breathing electric propulsion, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2010, https://arc.aiaa.org/doi/abs/10.2514/6.2010-6522

5. Shabshelowitz, Study of RF Plasma Technology Applied to Air-Breathing Electric Propulsion. (2013). https://deepblue.lib.umich.edu/handle/2027.42/98016

6. L. Pekker and M. Keidar, Journal of Propulsion and Power 28, 1399 (2012). https://doi.org/10.2514/1.B34441

7. Vladimir Hruby, Pote, Olsen, Szabo, Rostler and K. Hohman, Atmospheric Breathing Electric Thruster for Planetary Exploration vol. 11, Busek Co. Inc, 2012 01760–1023. https://www.nasa.gov/pdf/636899main_Hohman_Presentation.pdf

8. K. Fujita, Air-intake performance estimation of air-breathing ion engines, (2004). doi:10.2322/jjsass.52.514

9. F. Romano, B. Massuti-Ballester, T. Binder, G. Herdrich, S. Fasoulas, and T. Schönherr, Acta Astronautica (2018). https://doi.org/10.1016/j.actaastro.2018.03.031

10. MSIS-E-90 Atmosphere Model , https://ccmc.gsfc.nasa.gov/modelweb/models/msis_vitmo .php, (2021)

11. LXcat, https://nl.lxcat.net/home/, (2020)

12. S.Sasaki, K. Tanaka and K. Maki, "Microwave Power Transmission Technologies for Solar Power Satellites," oin *Proceedings of the IEEE*, vol. 101, no. 6, pp. 1438-1447, June 2013. doi: 10.1109/JPROC.2013.2246851

13. Igor D. Kaganovich et. al. Perspectives on Physics of E×B Discharges Relevant to Plasma Propulsion and Similar Technologies, Physics of Plasmas, 120601, 2020. https://doi.org/10.1063/5.0010135