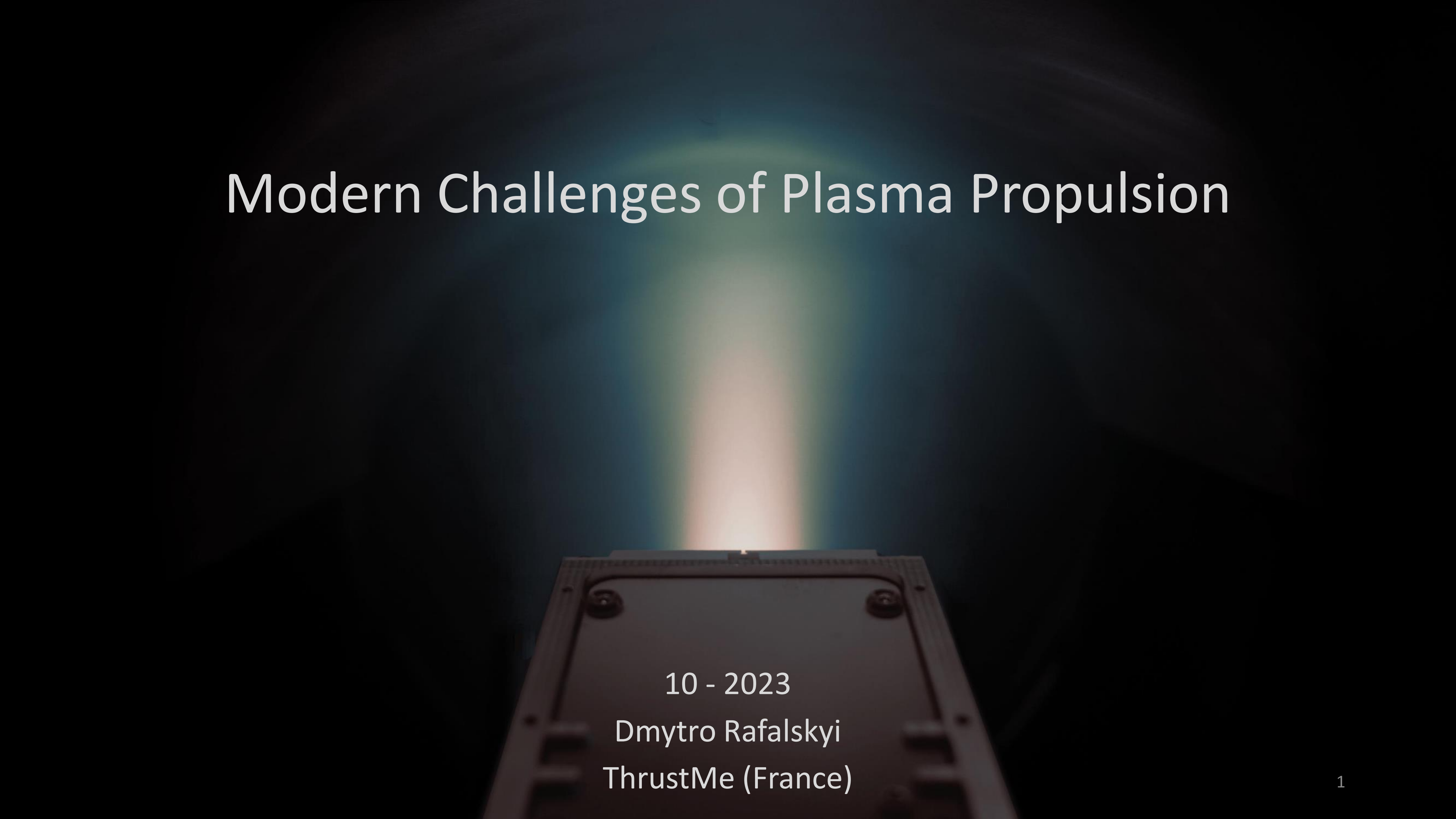
Modern Challenges of Plasma Propulsion



10 - 2023

Dmytro Rafalskyi
ThrustMe (France)

Dmytro Rafalskyi

- **2017-present:** CTO and co-founder at ThrustMe
- **2012-2017:** Ecole Polytechnique, CNRS, SATT Paris-Saclay as post-doc, researcher and maturation engineer
- **Until 2012:** VN Karazin Kharkiv University, Phys.-Tech. faculty (Master 2007, PhD 2010)

ThrustMe

- <u>Aerospace startup (France):</u>
  - Founded in 2017
  - 27 employees, growing
  - Mass Production of satellite propulsion systems
  - R&D in plasma and space domains
  - World leader in iodine propulsion technology

Why satellites need propulsion in space?

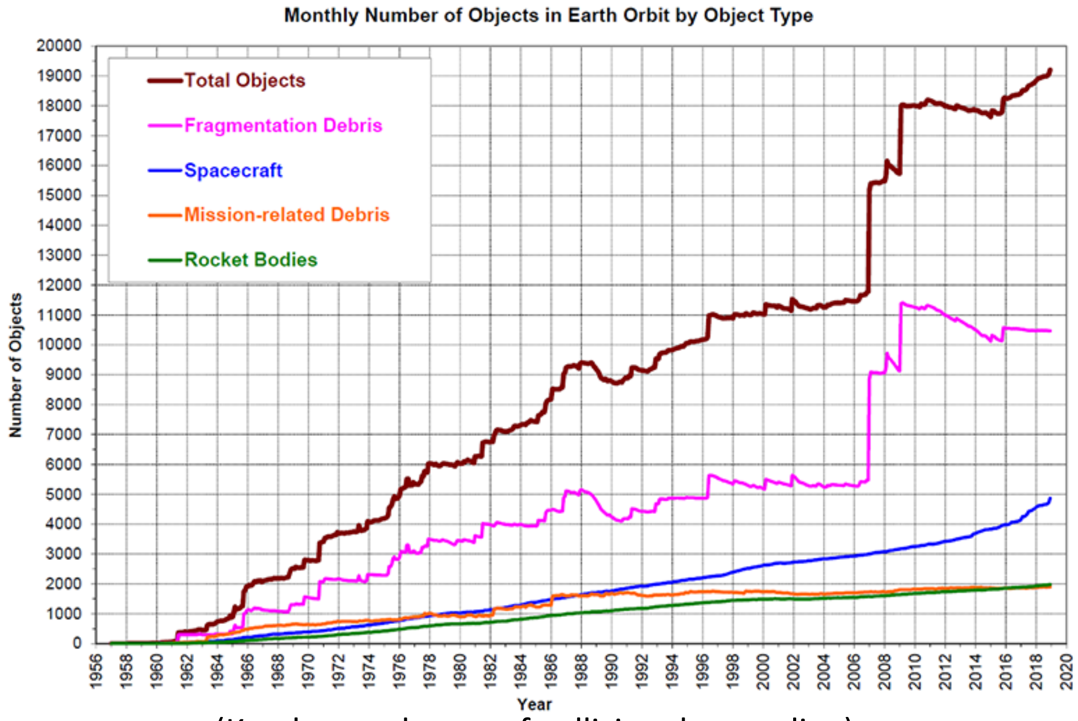
Space propulsion

Space propulsion is used for
- Atmospheric drag compensation, orbital transfer, collision avoidance
- Constellation deployment
- Deorbiting

Limitations
- Not common for very small satellites (<50 kg)
- High cost and integration problems
- Restricted resources (power, size, mass, thermal management)
- Harsh environment (temperature, radiation, vacuum, loads)

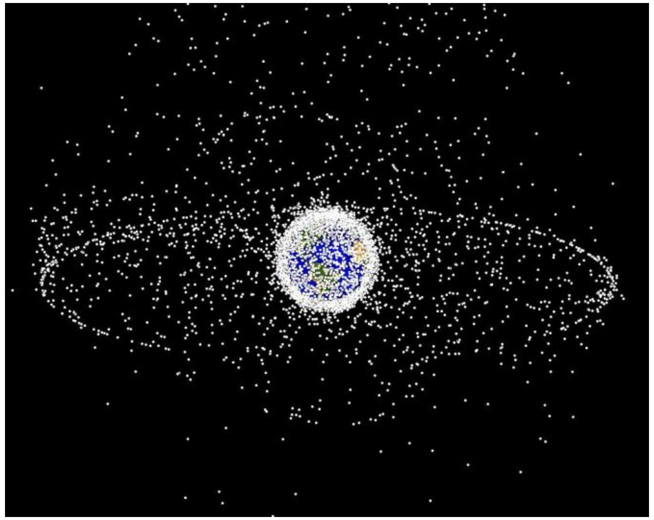
Importance
- Majority of space junk can be avoided if all satellites have propulsion

! Sustainable use of space requires propulsion

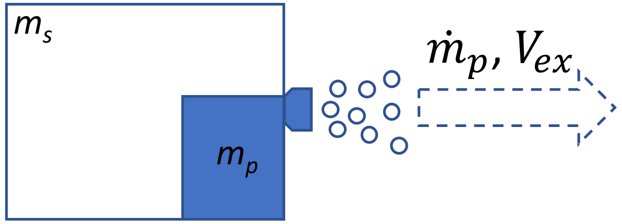


(Kessler syndrome of collisional cascading)

*image credit: NASA



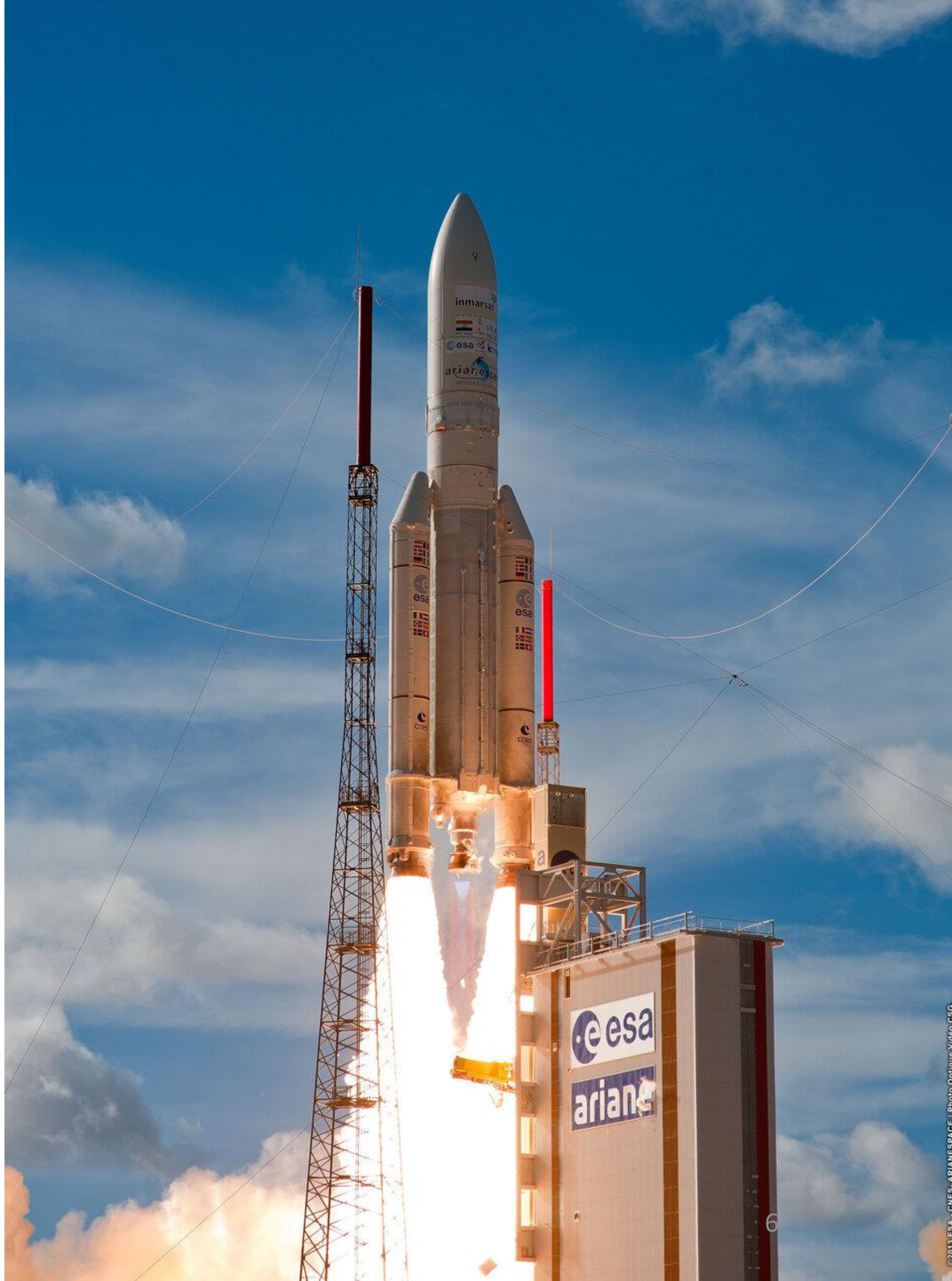
Propulsion basics



- Thrust: $T = \dot{m}_p \times V_{ex}$
- $I_{sp} = \frac{V_{ex}}{g} = \frac{T}{\dot{m}_p g}$ – measure of efficiency

Typical V_{ex} :

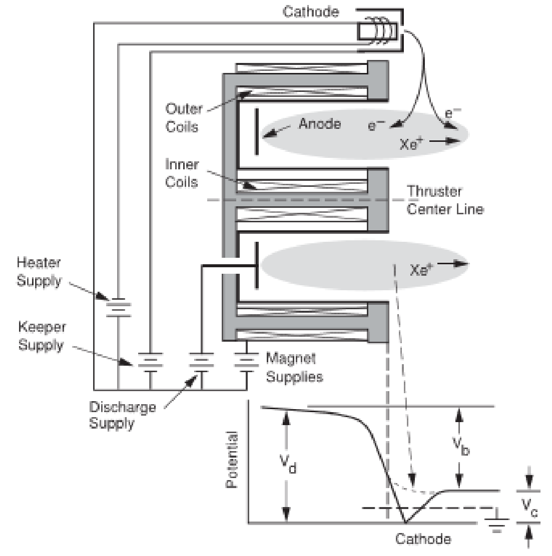
- for cold gas - < 500 m/s
- For chemical - < 4 km/s
- For EP – up to 50 km/s



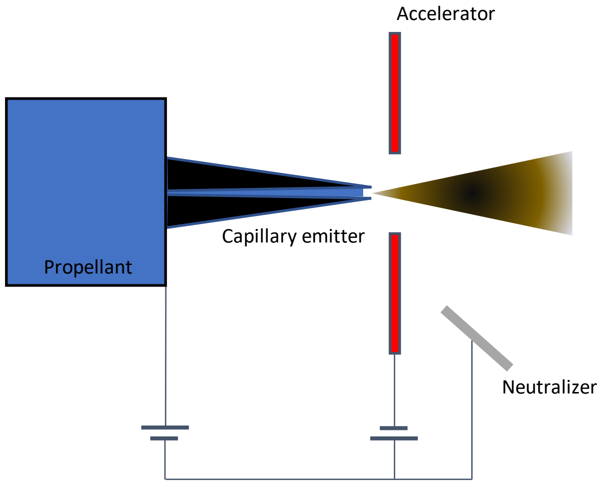
Types of electric propulsion systems

- Gridded ion thruster with different ionization techniques (RF, MW, electron beam, DC hollow cathode or discharge with electron bombardment)
- Hall effect thruster
- FEEP – field emission electric propulsion thruster
- PPT – pulsed plasma thruster
- Variety of plasma expansion systems, first flight last year

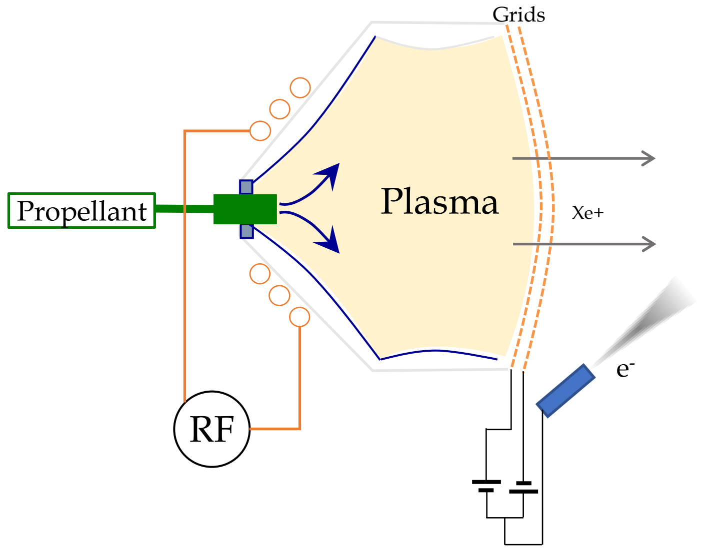
Hall effect thruster
(discharge in ExB field)



Field emission thruster
(no plasma)



Gridded ion thruster
(various plasma discharges used)



Read more: D. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters, Wiley, 2011.

Starlink constellation

- Few 1000s satellites using Kr HET
- New generation on Ar HET

Main drivers:

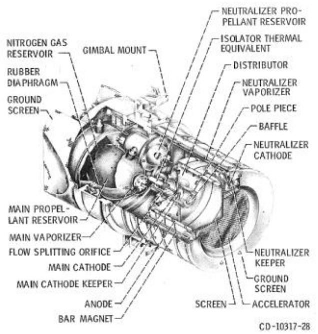
- cost
- convenience

Propellants for Electric Propulsion

$$T = \dot{m}_p \times V_{ex} = \sqrt{\frac{2M_i}{e}} I_i \sqrt{V_{acc}}$$

19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium [illegible]	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.90	56 Ba Barium 137.328	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018

SERT-2 by NASA:



Early EP era

Low ionization potential + low storage complexity
- **Caesium**: 3.89 eV, 132.9 u, 28.4°C melting
- **Mercury**: 10.4 eV, 200.59 u, -38.3°C melting

Currently "conventional"

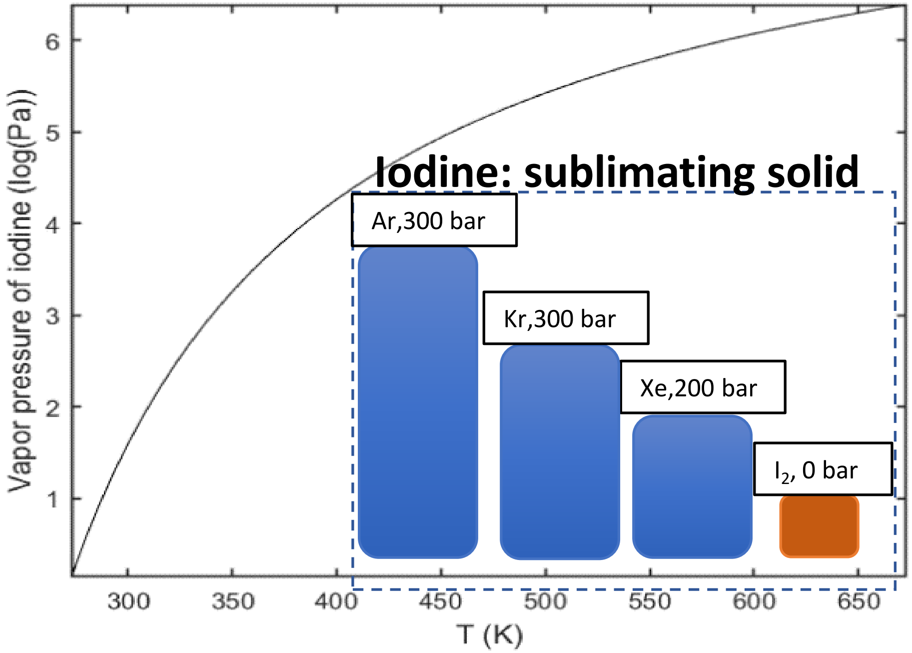
Inert + heavy
- **Xenon**: 12.1 eV, 131.2 u, gas (>200bar storage). "Safe" but expensive, very rare, storage and delivery problems

"New space" propellants

Cheap + easy to use
- **Krypton**: 13.99 eV, 84.8 u, gas (>200bar storage). Low cost, drawbacks as with Xenon. Used only by Starlink since 2019, but represents >50% of all EP.
- **Argon**: 15.76 eV, 39.9 u, gas (>200 bar). Very low cost, low efficiency. Starlink.
- **Indium**: Solid metal. Not suitable for plasma-based EP. Validated by Fotec and exploited only by Enpulsion (100+ systems).
- **Iodine**: 10.45 eV, 126.9 u, solid (<0.1 bar at room temp). Research started 1960s. Validated and exploited only by ThrustMe (5+ systems, since 2019).

Iodine for EP

FUTURE OF SPACE PROPULSION



Iodine advantages

- Same or lower ion energy cost as with Xe
- Pressure <<1 Bar, solid
- High storage density, up to 4.9 g/cm^{-3}
- Can enable propulsion for smallest sats
- Cost: the cheapest propellant

Main challenges

- Halogen: corrosion and toxicity
- Lack of fundamental data
- Various engineering problems

Iodine for EP

FUTURE OF SPACE PROPULSION

Property	Value
Density	4.93 g/cm^3
Atomic mass	126.9 g/mol
Melting point	113.7ºC
Enthalpy of sublimation	62.4 KJ/mol
Heat capacity (solid, 25ºC)	54.44 J/(mol·K)
Thermal conductivity (solid)	0.449 W/(m·K)
First ionization potential	10.45 eV
Electronegativity	2.66

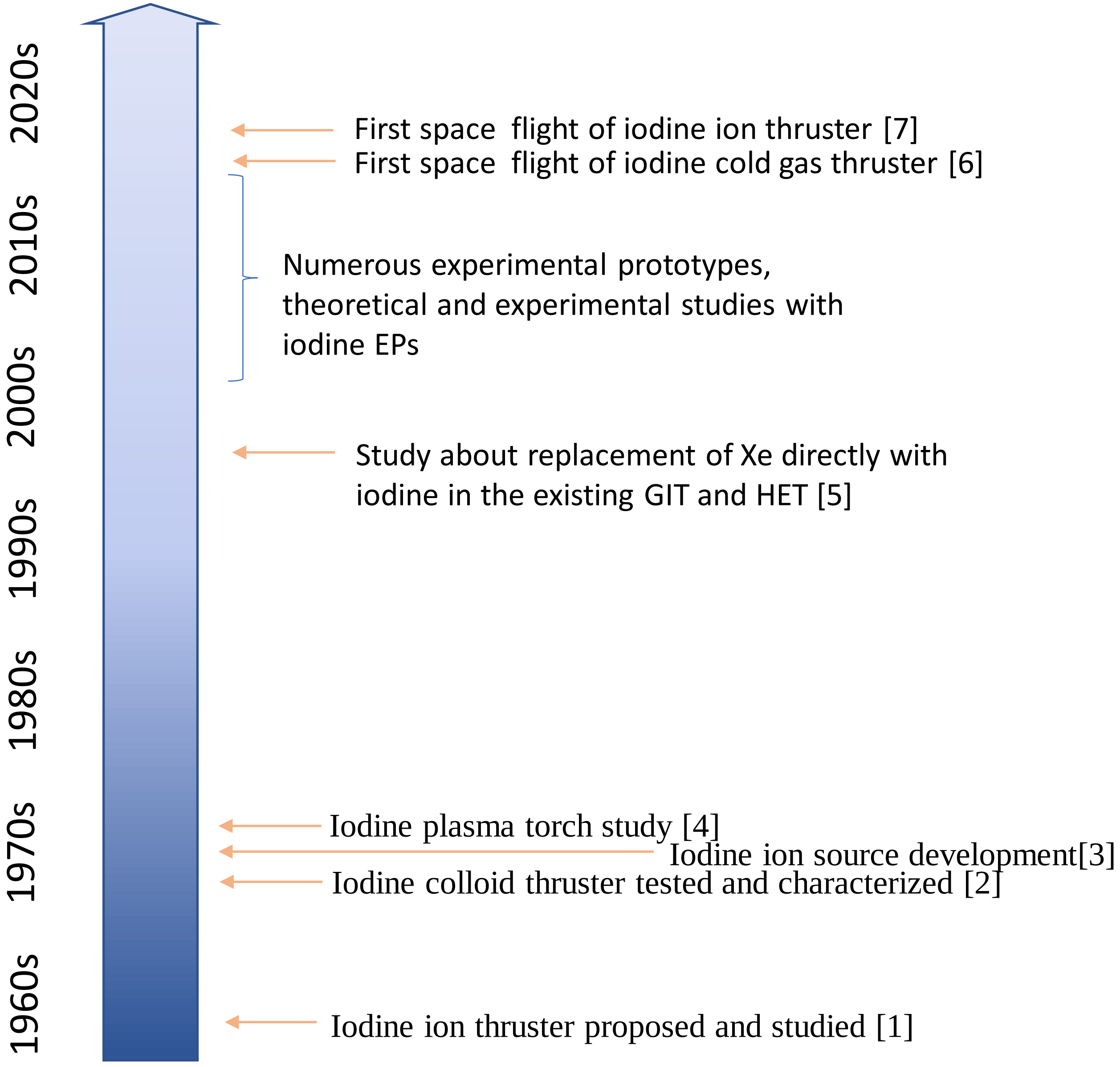
Missing iodine data

- Corrosion
- Basic thermal properties (vapour)
- Reaction cross-sections
- Some atomic properties

Internal studies

- Corrosion: 20+ materials tested and analysed
- Secondary electron emission yields

Iodine EP history



[1] Bussi, G. and Filippi, F., "Propulsion electrostatique par ions postifs et negatifs" *Institute di Machine E. Motori per Aeromobile, Turin, Pubblicazione 26 (July 1963)**

[2] E. Cohen And R. Kemp "Pulsed and alternating current colloid thruster studies", *8th Aerospace Sciences Meeting 1970, West Germany*

[3] Harry J King "Advanced Ion Source" *Final report N74-20448 , Hughes Research Labs 1973*

[4] H Liebl and W W Harrison "Study of an iodine discharge in a duoplasmatron" *International Journal of Mass Spectromctry and Ion Physics, 22 (1976) 237-246*

[5] R A Dressler, Y-H Chiu, D J Levandier "Propellant Alternatives for Ion and Hall Effect Thrusters", *AIAA 2000-0602, 2000.*

[6] Martínez J M et al. "Development, Qualification and First Flight Data of the Iodine Based Cold Gas Thruster for CubeSats" *In 5th IAA Conference on University Satellite Missions and CubeSat Workshop, 2020*

[7] Rafalskyi D et al. "In-orbit demonstration of an iodine electric propulsion system." *Nature Vol 599 No 7885: 411-415, 2021*

* Hardly accessible reference, brief review here: William J. Guman "Electric Propulsion Activities outside of the United States" *J. Spacecraft vol. 4, No. 11, pp.1424-1430 (1967)*

Iodine for EP

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Missing iodine data

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Internal studies

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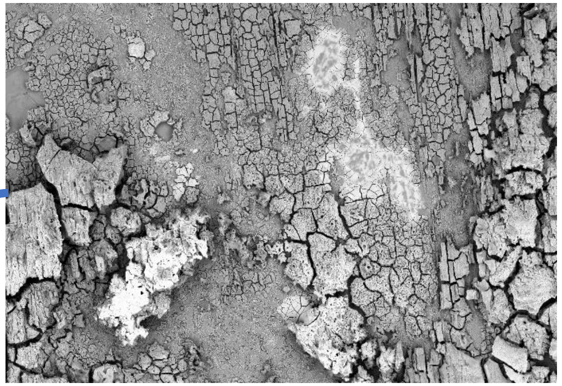
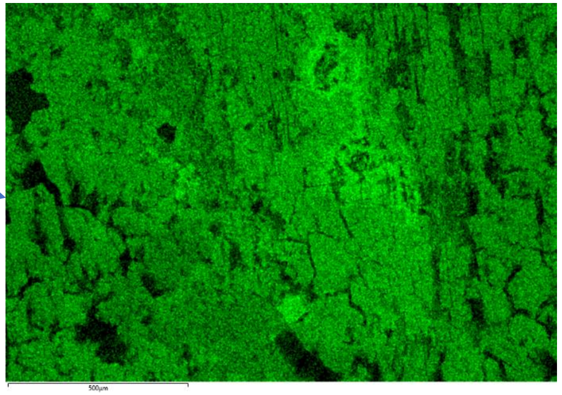
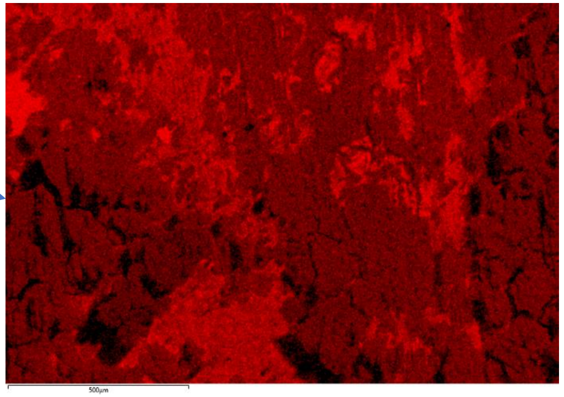
Cr surface after exposure to I_2



I_2 mapping



Cr mapping



Corrosion testing results:

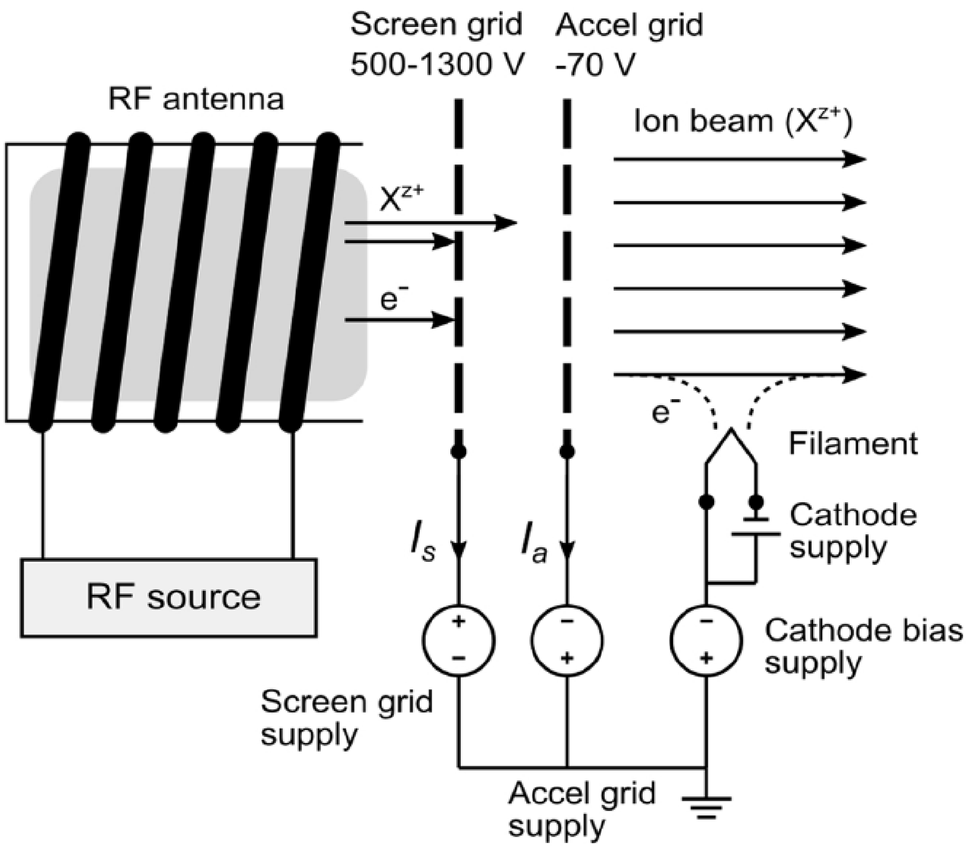
- Material database
- Strong impact of both process and environment
- More details: CEAS Space J, 14, 91–107 (2022)

Iodine for EP: ion source

Iodine ion thruster

- RF ICP discharge
- 2-grid ion acceleration
- Filament neutralizer

Ion thruster = broad beam ion source



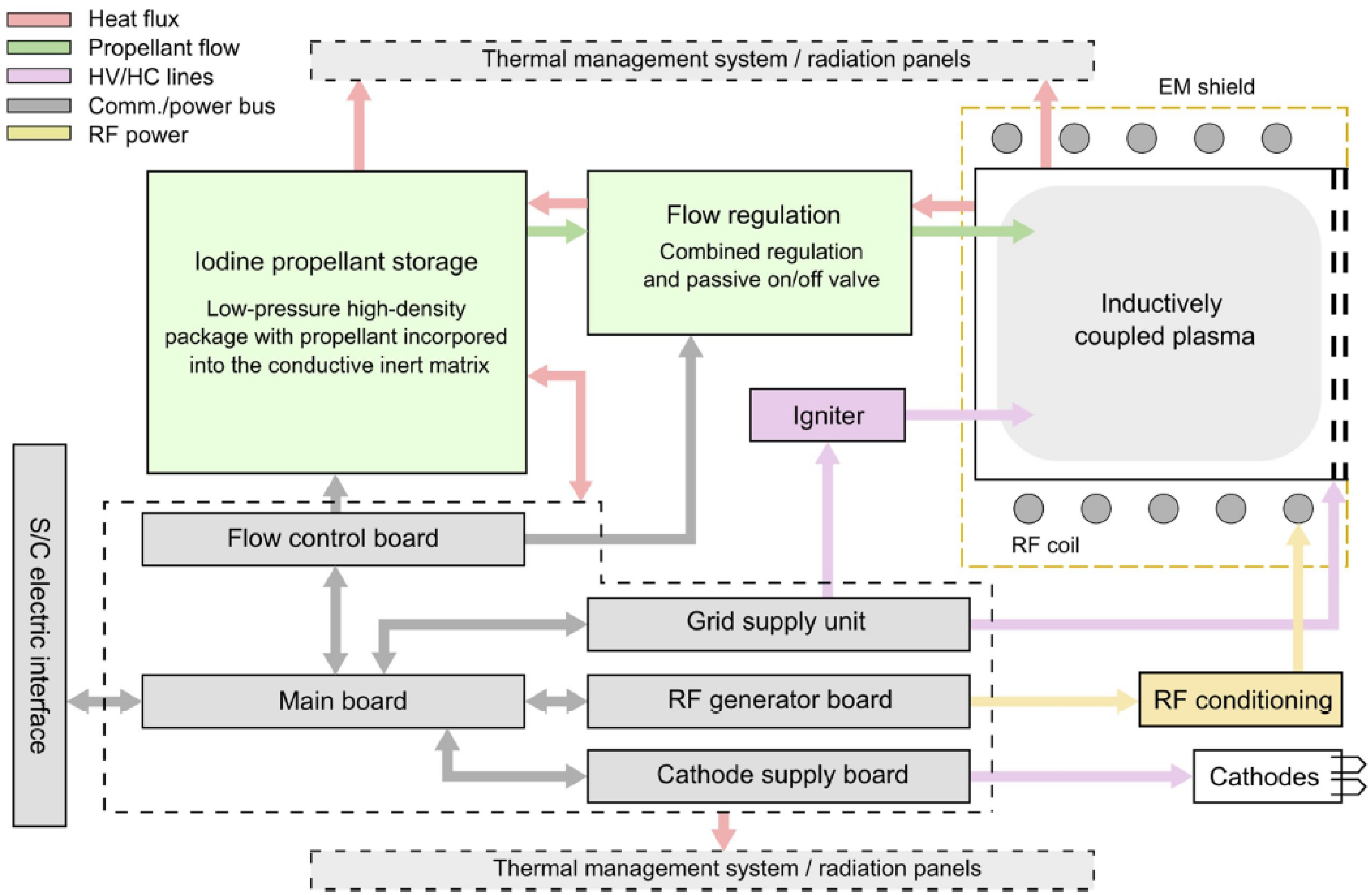
RF ICP discharge for ionization, double grid system for ion acceleration and filament cathode for neutralization

Iodine for EP: System architecture

Iodine ion thruster

- Integrated tank
- Fully autonomous
- Embedded intelligence and power electronics
- Thermal management

First to fly iodine ion thruster NPT30-I2 architecture: internal schematics (simplified)



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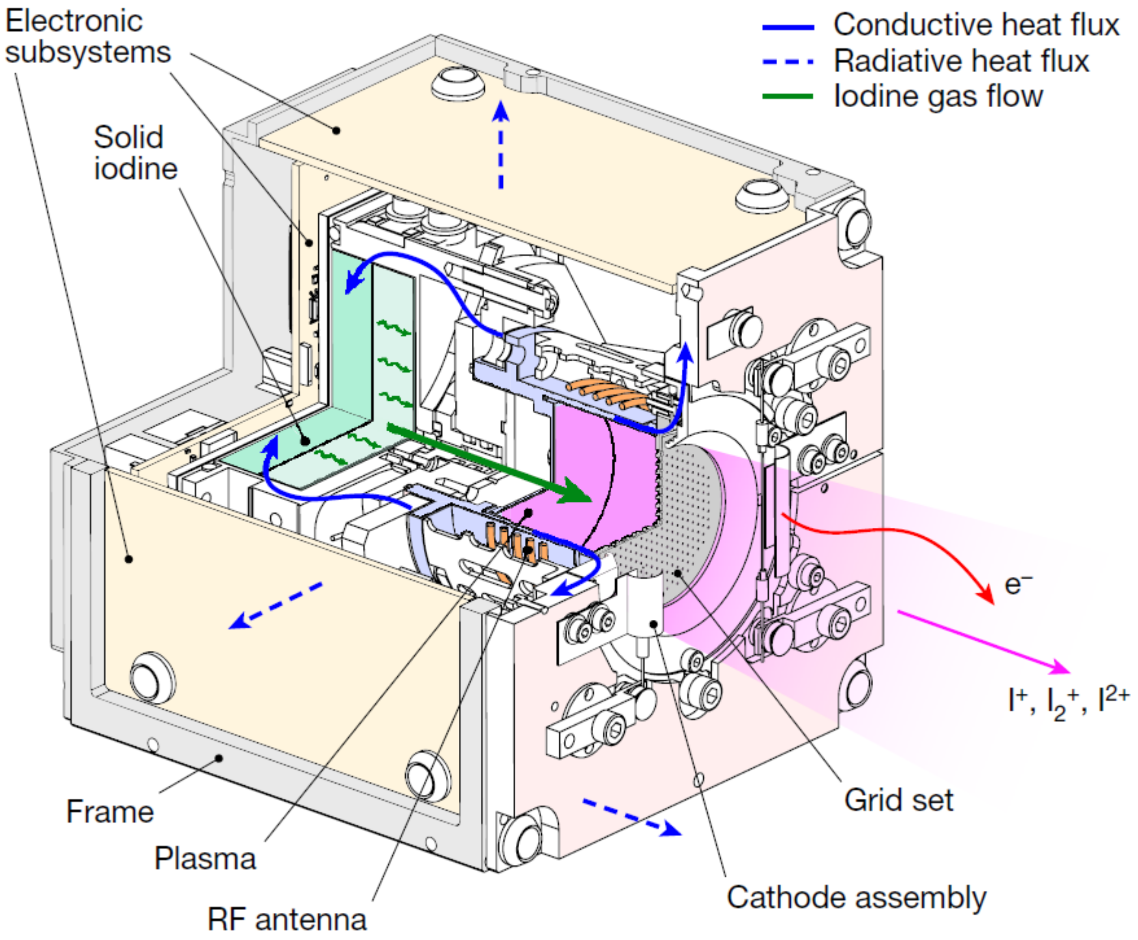
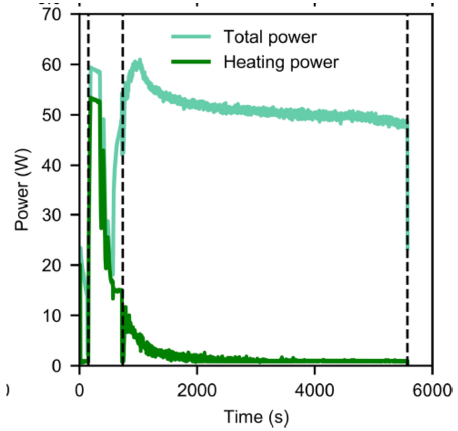
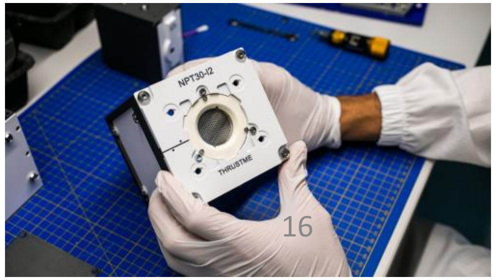
Iodine for EP: System architecture

NPT30-I2: first to fly iodine ion thruster

[1]**Nature, 2021, 599: 411-415**







Dimensions: 10x10x10 cm

Iodine for EP: System architecture

Iodine ion thruster

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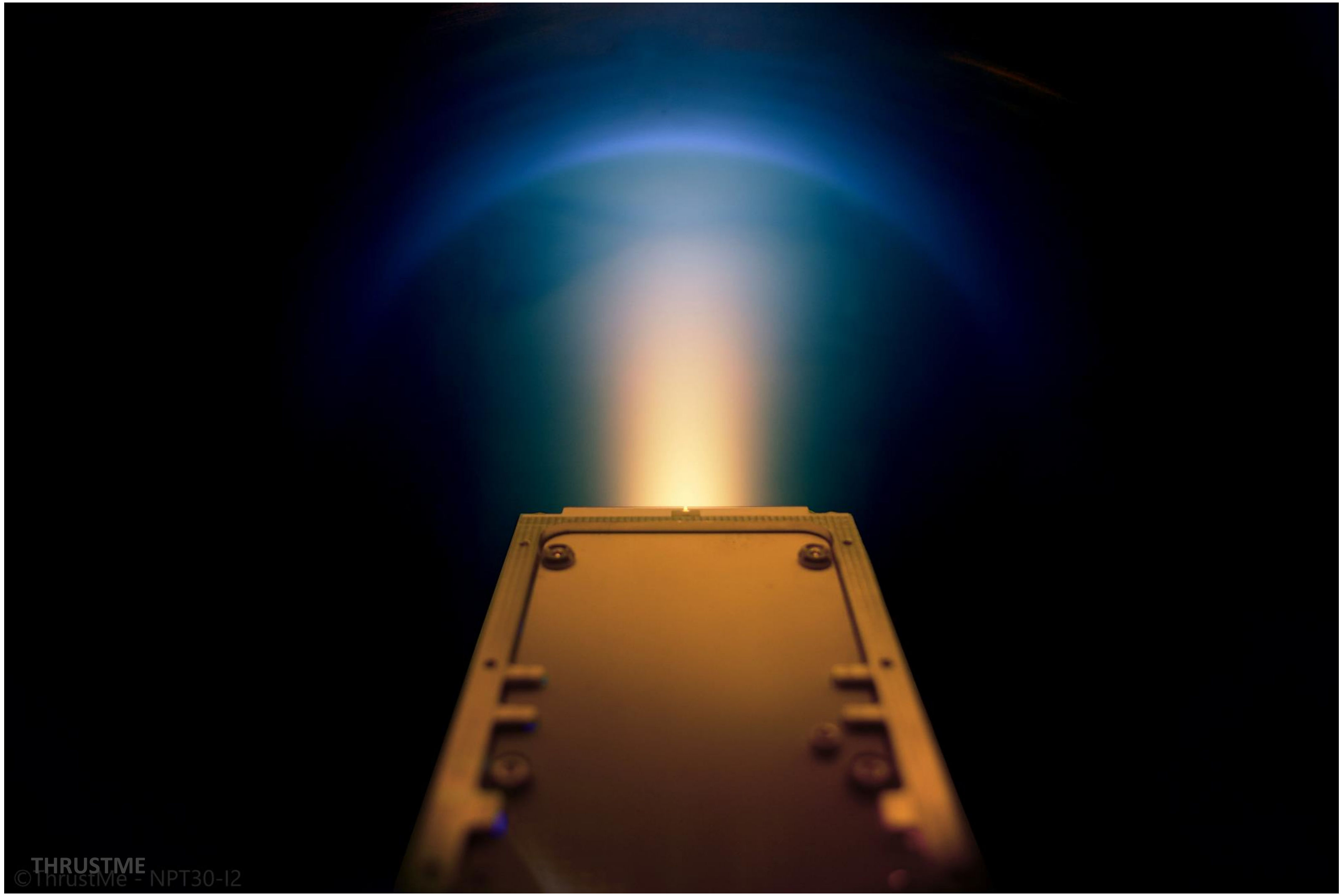
NPT30-I2: first to fly iodine ion thruster



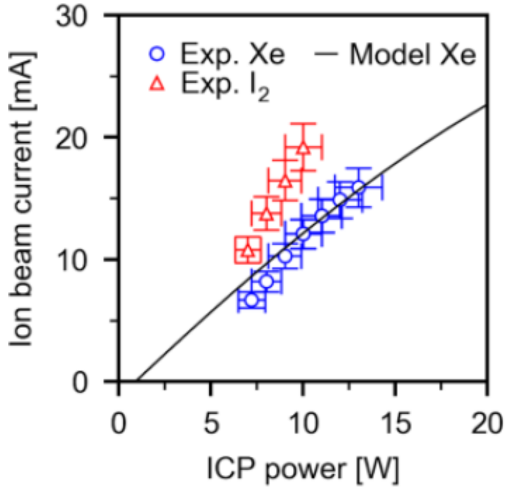
Iodine for EP: plasma simulation

Iodine specific problems

- Unknown reaction cross-sections
- Plasma-related surface properties (secondary emission, work function)
- Fundamental properties (thermal conductivity at high temperatures)
- Corrosion-related data
- General data is very scarce

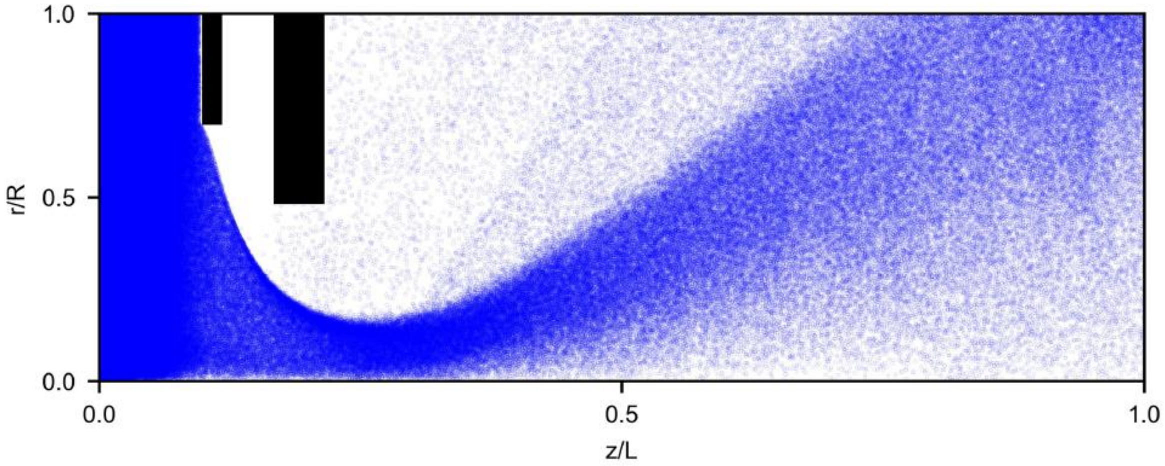
Simulation of iodine plasmas: global model coupled to the ICP transformer model

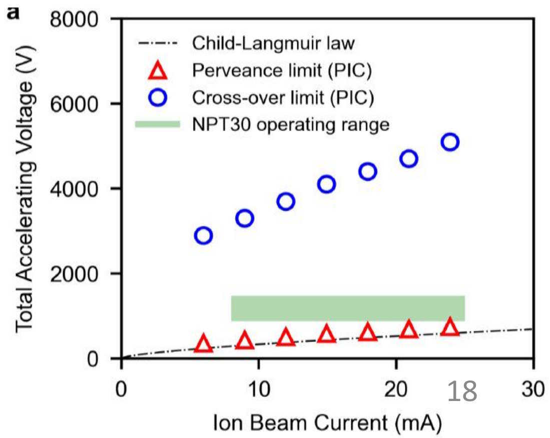
! Unreliable cross-section data: Xe simulation with empiric fits to the iodine case.



New study on I cross-sections: Atoms **2021**, 9, 103. https://doi.org/10.3390/atoms9040103

Simulation of ion acceleration: 2D PIC code





Iodine for EP: beam characterization

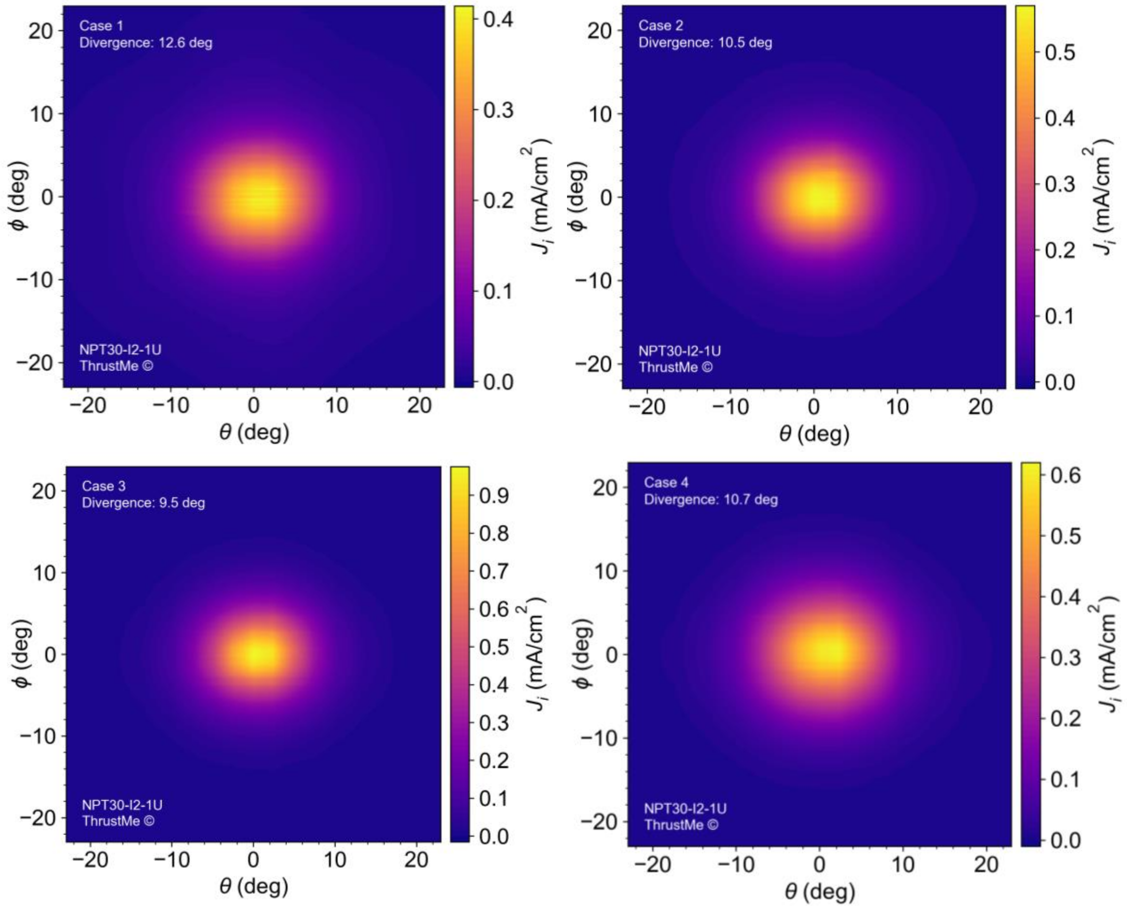
Iodine specific problems

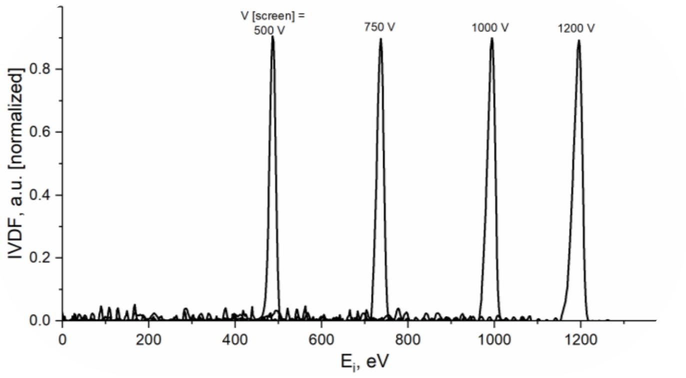
- Unknown reaction cross-sections
- Plasma-related surface properties (secondary emission, work function)
- Fundamental properties (thermal conductivity at high temperatures)
- Corrosion-related data
- General data is very scarce

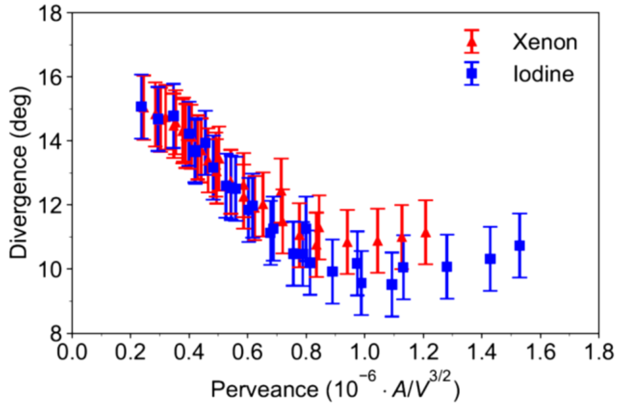
Ion beam mapping

[1]Review of Scientific Instruments, 2020; 91: 093501

Divergence half-angle: 8-15°







Iodine for EP: Thrust measurements

- Very small force, high precision balance required
- Estimation from the ion beam parameters requires precise characterization

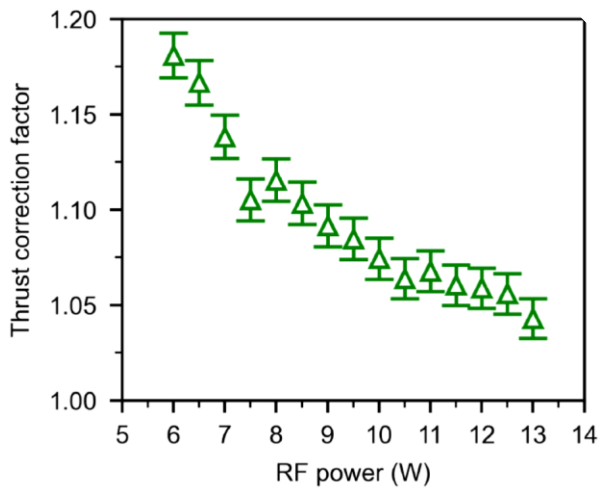
Thrust: $T = \alpha\gamma\sqrt{\frac{2M_i}{e}} I_i \sqrt{V_{acc}}$

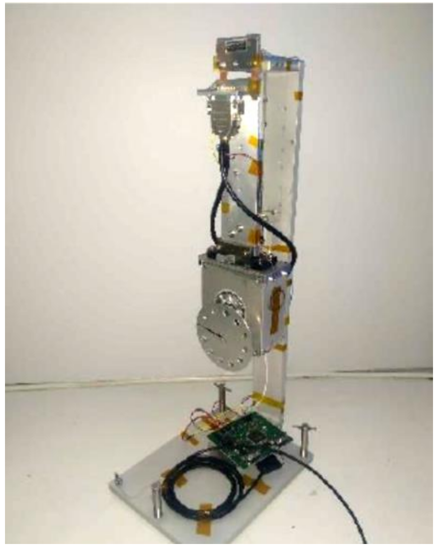
Divergence correction: $\gamma = cos\Theta_{div}$

Composition correction:

$\alpha = \beta_{I+} + \sqrt{2}\,\beta_{I_2+} + {}^{1}/_{\sqrt{2}}\,\beta_{I^{++}}$

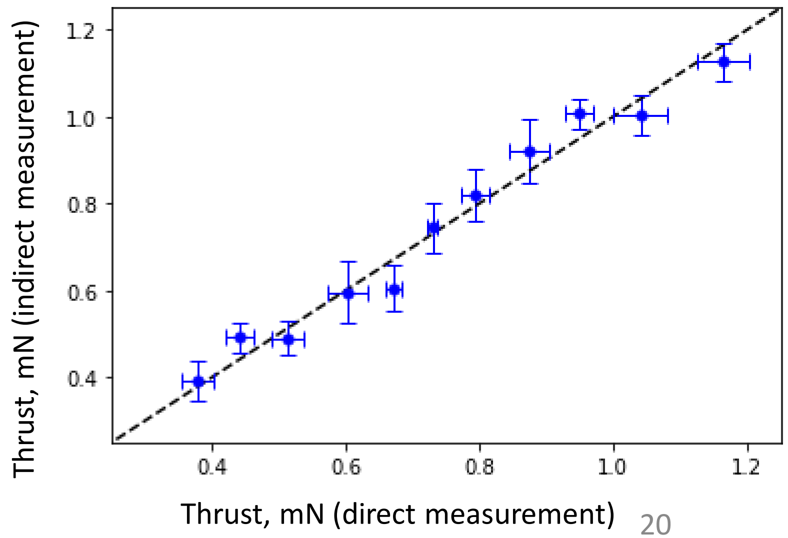
Beam composition correction:





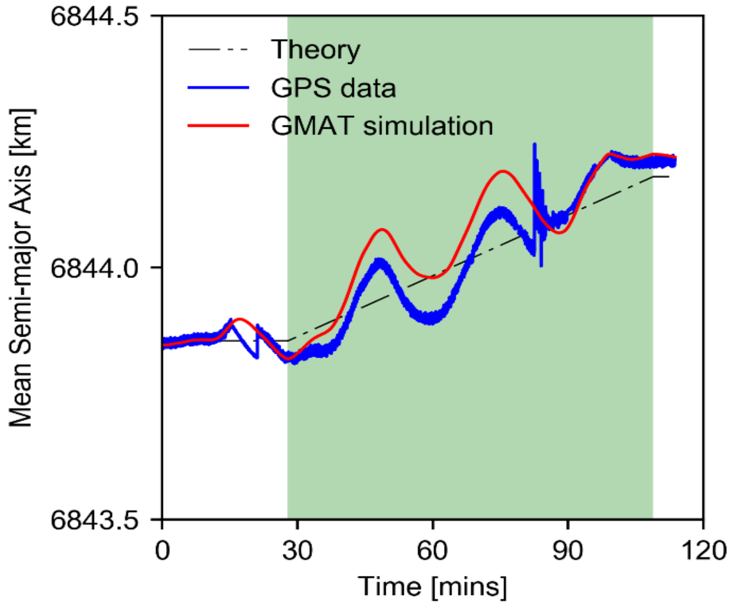
0.1 mN thrust balance

Correction coefficients applied:

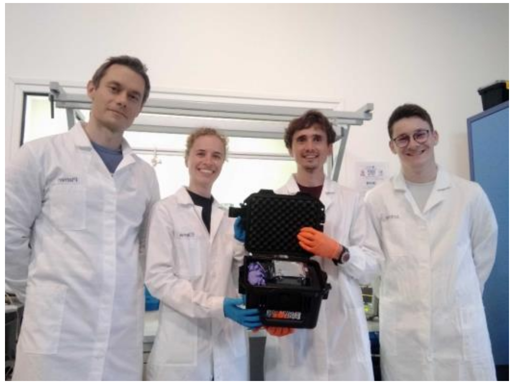


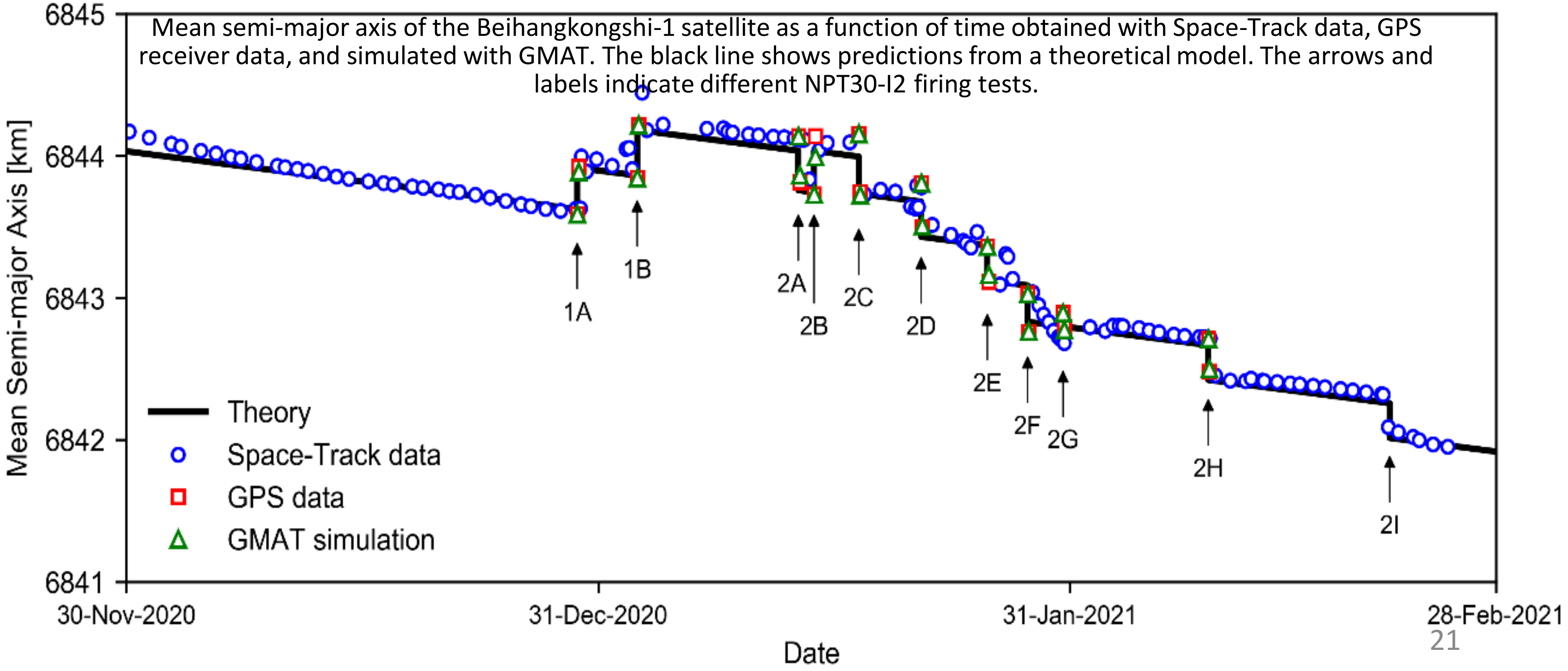
Iodine for EP: Space flight

[1]Nature, 2021, 599: 411-415



Mean semi-major axis calculated from GPS receiver data, and simulated with GMAT, as a function of time for firing test 1B. The green shaded region denotes times when the NPT30-I2 is on, and the black dash-dot line shows predictions from a theoretical model.





Mean semi-major axis of the Beihangkongshi-1 satellite as a function of time obtained with Space-Track data, GPS receiver data, and simulated with GMAT. The black line shows predictions from a theoretical model. The arrows and labels indicate different NPT30-I2 firing tests.

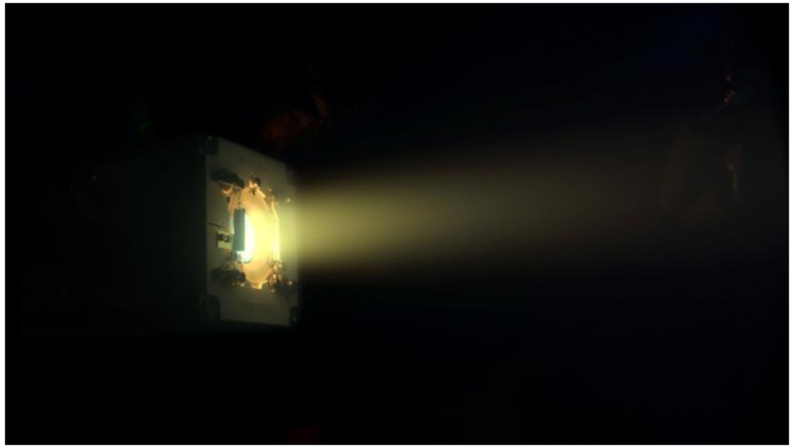
Iodine for EP: Qualification and launch

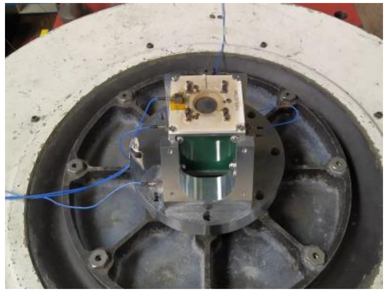
Qualification campaign

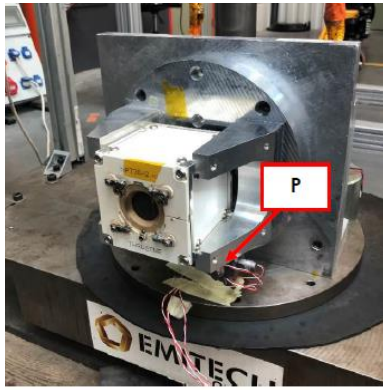
- Operational cycles
- Failure handling
- Mechanical shock
- Vibrations
- Thermal-vacuum cycling
- Ambient thermal cycling

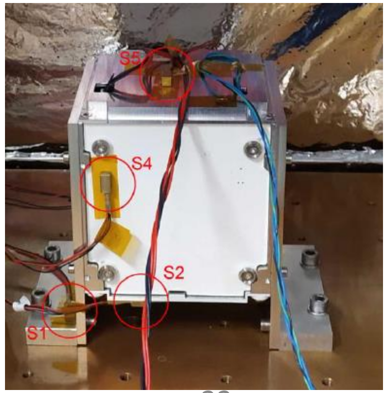
System specs
Thrust: 0.4-1.2 mN
Isp: up to 2450 s
Input power (10-36V dc): 35-65 W
Total impulse: up to 5500 Ns
Mass/Volume: 1.3 kg, 10x10x10 cm

Timeline
Development: 2016-2020
Qualifications: (04-06) 2020
Integrated to satellite: 09/2020
Launched to space: 11/2020
Testing: 2020-2021
Lifetime (on ground): 2021-2022
Mass production: 2023



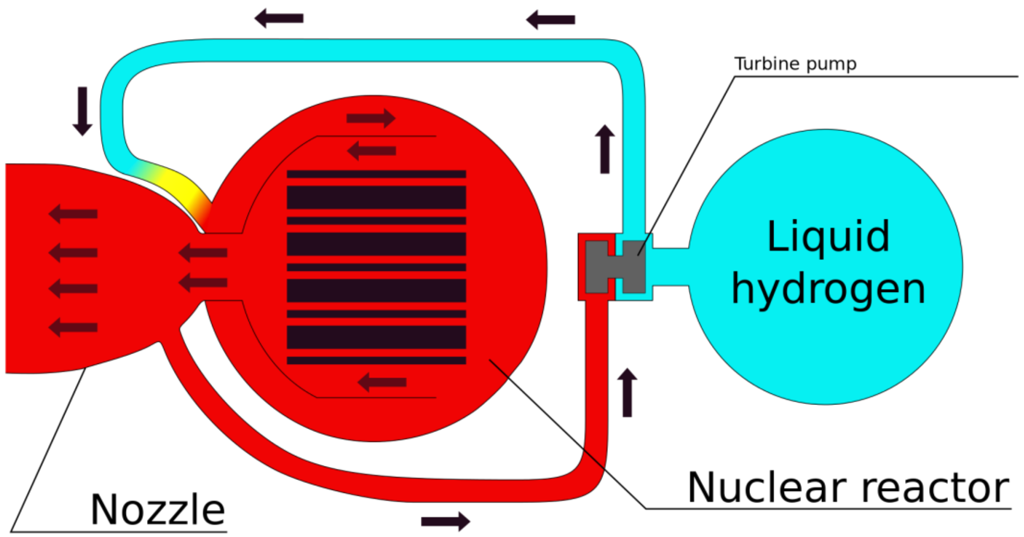






What’s next?

- Iodine for high-power Hall thrusters: sustainable satellite services for Earth
- High-power clusters powered by nuclear power: viable exploration of the solar system
- Nuclear propulsion: high speed space travel*



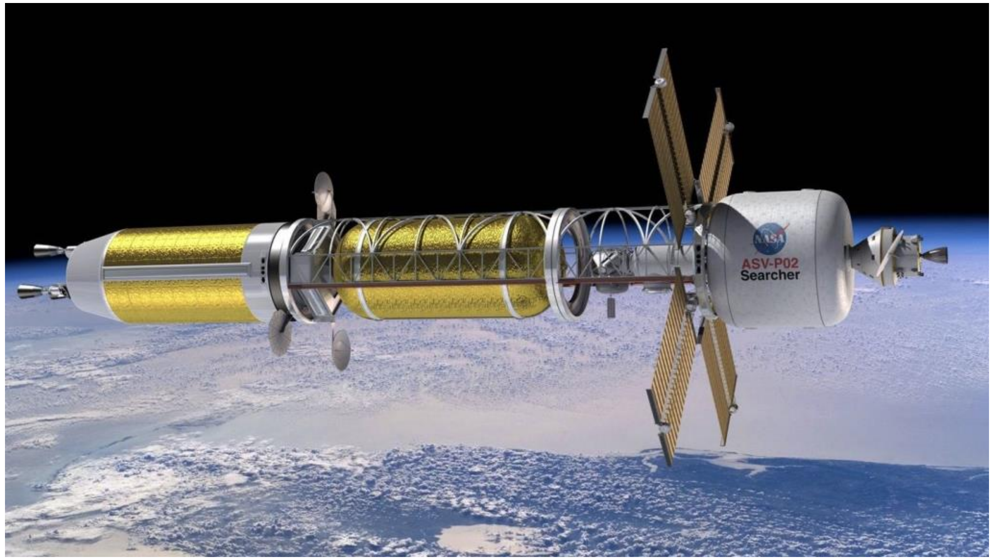


*Image credit: NASA

THRUSTME

PROPULSION TOWARDS SUSTAINABLE SPACE

Thank you for attention!

www.thrustme.fr