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EPFL Space Center eSpace

Space Propulsion ENG-510

Lecture # 6 Introduction & General Course Information

Brief update on space propulsion course

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Exercise

Exercise # 5 Description:

- Due date on 4.5.2025: Qualification Review
  - Final report (summary of all reports so far with updates on final design / configuration) with description of the Water rocket (Description of all products used, fluidical architecture, electrical architecture, mass budget, propellant budget, pressure budget, launch phases) and clear summary of verification results performed
  - Objective is to get ‘green light’ for trial launch
- Evaluation on 5.5. + 6.5.2025

Exercise

Exercise # 6 Description:

- Due date on 13.5.2025: Trial Launch
  - Everything clear?
  - Location?
  - Schedule?
  - Please make videos!
- Evaluation on Friday, 16.5.2025
- Launch event on 27.5.2025

Oral Exam

Schedule:

- Excel table is uploaded on Moodle
- Please fill out table
- Information on oral exam will be given after the lecture on May 20

Lecture

Lecture # 7 on May 20:

- Special lecture on VLEP / ABEP will be given on May 20 at 10:15 am
- Please join!
- Remaining space propulsion lecture @ 9:15 am
- Information on oral exam will be given after the lecture on May 20
- Potentially some final information on launch event will be given
- Potentially some final exercise will be given

Test Facility Visit

ERT Test Facility Visit (including firing demonstration):

- Test facility visit is proposed for Wednesday, May 28 starting between 9 to 10 am
- Who is interested to join?
- Agenda
  - Test facility tour
  - Hot firing test (TBC)
- Excel is uploaded on Moodle
- Please fill out table

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Lecture # 6 Chemical Propulsion Systems

Brief overview on all space propulsion systems

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Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- And thruster for sure…

10N RCT

200N RCT

400N LAE

Which Liquid Bi-propellant Propulsion Systems exist?

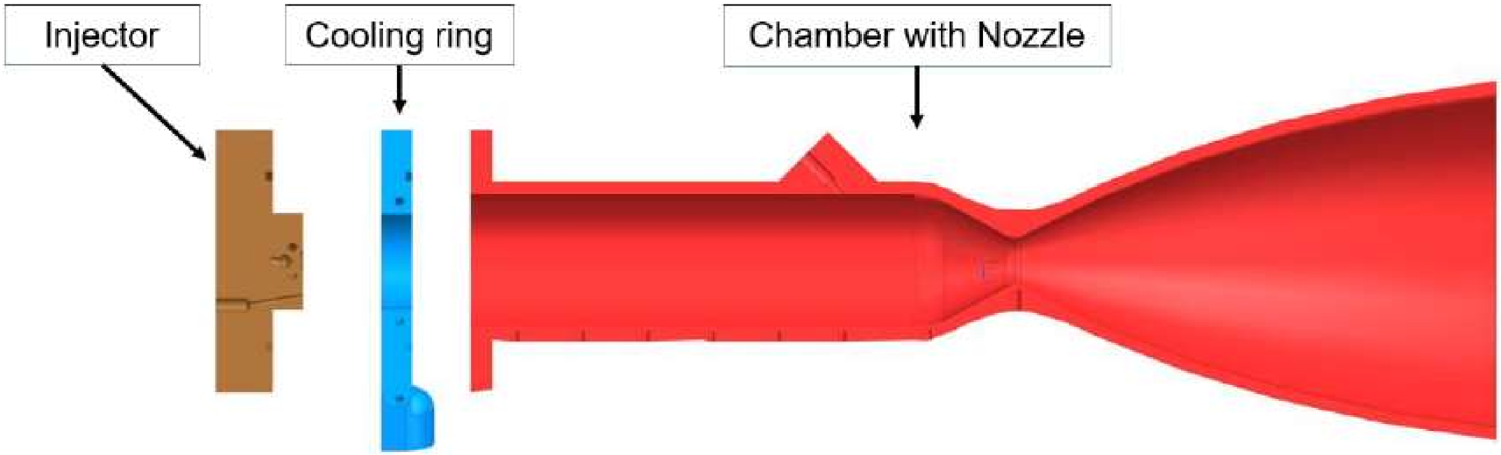
Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants (e.g. spin, showerhead, …)
  - Cooling of engine
  - Trimming of engine
  - Ignition of propellants

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines

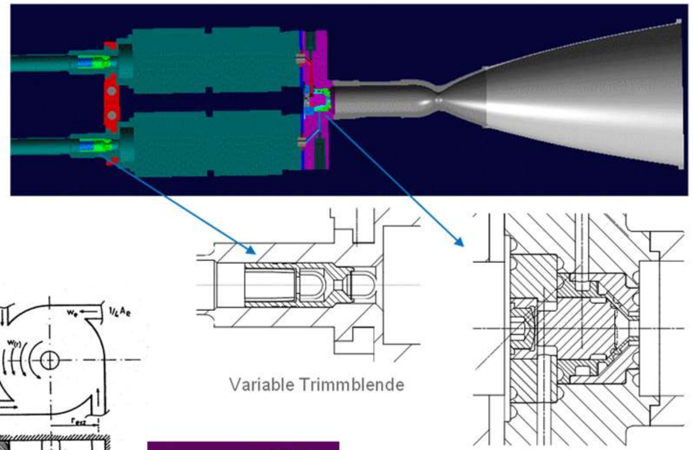


Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

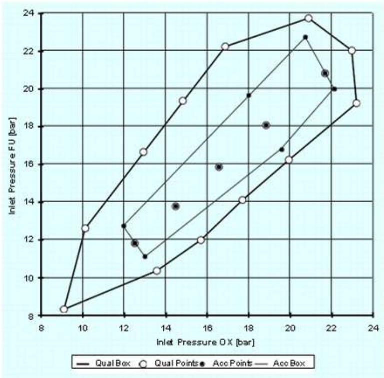
- Bi-propellant thrusters / engines
  - Trimming / calibration of engine
    - Orifice (passive)
    - Throttling valve / injector (active)

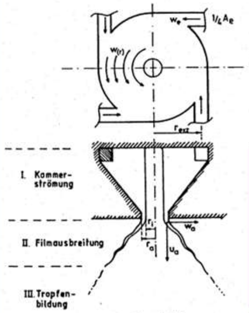
22N Zweistoff-Triebwerk



Variable Trimmblende

Doppeldrall-Einspritzsystem



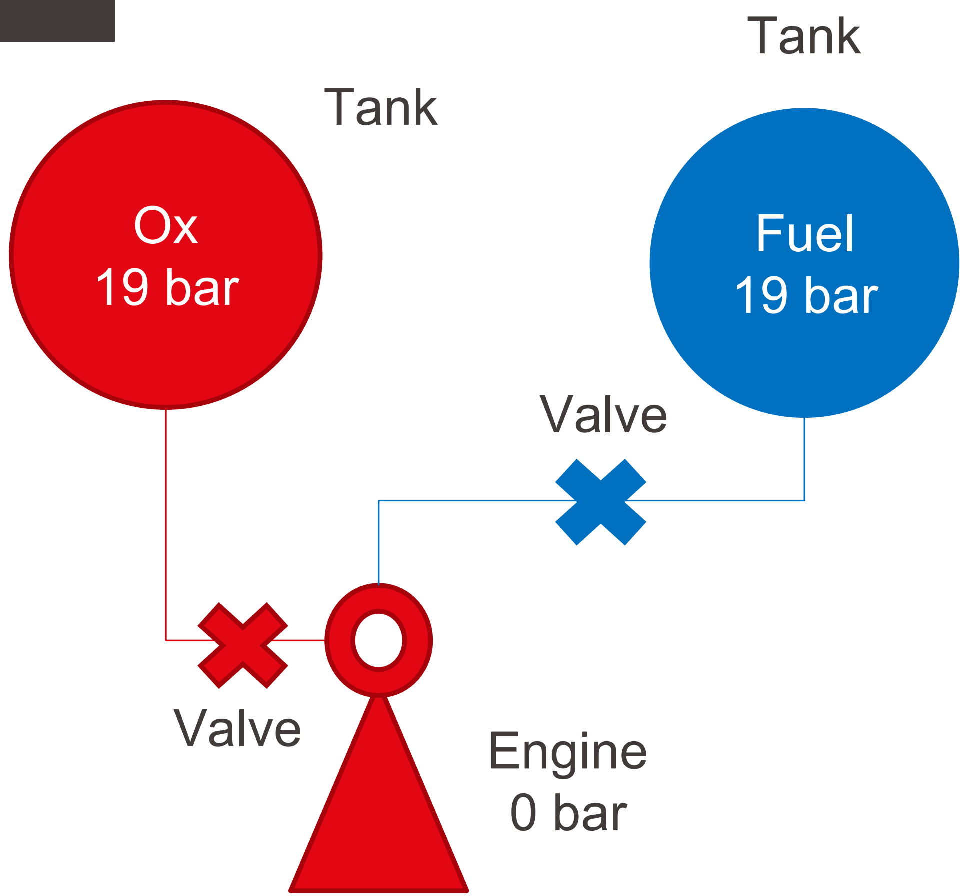


Funktionsmechanismen bei Dralleinspritzdüsen

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines



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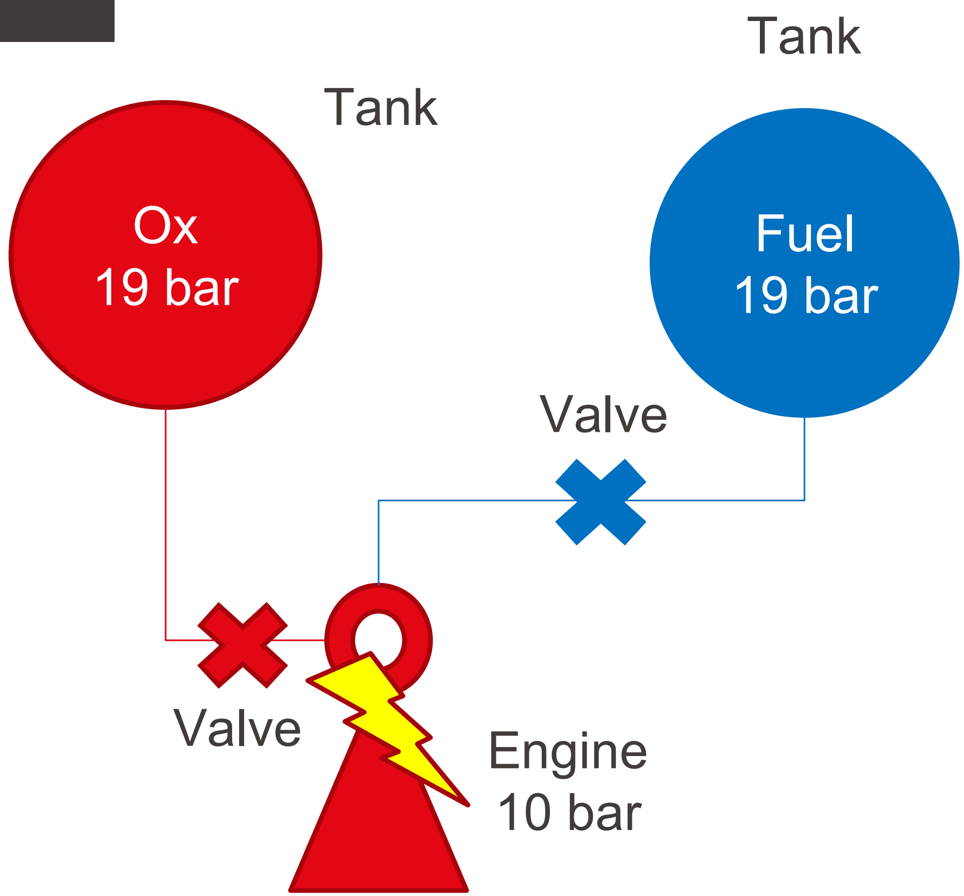
Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Pressure losses need to be adjusted that mass flow rates respect optimal mixture ratio for selected propellants (e.g. MR = 1.65 for MON oxidizer over MMH fuel)



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Radiative cooling
    - Capacitive cooling (Phase change material)
    - Film cooling
    - Vortex cooling
    - Regenerative cooling
    - Ablative cooling
    - Transpiration cooling

Which Liquid Bi-propellant Propulsion Systems exist?

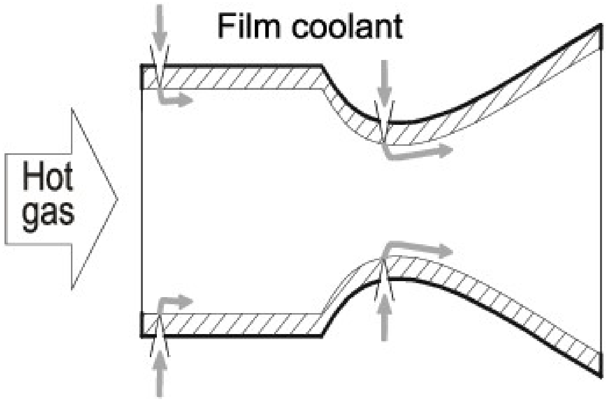
Propulsion Equipment:

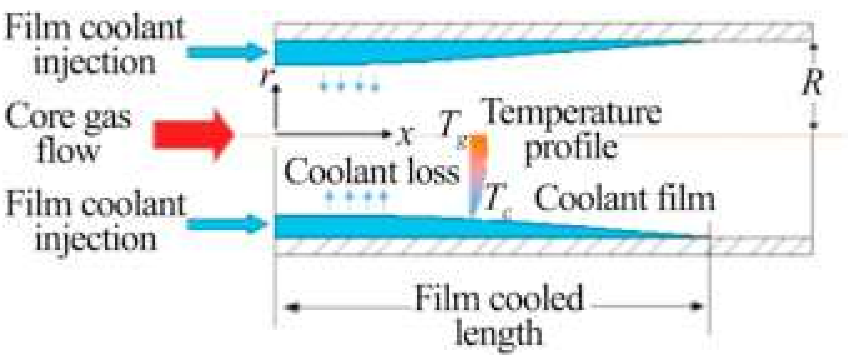
- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Radiative cooling – Heat from combustion is radiated to environment (i.e. deep space)
      Radiation cooling is always given (during ground testing, in-space firing, …) similar to conduction
      Magnitude of radiation cooling is to be assessed
    - Capacitive cooling (Phase change material) – Heat from combustion is transferred to container with phase change material which stores heat for certain time by changing phase from solid to liquid for example
      Capacitive cooling is limited in performance
      In long term heat is then further transported by conduction and / or radiation

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Film cooling

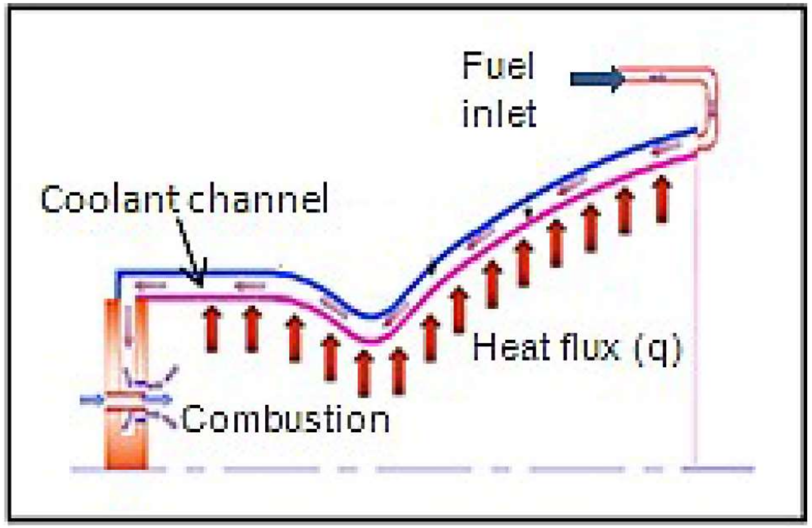




Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Regenerative cooling

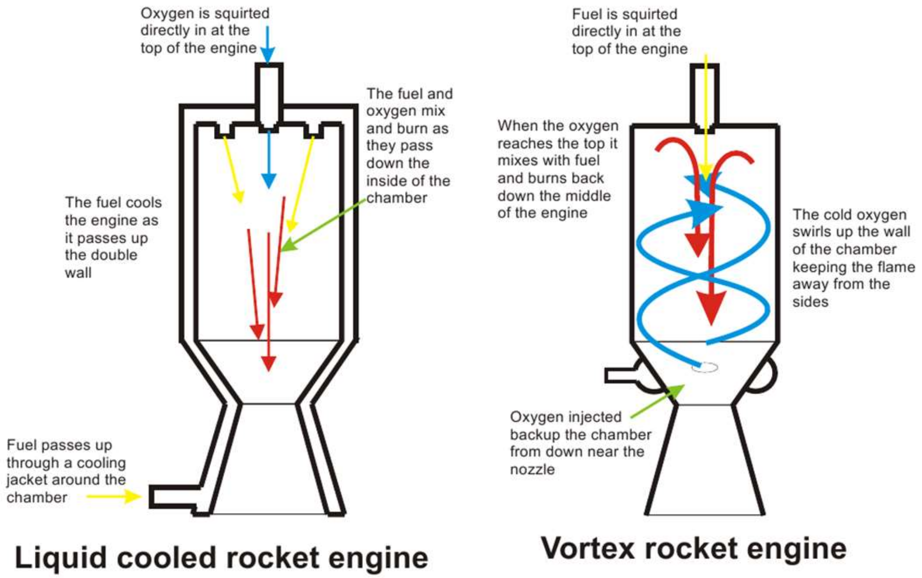


Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Vortex cooling

Which Liquid Bi-propellant Propulsion Systems exist?



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Ablative cooling – Heat from combustion degrades / ablates combustion chamber material over time and ablated material is then exhausted through nozzle extension
    - Transpiration cooling – Combustion chamber is made out of porous material and cooling liquid is injected into the combustion chamber through the porous material so that the complete inner wall of the combustion chamber is covered by cooling liquid which is then immediately evaporated by the hot combustion chamber and such cooling down the wall material (similar to human boy with skin + sweat)

Which Liquid Bi-propellant Propulsion Systems exist?

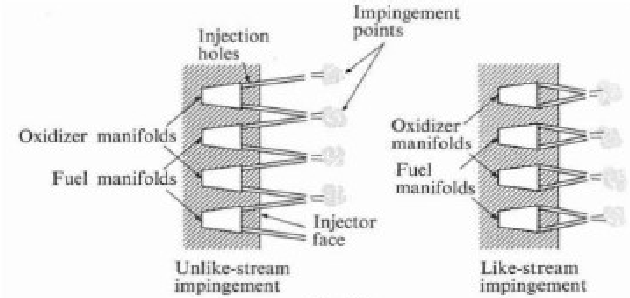
Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants (e.g. spin, showerhead, …): Objective is to achieve good atomization, low accumulation and such no hard start
    - Impingement
    - Showerhead
    - Concentric tube (with or without swirl)
    - Splash plate

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants
    - Impingement



Which Liquid Bi-propellant Propulsion Systems exist?

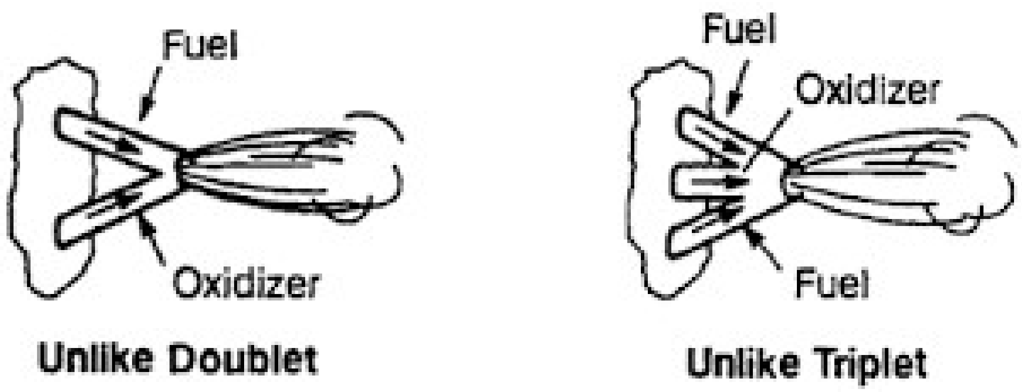
Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants
    - Impingement - Like impinging doublets/triplets… : two, three or more spray of the same propellant are directed to an impinging point. Therefore the difference with an unlike impinging comes from the propellant directed, for a like impinging it is the same (only the Ox or only the fuel) while for an unlike impinging, fuel and oxidizer are directed to a common point

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

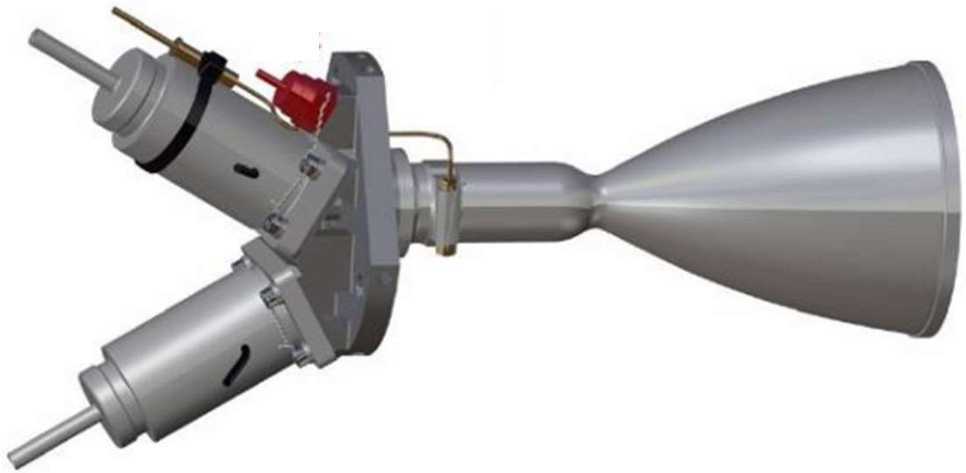
- Bi-propellant thrusters / engines
  - Injection method for propellants



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

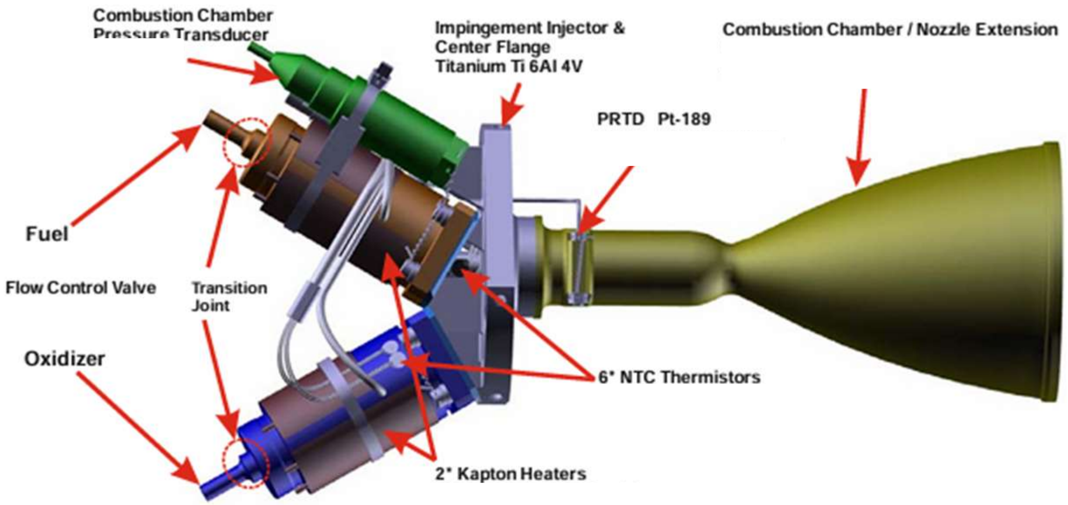
- Bi-propellant thrusters / engines
  - Injection method for propellants
    - Impingement



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants
    - Impingement



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants
    - Impingement
      In this example the injector is comprised of fuel manifold, oxidizer manifold, 4 unlike impinging pairs and 8 fuel film cooling holes
      The fuel enters the injector from a central inlet into a central distribution where 4 injector holes and 8 film cooling holes are fed
      The oxidizer enters from the side into a channel manifold that feeds the 4 injector holes

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L6 – Propulsion Systems

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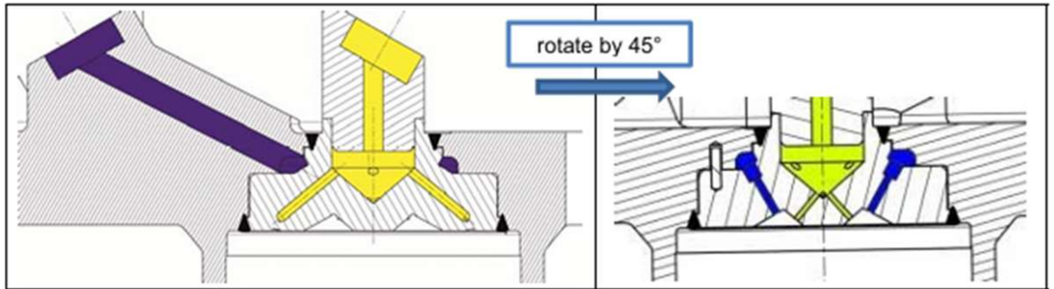
Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants
    - Impingement



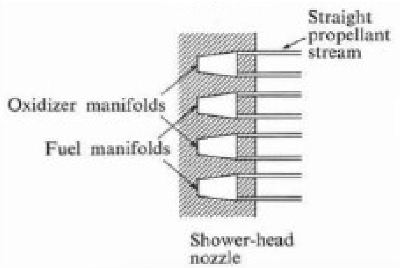
Injector cross section showing Oxidizer (blue) and Fuel (yellow) main and cooling hole feed	Injector cross section showing Oxidizer (blue) and Fuel (yellow) impingement channels.

L6 – Propulsion Systems

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants
    - Showerhead



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Which Liquid Bi-propellant Propulsion Systems exist?

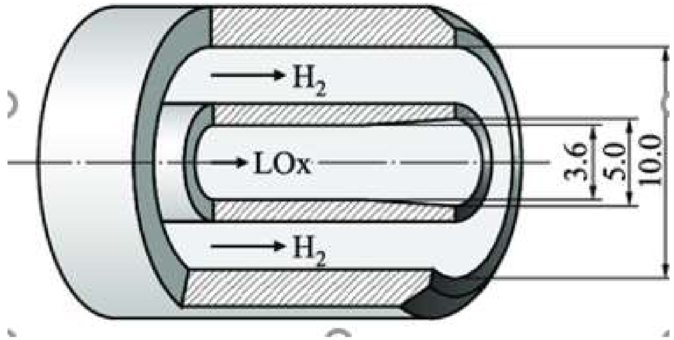
Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants
    - Showerhead - (parallel jet of propellants): not used for propellant injection into the CC because of the low effectiveness of the atomization, therefore they require a large CC. It is commonly used for cooling injection

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

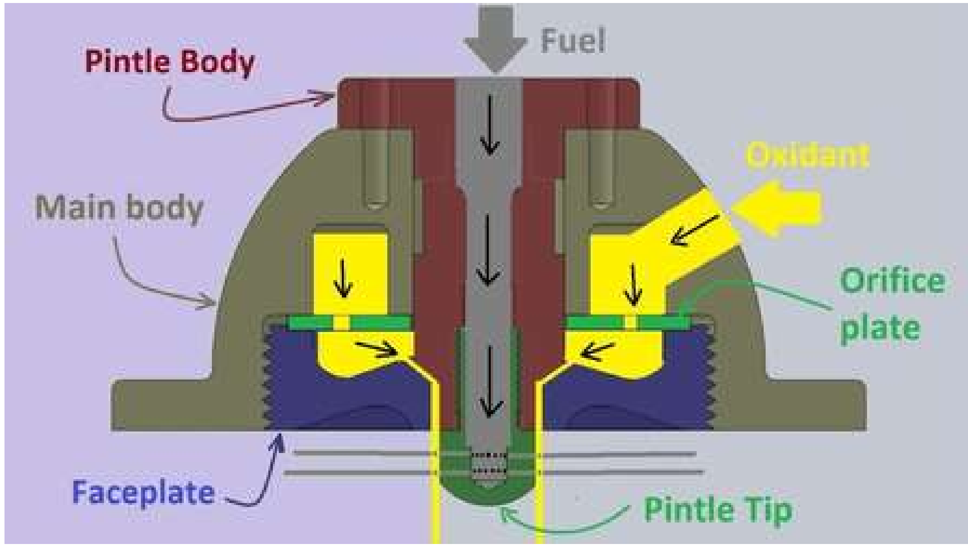
- Bi-propellant thrusters / engines
  - Injection method for propellants (e.g. spin, showerhead, …)
    - Concentric tube (with or without swirl) or coaxial tube - a central liquid oxidizer stream is injected surrounded by the gaseous fuel. This design provides a stable injection and high performances



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

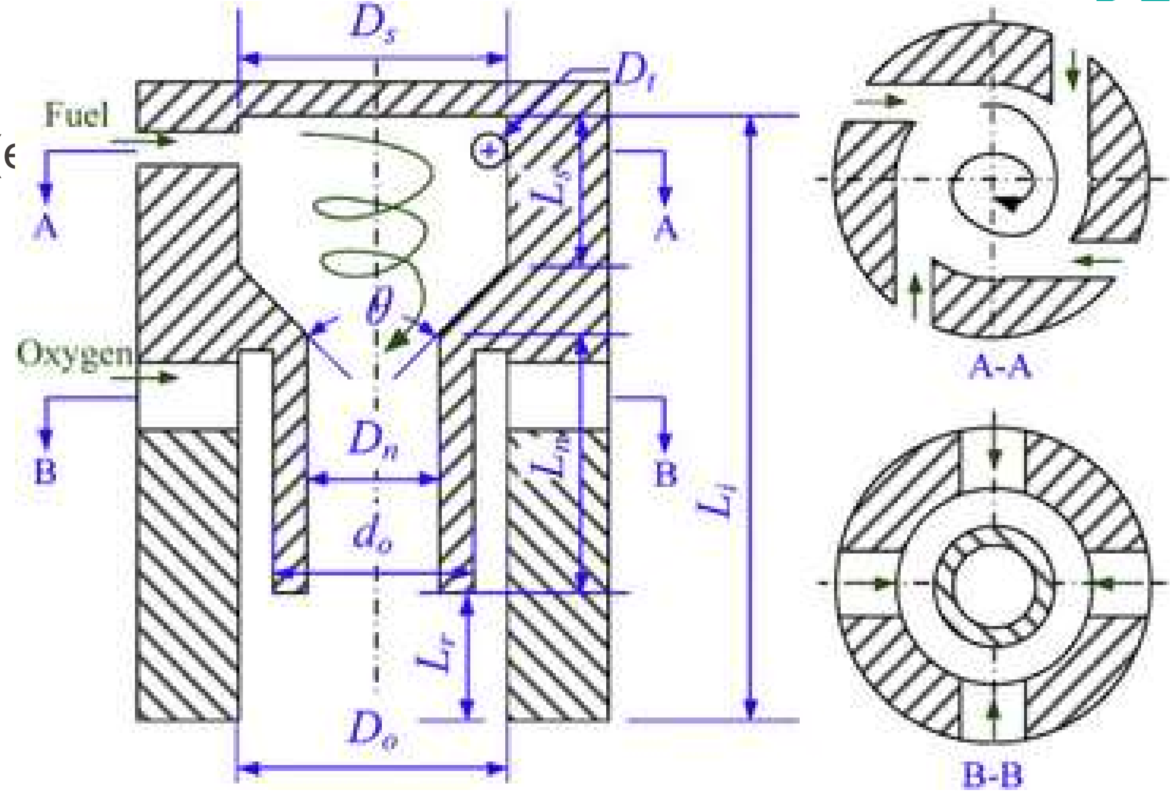
- Bi-propellant thrusters / engines
  - Injection method for propellants (e.g. spin, showerhead, …)
    - Concentric tube (with or without swirl) or coaxial tube – Pintle injector



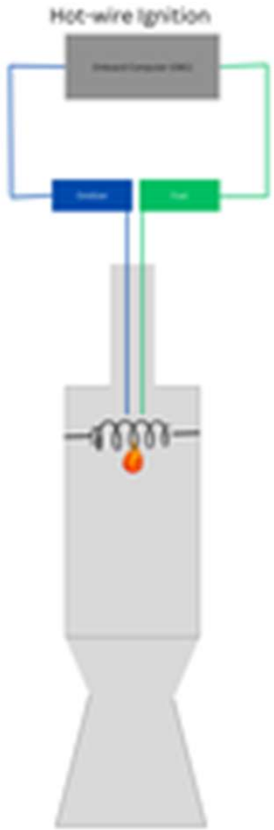
Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants (e
    - Concentric tube (with or without swirl) or coaxial tube – Swirl injector



Which Liquid Bi-propellant Propulsion Systems exist?

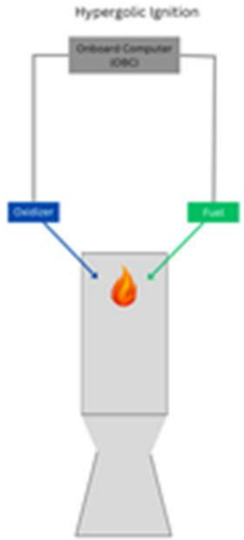


ulsion Equipment:

-propellant thrusters / engines

Ignition of propellants

- Hypergolic ignition – Ignition upon contact
- Catalytic decomposition – Decomposition upon contact with reactive material
- Thermal decomposition – Decomposition upon contact with hot surface
- …



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Which Liquid Bi-propellant Propulsion Systems exist?

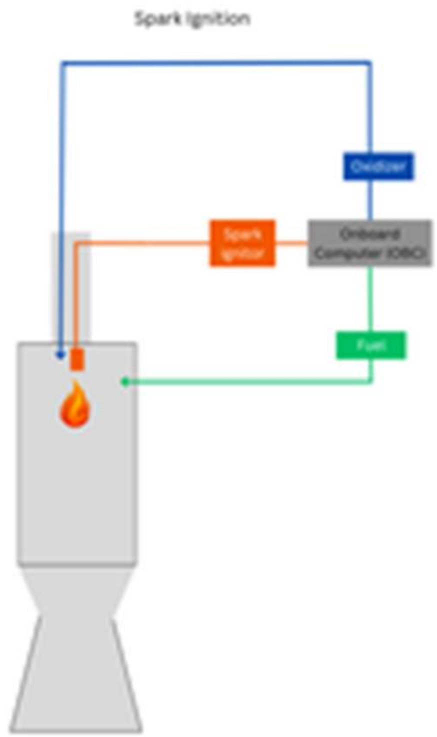
Propulsion Equipment :

- Bi-propellant thrusters / engines
  - Ignition of propellants
    - Spark plug
    - Glow plug
    - Laser ignitor
    - Resonance acoustic ignition
    - …
    - Torch ignitor (Different propellant or same propellants with smaller amount)

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment :

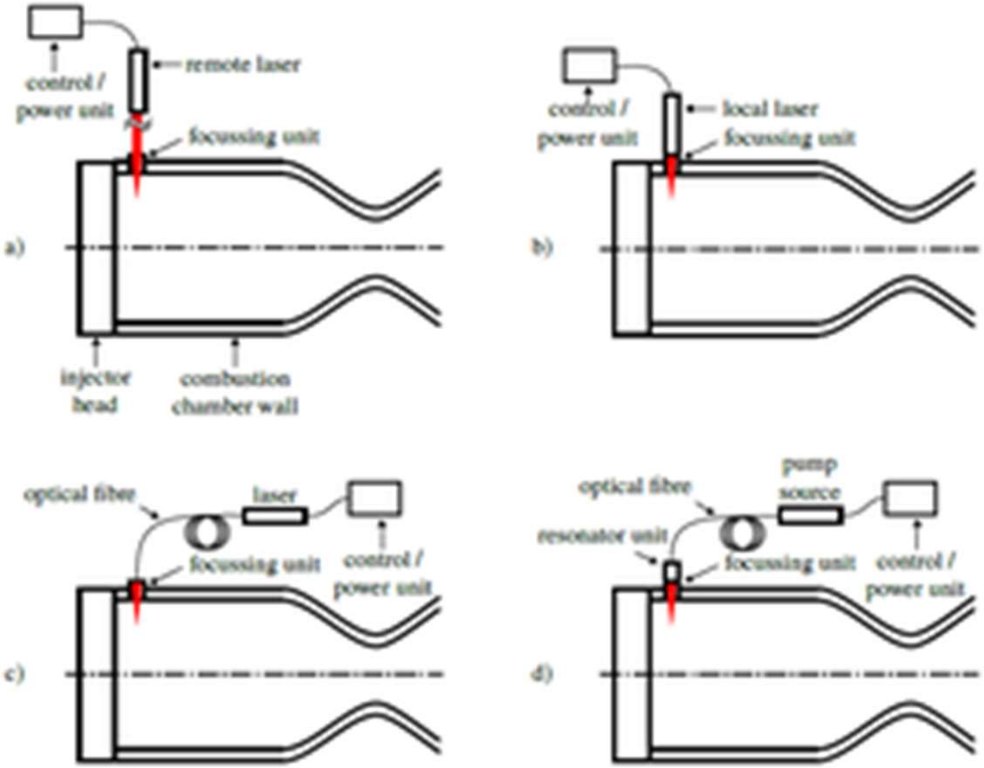
- Bi-propellant thrusters / engines
  - Ignition of propellants
    - Spark plug
    - Glow plug (similar to cars)



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment :

- Bi-propellant thrusters / e
  - Ignition of propellants
    - Laser ignitor

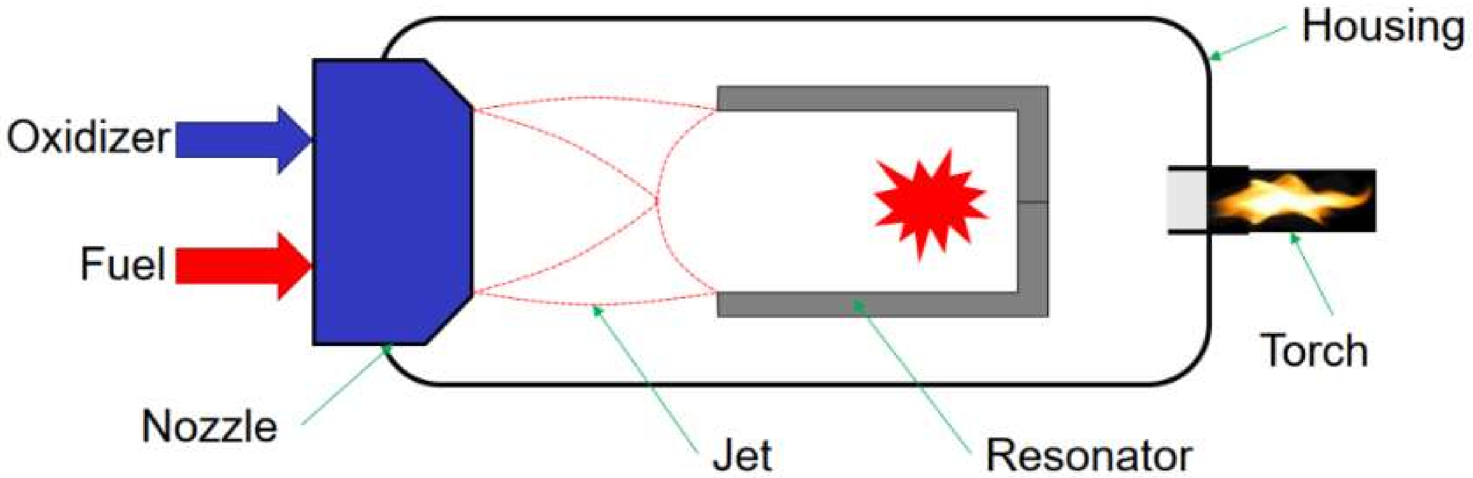


Laser system architectures for radial integration of the focusing unit: a) remote laser system with free beam propagation, b) local laser, c) central laser, d) central pump source

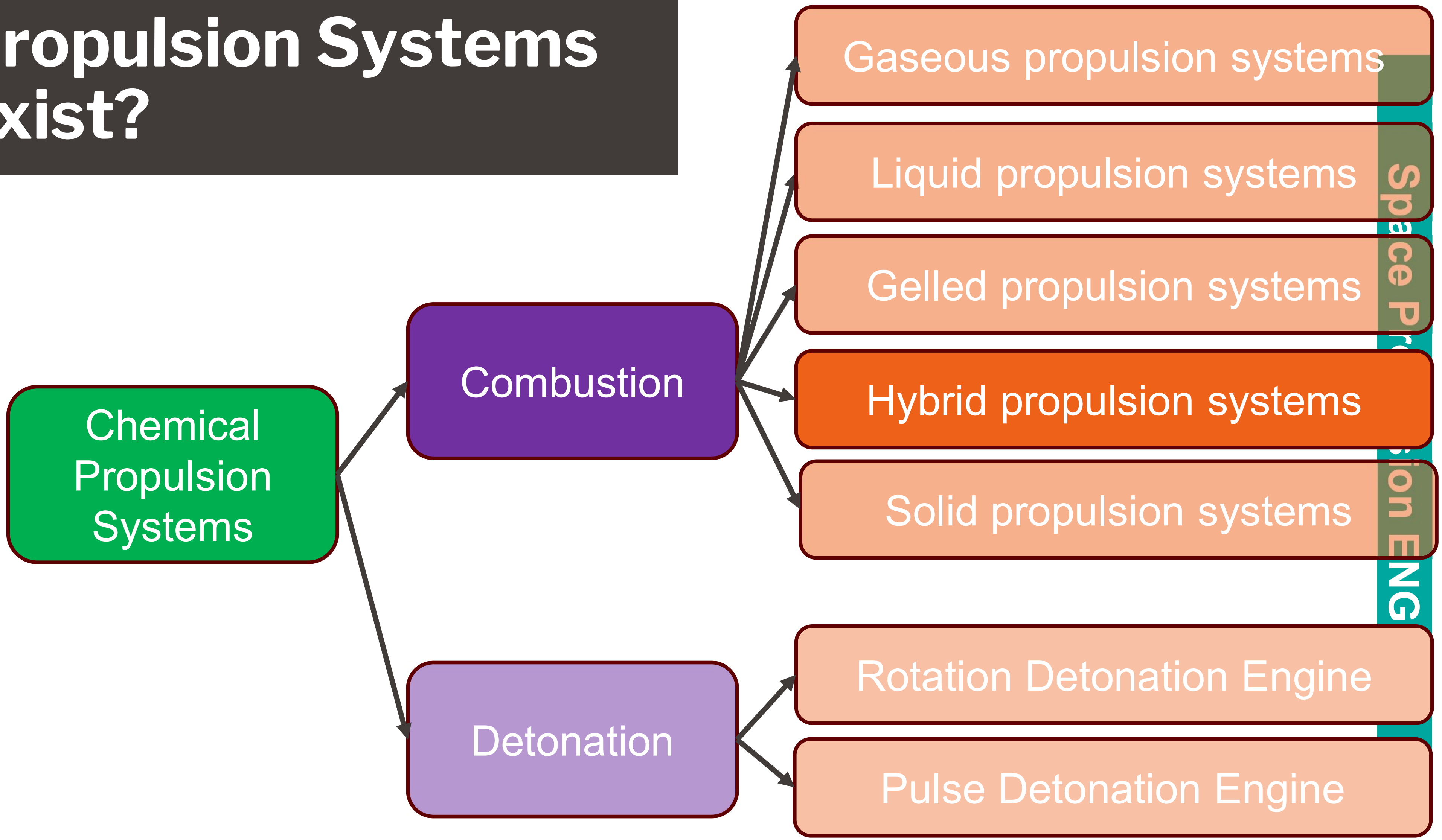
Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment :

- Bi-propellant thrusters / engines
  - Ignition of propellants
    - Resonance acoustic ignition



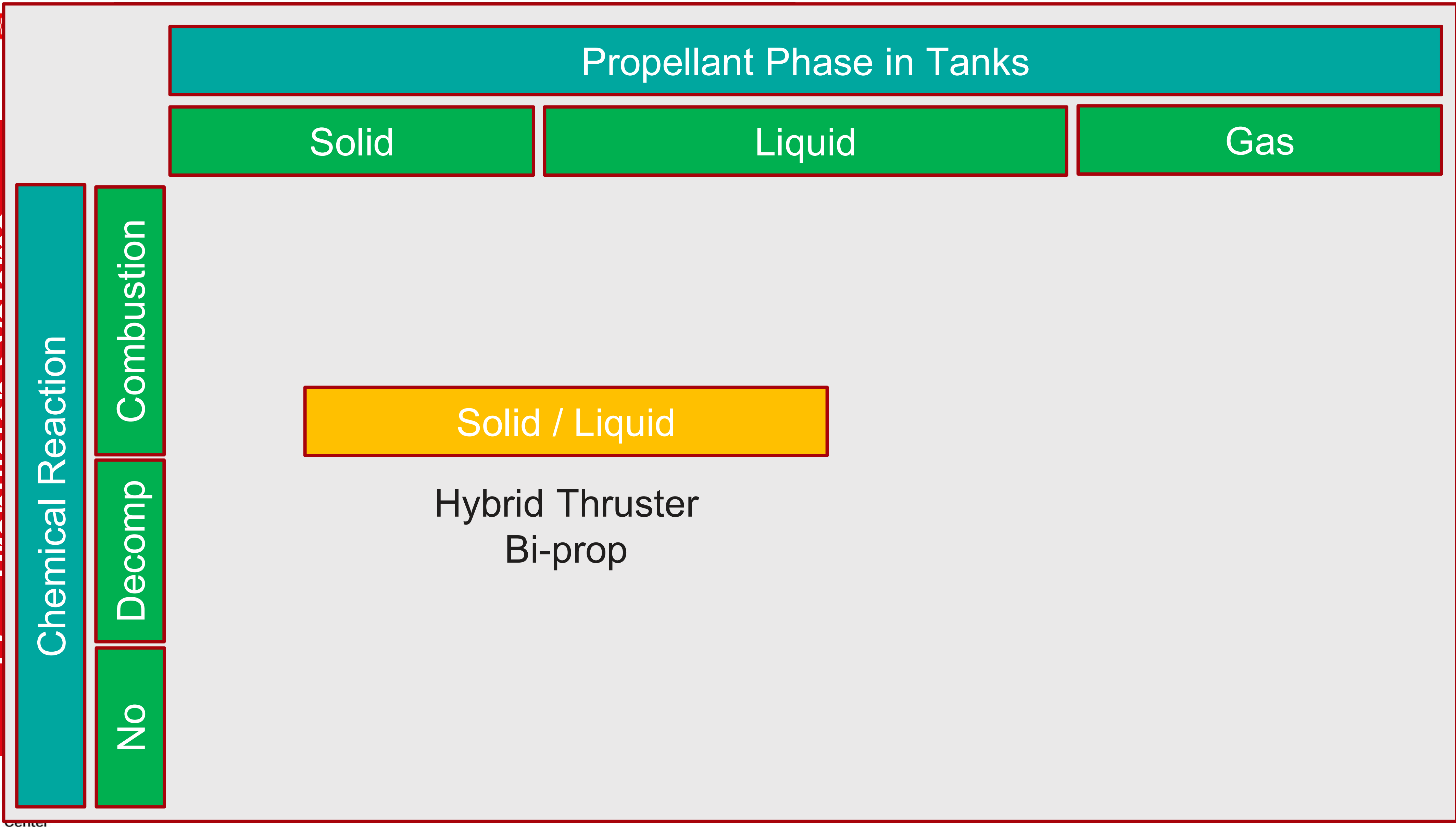
Which Chemical Propulsion Systems exist?



Which Hybrid Propulsion Systems exist?

Chemical Propulsion Systems:

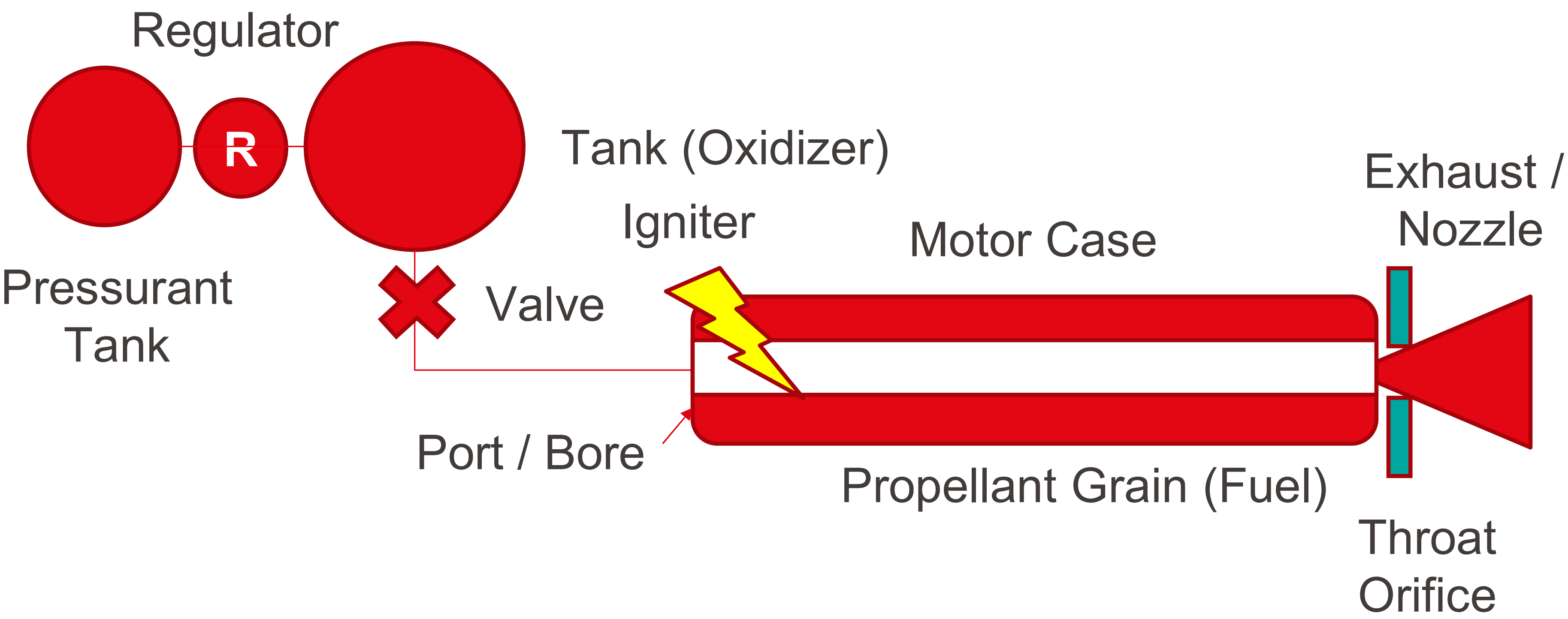
- Gaseous propulsion systems
- Liquid propulsion systems
- Gelled propulsion systems
- Solid propulsion systems
- **Hybrid (liquid / solid) propulsion systems**



Propellant Phase in Tanks
Solid
Liquid
Gas
Chemical Reaction
Combustion
Decomp
No
Solid / Liquid
Hybrid Thruster
Bi-prop

Which Hybrid Propulsion Systems exist?

Architecture for Hybrid (Solid / Liquid) Propulsion Systems:



Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Pressurant Tank stores pressurant gas (e.g. Helium or Nitrogen), maintains propellant tank pressure
- Pressure Regulator reduces pressurant pressure to desired propellant tank pressure level (@ constant level)
- Propellant Tank stores liquid oxidizer (or gaseous oxidizer)
- Flow valve controls propellant flow (on / off), could provide throttling
- Motor case contains combustion pressure
- Ports or Bores determine regression rate (number and shape can vary)
- Nozzle allows exhaust products to expand into ambient

Which Hybrid Propulsion Systems exist?

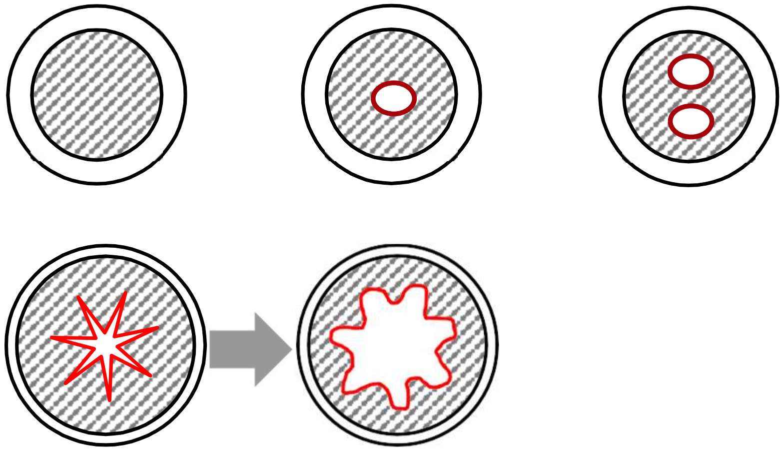
Hybrid Propulsion Systems:

- Hybrid propulsion systems stores propellant in 2 different states – liquid and solid
- In a typical hybrid, the fuel is a solid propellant and the oxidizer is a liquid propellant
- However it is also possible to use «reverse hybrids», solid oxidizers with liquid fuels

Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Shape of Ports / Bores



- Shape and number can vary
- Interesting is constant regression rate (similar to solid propulsion systems)

Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Advantages
  - Simple
  - High thrust
  - Thrust can be adapted (by terms of port shape and number - surface)
  - Thrust modulation (throttling), thrust termination and re-ignition are possible (by terms of oxidizer flow control)
  - Solid fuel grain eases the use of metallic additives which can lead to propulsion systems featuring greater specific impulse than LH2 / LOX
  - Even in case of failure, the propellants cannot be mixed to undergo violent explosion

Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Advantages compared with liquid propulsion systems
  - Mechanically simpler – requires only a single liquid propellant resulting in less plumbing, fewer valves, and simpler operations.
  - Denser fuel – fuels in the solid phase generally have higher density than those in the liquid phase, reducing overall system volume.
  - Metal additives – reactive metals such as Aluminum, magnesium, lithium or beryllium can be easily included in the fuel grain increasing specific impulse, density or both
  - Combustion instabilities – Hybrid rockets do not typically exhibit high frequency combustion instabilities like liquid rockets due to the solid fuel grain breaking up acoustic waves that would reflect in an open liquid engine combustion chamber

Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Advantages compared with liquid propulsion systems
  - Propellant pressurization – One of the most difficult to design portions of a liquid rocket system are the turbopumps. Turbopump design is complex as it has to precisely and efficiently pump and keep separated two fluids of different properties in precise ratios at very high volumetric flow rates, often cryogenic temperatures, and highly volatile chemicals while combusting those same fluids in order to power itself
  - Cooling – Liquid rockets often depend on one of the propellants, typically the fuel, to cool the combustion chamber and nozzle due to the very high heat fluxes and vulnerability of the metal walls to oxidation and stress cracking. Hybrid rockets have combustion chambers that are lined with the solid propellant which shields it from the product gases. Their nozzles are often graphite or coated in ablative materials

Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Advantages compared with solid propulsion systems
  - Higher theoretical specific impulse – Possible due to limits of known solid oxidizers compared to often used liquid oxidizers
  - Less explosion hazard – Propellant grain is more tolerant of processing errors such as cracks since the burn rate is dependent on oxidizer mass flux rate. Propellant grain cannot be ignited by stray electrical charge and is very insensitive to auto-igniting due to heat. Hybrid rocket motors can be transported to the launch site with the oxidizer and fuel stored separately, improving safety

Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Advantages compared with solid propulsion systems
  - Fewer handling and storage issues – Ingredients in solid rockets are often incompatible chemically and thermally. Repeated changes in temperature can cause distortion of the grain
  - More controllable – Stop / restart and throttling are all easily incorporated into most designs. Solid rockets rarely can be shut down easily and almost never have throttling or restart capabilities

Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Dis-advantages
  - Oxidizer-to-fuel ratio shift (mixture ratio shift) – with a constant oxidizer flow-rate, the ratio of fuel production rate to oxidizer flow rate will change as a grain regresses. This leads to off-peak operation from a chemical performance point of view. However, for a well-designed hybrid, O/F shift has a very small impact on performance because specific impulse is insensitive to O/F shift near the peak
  - Poor regression characteristics often drive multi-port fuel grains. Multi-port fuel grains have poor volumetric efficiency and, often, structural deficiencies
  - Compared with liquid-based propulsion, re-fueling a partially or totally depleted hybrid rocket would present significant challenges

Which Hybrid Propulsion Systems exist?

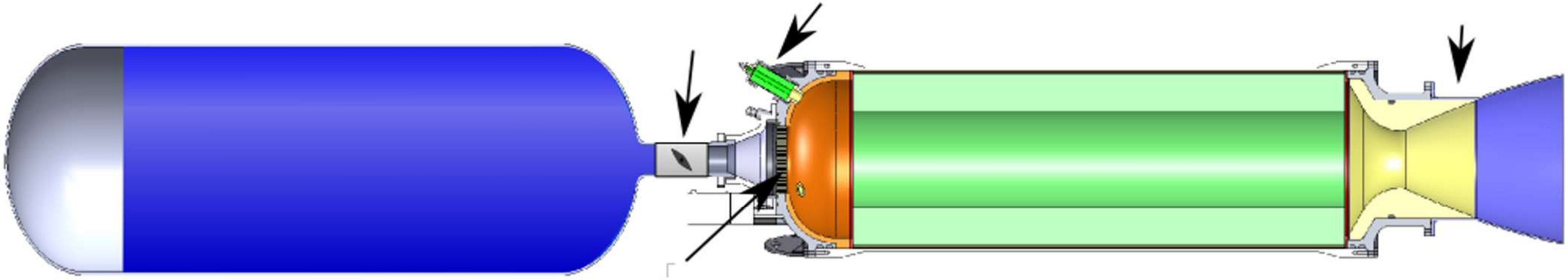
Hybrid Propulsion Systems:

- Example: EPFL rocket team hybrid rocket

Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Example: Hybrid propulsion system



Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

- Example: Autophage rocket from Alpha Impulsion
  - Autophage propulsion is an overhaul of the classical space launcher architecture, using fuel as structure
  - As the rocket ascends, the engine gradually burns the rocket's body, starting from the bottom and moving upwards, getting shorter during the flight like an upside-down candle
  - The vehicle consumes itself, until only the engine and the payload remain

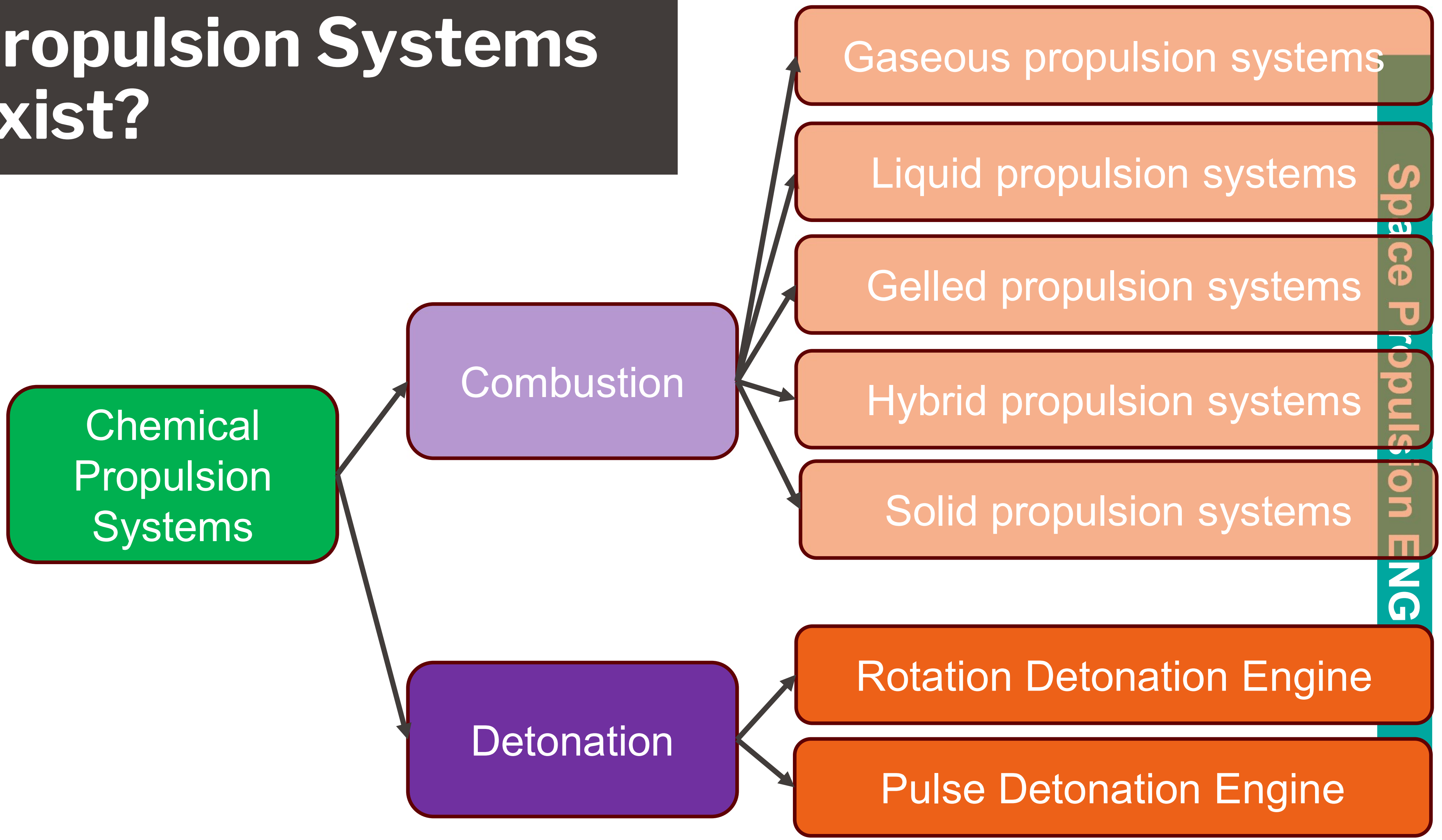
Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

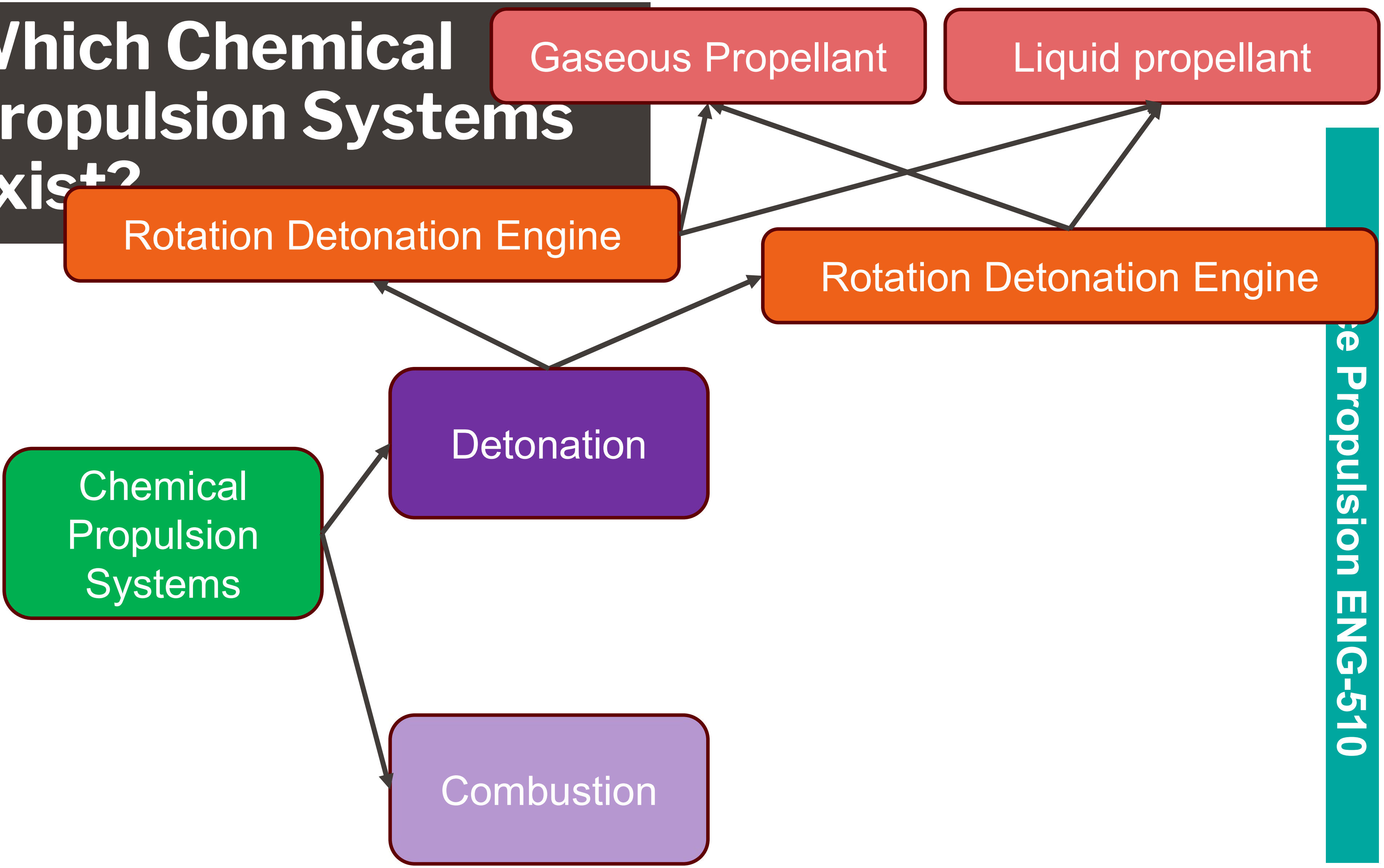
- Example: Autophage rocket from Alpha Impulsion

Height	25 m
Diameter	1 m
Propulsion	HDPE – LOX
Payload	1000kg

Which Chemical Propulsion Systems exist?



Which Chemical Propulsion Systems exist?



Which Chemical Propulsion Systems exist?

Rotation Detonation Engine

- Principle
  - The basic concept of an RDE is a detonation wave that travels around a circular channel (annulus)
  - Fuel and oxidizer are injected into the channel, normally through small holes or slits
  - A detonation is initiated in the fuel / oxidizer mixture by some form of igniter
  - After the engine is started, the detonations are self-sustaining
  - One detonation ignites the fuel / oxidizer mixture, which releases the energy necessary to sustain the detonation
  - The combustion products expand out of the channel and are pushed out of the channel by the incoming fuel and oxidizer

Which Chemical Propulsion Systems exist?

Rotation Detonation Engine

- Principle
  - Although the RDE's design is similar to the pulse detonation engie (PDE), the RDE can function continuously because the waves cycle around the chamber, while the PDE requires the chambers to be purged after each pulse
  - In detonative combustion, the flame front expands at supersonic speed
  - It is theoretically up to 25% more efficient than conventional deflagrative combustion offering potentially major fuel savings
  - Disadvantages include instability and noise

Which Chemical Propulsion Systems exist?

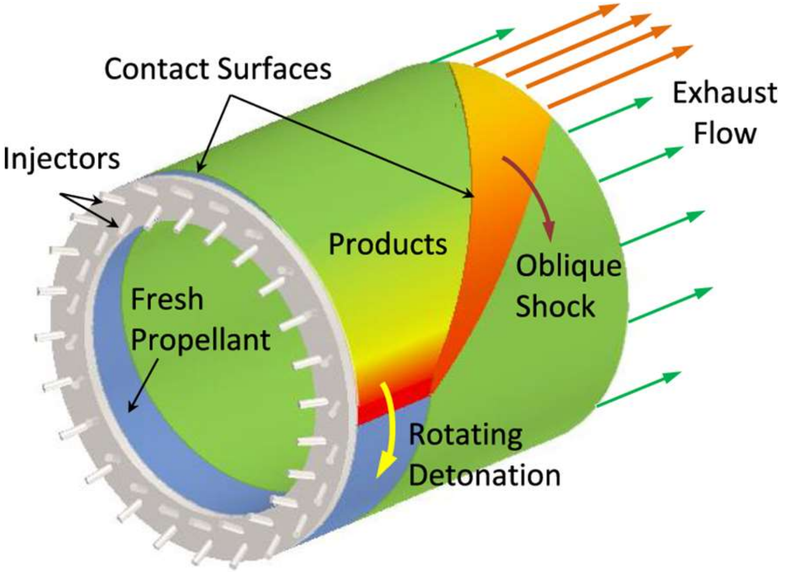
Rotation Detonation Engine

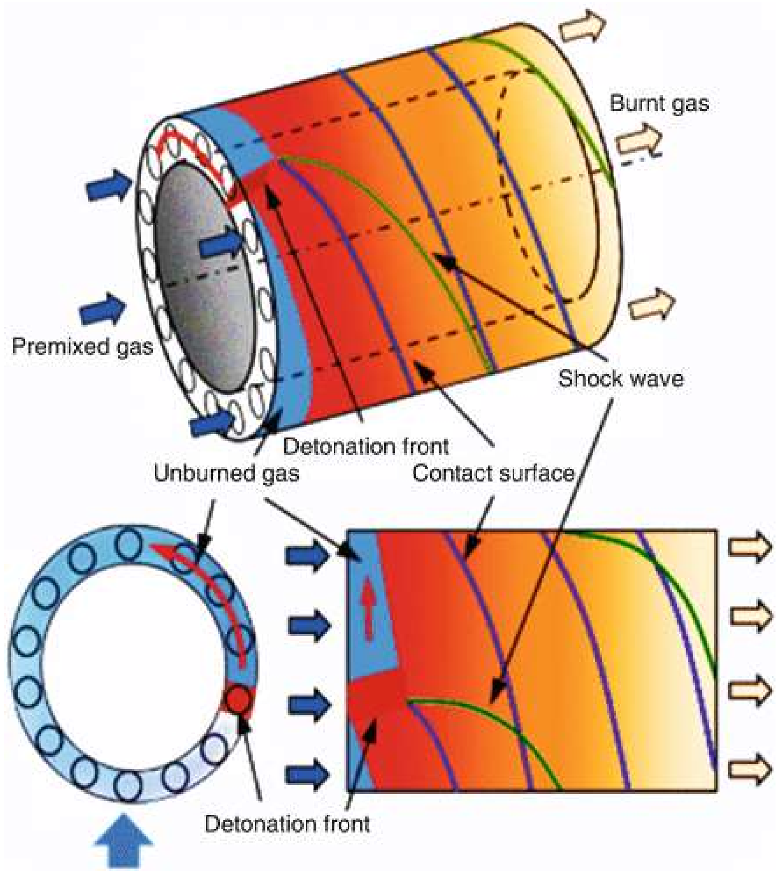
- Principle
  - From a thermodynamic point of view, detonations are more efficient than the more commonly known deflagration (classic combustion)
  - While classic combustion in rocket engines takes place at constant pressure or even with a slight loss of pressure, the pressure increases significantly during detonation
  - A rocket engine based on detonative combustion could therefore theoretically have significantly higher efficiency than today's engines

Which Chemical Propulsion Systems exist?

Rotation Detonation Engine

- Principle





Which Chemical Propulsion Systems exist?

PTE (Pulse Detonation Engine)

- Principle
  - A pulse detonation engine (PDE) is a type of propulsion system that uses detonation waves to combust the fuel and oxidizer mixture
  - The engine is pulsed because the mixture must be renewed in the combustion chamber between each detonation wave and the next
  - Theoretically, a PDE can operate from subsonic up to a hypersonic flight speed of roughly Mach 5
  - Key issues for further development include fast and efficient mixing of the fuel and oxidizer, the prevention of autoignition, and integration with an inlet and nozzle

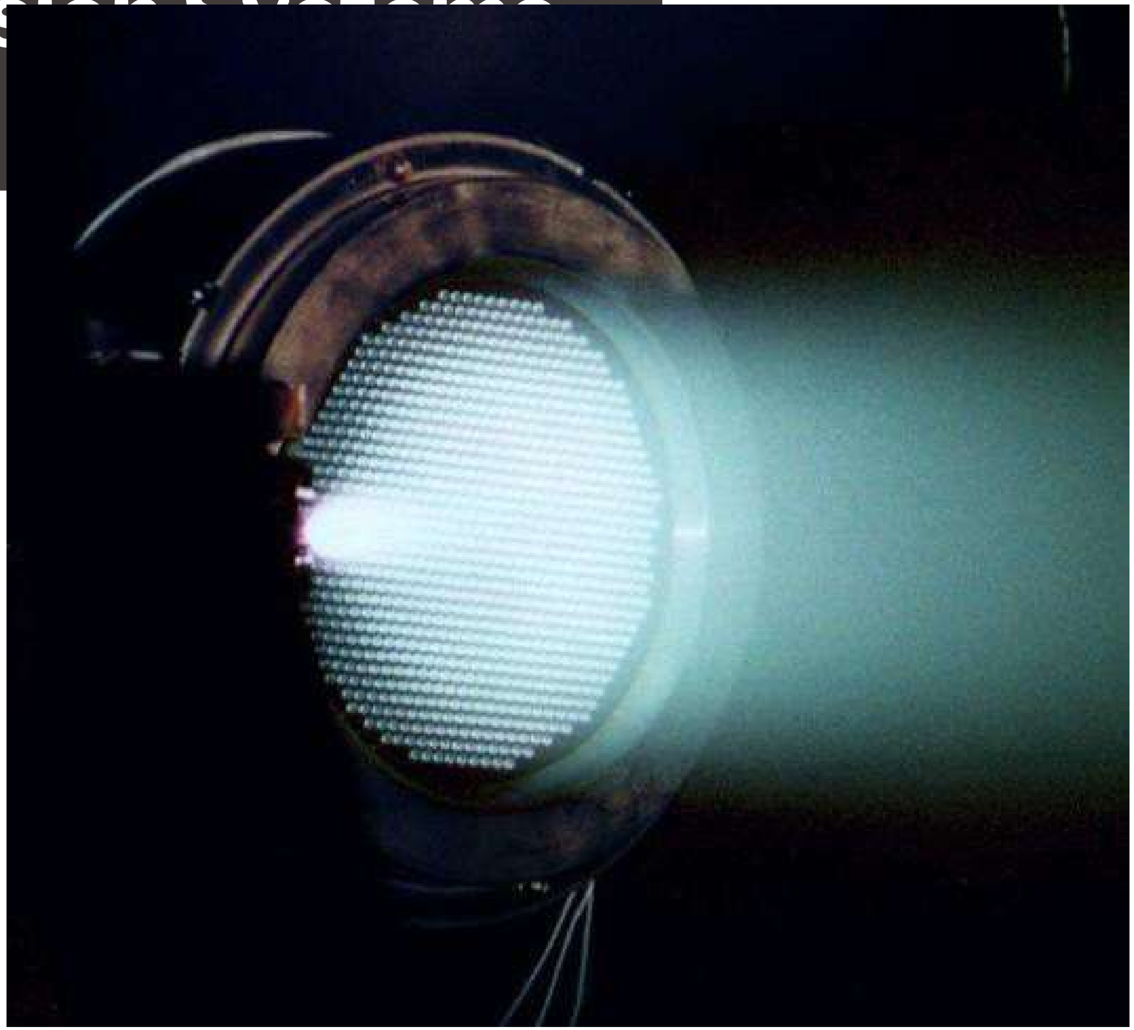
EPFL

Lecture # 6 Eletrical Propulsion Systems

Brief overview on all space propulsion systems

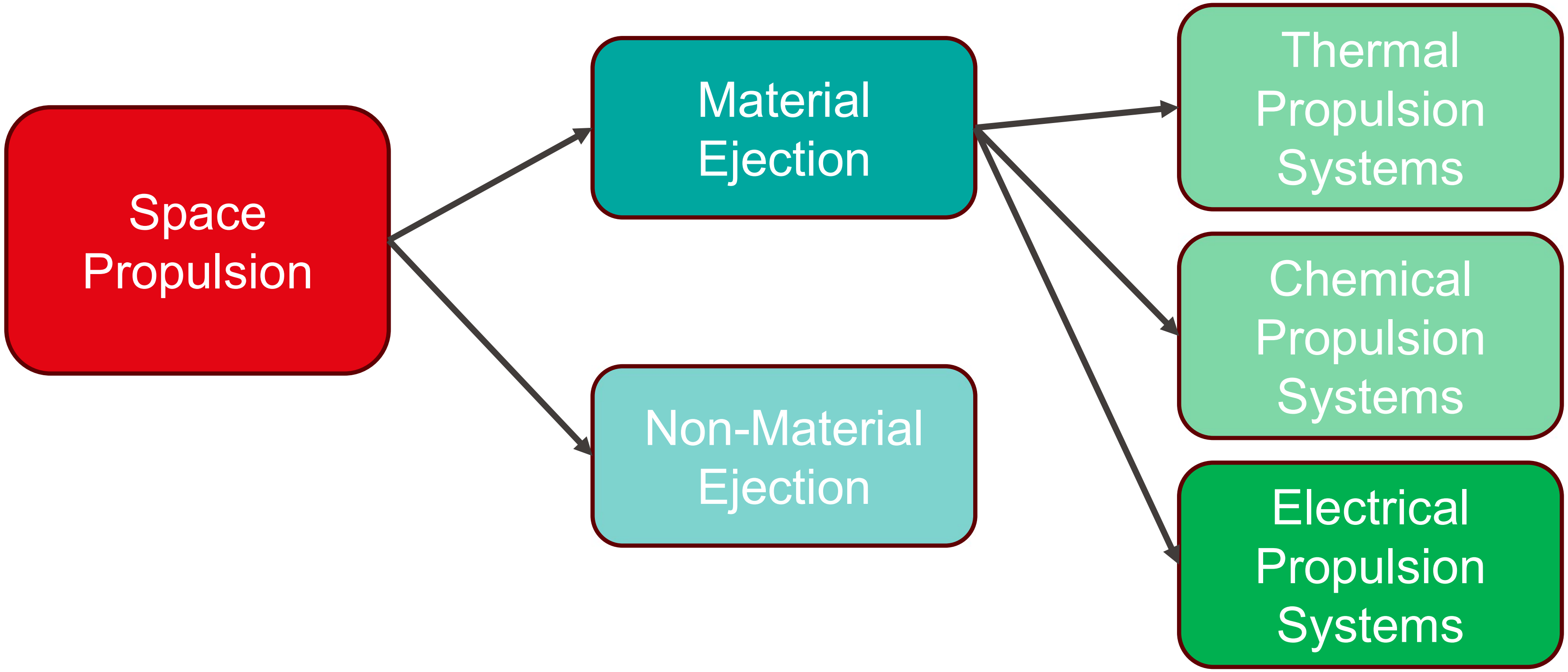
eSpace
EPFL Space Center

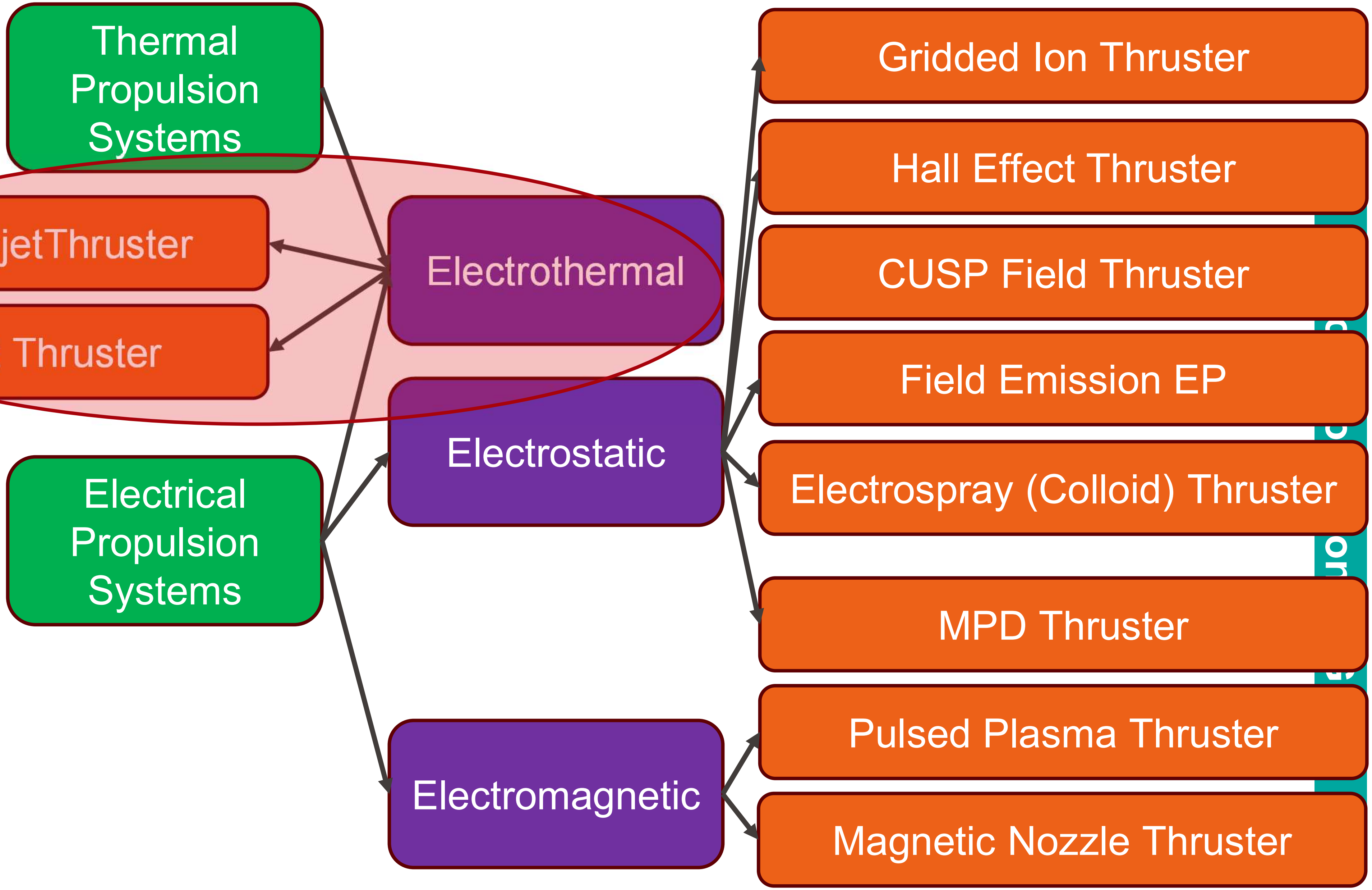
Which Electrical Propuls
exist?



Which Electrical Propulsion Systems exist?

Electrical Propulsion Systems:




Thermal Propulsion Systems
Electrical Propulsion Systems
ResistojetThruster
Arcjet Thruster
Electrothermal
Electrostatic
Electromagnetic
Gridded Ion Thruster
Hall Effect Thruster
CUSP Field Thruster
Field Emission EP
Electrospray (Colloid) Thruster
MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster

What is the interest of Electrical Propulsion Systems?

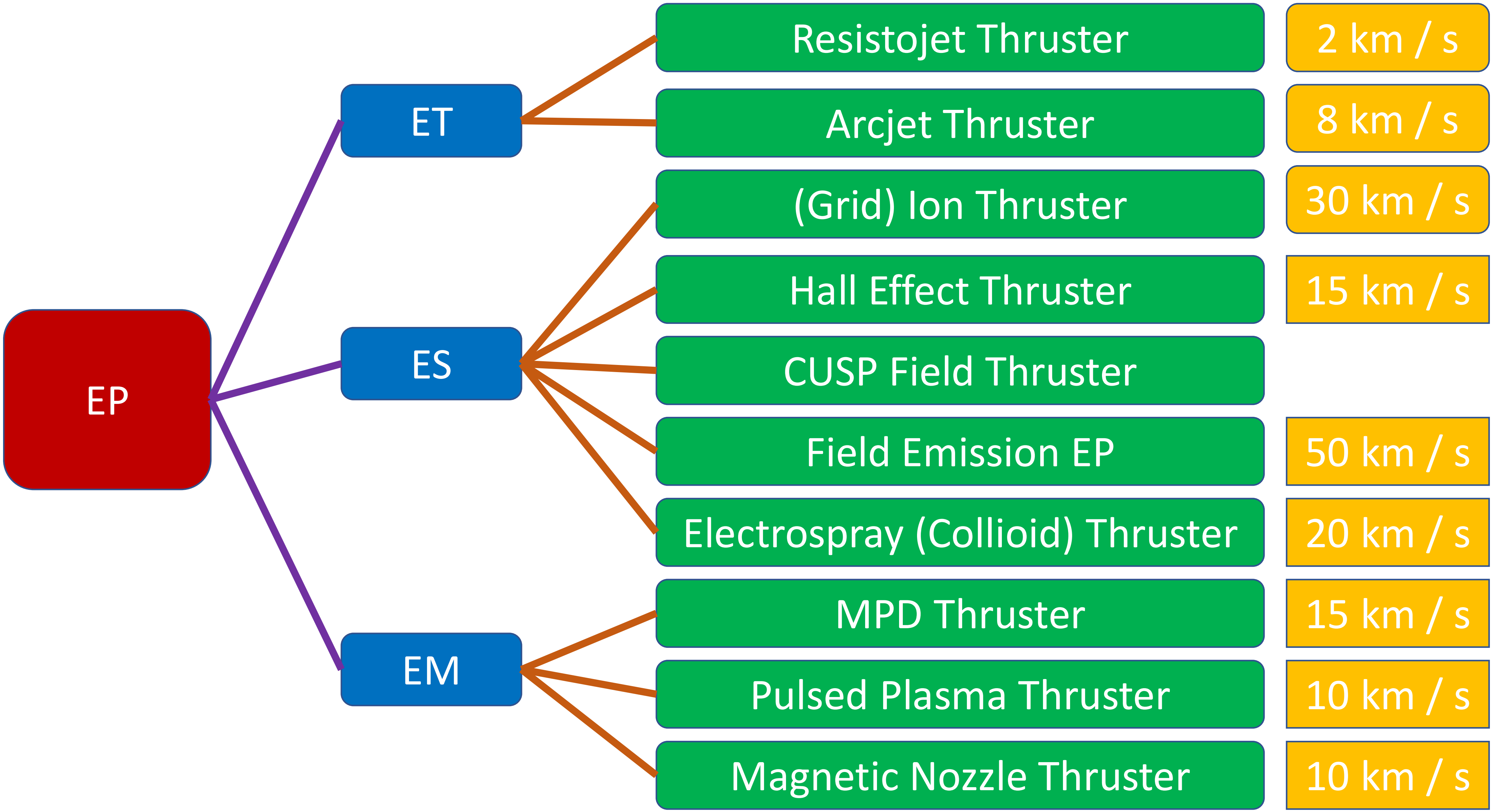
Electrical Propulsion Systems:

- Basics
  - EP systems achieve high specific impulse by acceleration of charged particles to high velocity
  - Charged particles are produced by ionization of a propellant gas which creates both ions and electrons and forms what is called plasma
  - Plasma is then a collection of the various charged particles that are free to move in response to fields they generate or fields that are applied to the collection

What is the interest of Electrical Propulsion Systems?

Electrical Propulsion Systems:

- History
  - EP systems were described in early by Robert Goddard in 1906
  - Physics was described in detail by Robert Jahn in 1968
  - First experimental ion thrusters were launched into orbit in the 1960s by the USA
  - First extensive application of EP was by Russia using Hall thrusters for station keeping on communication satellites


EP
ET
ES
EM
Resistojet Thruster
2 km / s
Arcjet Thruster
8 km / s
(Grid) Ion Thruster
30 km / s
Hall Effect Thruster
15 km / s
CUSP Field Thruster
Field Emission EP
50 km / s
Electrospray (Collioid) Thruster
20 km / s
MPD Thruster
15 km / s
Pulsed Plasma Thruster
10 km / s
Magnetic Nozzle Thruster
10 km / s

What is the interest of Electrical Propulsion Systems?

Description of EP:

- Spacecraft electric propulsion (or just electric propulsion - EP) is a type of propulsion technique that uses electrothermal, electrostatic or electromagnetic energy / forces to accelerate mass to high speed and thus generate thrust
- Electric thrusters typically use much less propellant than chemical propulsion systems because they have a higher exhaust speed (operate at a higher specific impulse) than chemical propulsion systems
- Due to limited electric power the thrust is much weaker compared to chemical propulsion, but electric propulsion can provide thrust for a longer time

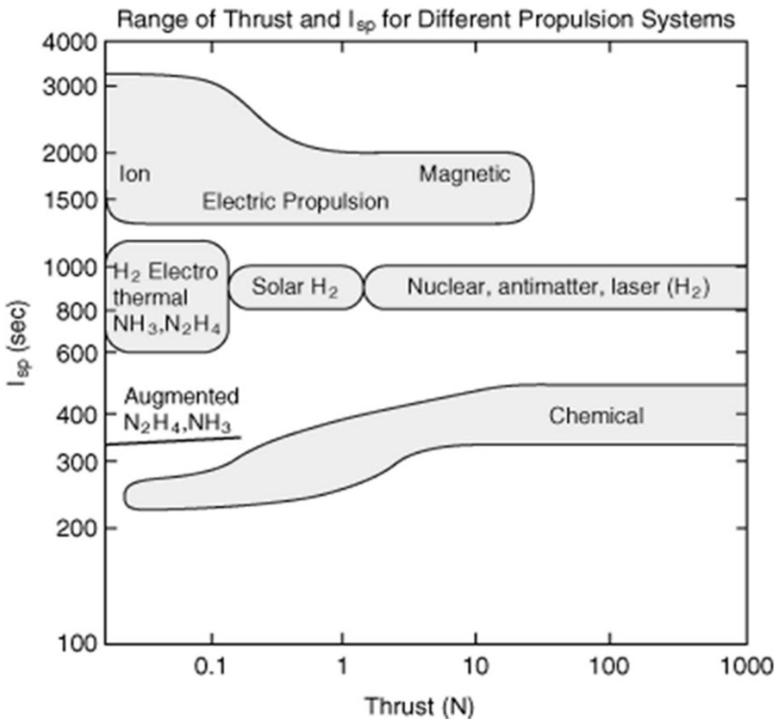
What is the interest of Electrical Propulsion Systems?

Comparison of EP with CP:

- CP
  - You can freely use the stored energy in time (Flexible for impulse / time and therefore flexible for thrust)
  - You must increase the mass to increase the energy (Limitation for impulse / mass and therefore limitation for exhaust velocity / specific impulse)
- EP
  - You can freely choose the energy to mass ratio (Flexible for impulse / mass and therefore flexible for specific impulse)
  - You must increase the charging time for energy (Limitation for impulse / time and therefore limitation for thrust)

What is the interest of Electrical Propulsion Systems?

Comparison of EP with CP:



What is the interest of Electrical Propulsion Systems?

Comparison of EP with CP:

- CP
  - Low specific impulse
  - High propellant mass
  - Need for nozzle extension
- EP
  - High specific impulse
  - Limitation by power source (i.e. battery and / or solar cell)
  - Not always nozzle extension needed (i.e. no laval nozzle)

What is the interest of Electrical Propulsion Systems?

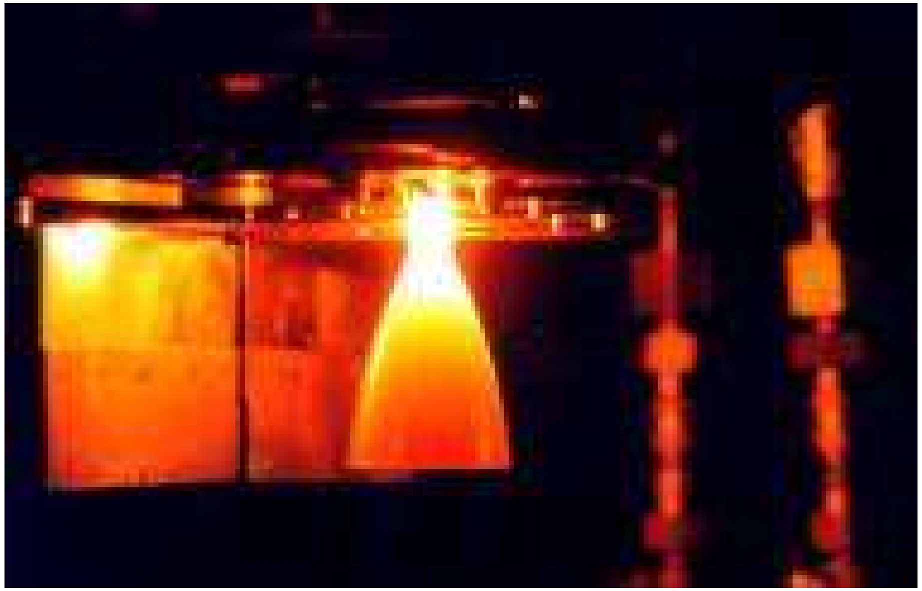
Comparison of EP with CP:

- CP
  - Should be used when you want to obtain ΔV in a short time at the expense of mass increase (short time / high thrust -> massive rocket)
- EP
  - Should be used when you want to obtain ΔV with a small mass at the expense of time increase (long time / low thrust -> compact S/C)

What is the interest of Electrical Propulsion Systems?

Comparison of EP with CP:

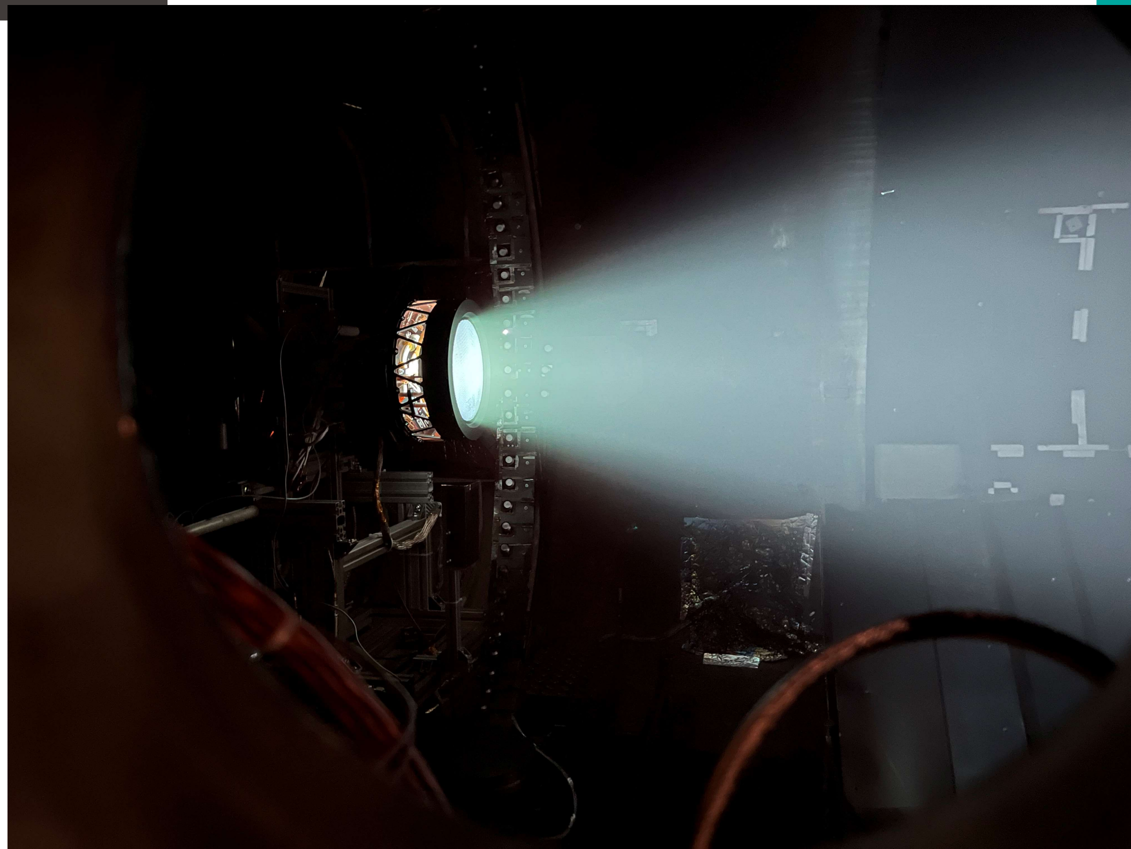
- CP
  - For high exhaust velocity – High temperature (Materials limit the maximal acceptable temperatures)



What is the interest of Electrical Propulsion Systems?

Comparison of EP with CP:

- EP
  - For high exhaust velocity – High voltage electrics



Which Electrical Propulsion Systems exist?

Electrical Propulsion Systems:

- Performance description
  - Isp
  - Thrust
  - Propellant mass compared to delta v requirement
  - Structural mass
  - **Power need**

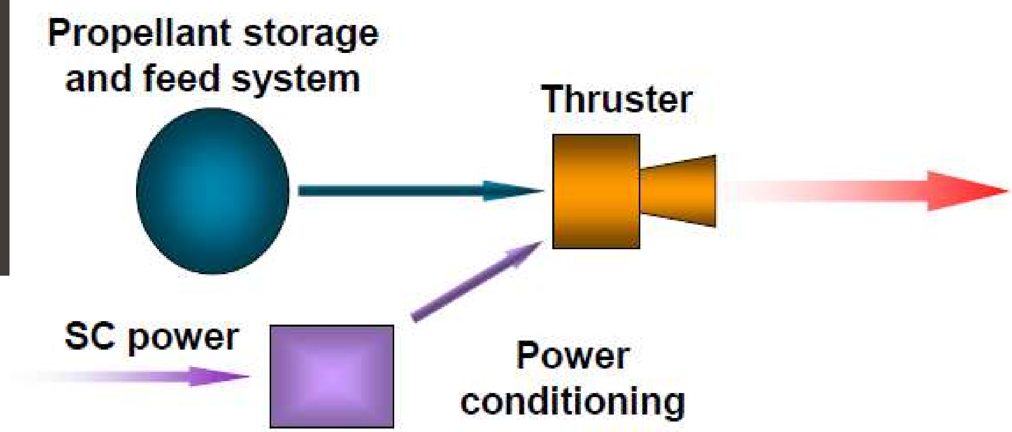
Which Electrical Propulsion Systems exist?

Electrical Propulsion Systems:

- Electric Propulsion Definitions
  - Electric propulsion (EP): Any propulsion system which uses electrical power to provide propellant acceleration, and hence thrust
    - Excludes systems which only use power for thermal control, valve actuation, etc.
    - *Implicitly includes "hybrid" systems, which use electrical power to accelerate combustion products of chemical thrusters (**considered as thermal propulsion system in this course**)*
  - Solar electric propulsion (SEP) uses solar energy (from solar arrays) as power source
  - Alternatives are radio-isotope electric propulsion (REP) and nuclear electric propulsion (NEP)
    - Comparatively low level of development

EPFL

Which Electrical Propulsion Systems exist?



Electrical Propulsion Systems:

- Basics
  - For all EP, the following elements are required:
    - Propellant storage and feed system (similar to CP)
    - **Electrical power supply and power conditioning**
    - **Power conditioning is usually considered to be part of the EP system; the power supply is part of the overall spacecraft power system architecture**
    - **The thruster, which converts the electrical power into propellant kinetic energy, providing thrust**
    - Many EP systems also use thrust pointing mechanisms (gimbals), to ensure thrust vector passes through spacecraft center of mass (somehow similar to CP)

Which Electrical Propulsion Systems exist?

Electrical Propulsion Systems:

- Basics
  - EP translates electrical energy into kinetic energy in the propellant
    - Simple power balance equation lead to definition of overall EP system efficiency η, which defines relationship between power, thrust and specific impulse:

$$\eta = \frac{F * Is + p * g}{2 * P}$$

P…Input power [W]

  - Current state-of-the-art:
    - Thruster efficiencies ~ 45 to 65 %
    - EP system efficiencies (including power conditioner losses) ~ 40 to 60 %
    - Some technologies have efficiencies above or below this range
    - Each technology / product has optimum operating range, with maximum efficiency

Which Electrical Propulsion Systems exist?

Electrical Propulsion Systems:

- Basics
  - Electrothermal (or part of Thermal Propulsion Systems…)
    - Power heats propellant
    - Expansion through a nozzle (same as for a chemical thruster)
  - Electrostatic
    - Propellant is ionized
    - Accelerated using electrostatic fields
  - Electromagnetic
    - Propellant is ionized
    - Accelerated by interaction of discharge current with magnetic field (JxB Lorentz force)

Which Electrical

ETA: Eletrothermal Acceleration

Electric energy → Thermal Energy → Kinetic energy

Joule heat **Nozzle**

ESA: Electrostatic Acceleration

Electric energy → Kinetic energy

Electrostatic force（Coulomb force）

EMA: Electromagnetic Acceleration

Electric energy → Kinetic energy

Electromagnetic force（Lorentz force）

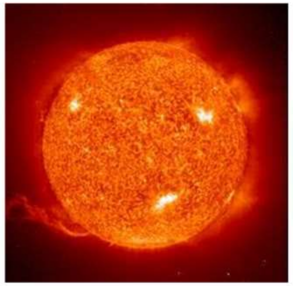
Which Electrical Propulsion Systems exist?

Electrical Propulsion

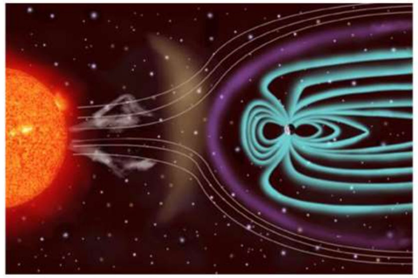
- Basics
  - Plasma is needed..

Fluorescent lamp

Sun

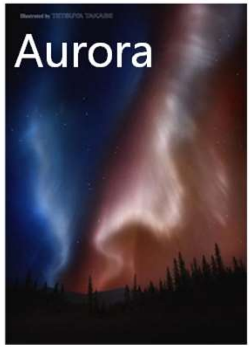


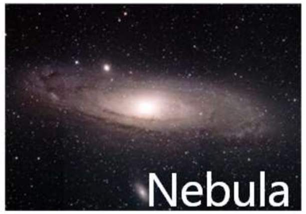
Solar wind



Lightning

Neon lamp





Which Electrical Propulsion Systems exist?

Electric Propulsion S

- Basics
  - What is Plasma? Heated gas

Macroscale : electrical gas

Microscale : Mixture of ions, electrons, and neutrals

Normal gas

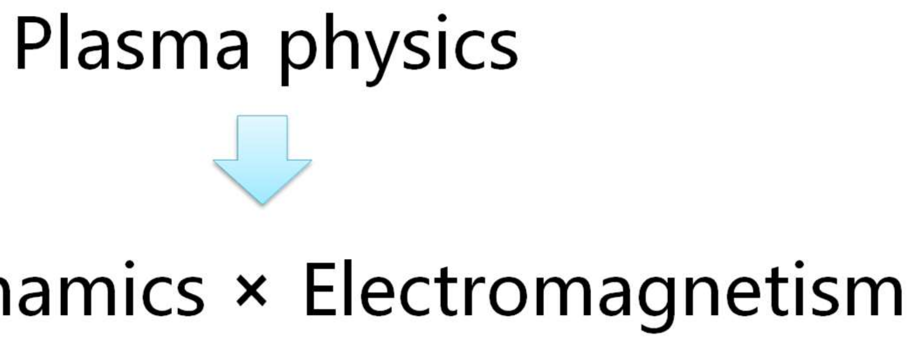
Electrons come off from neutral particles = negative charge

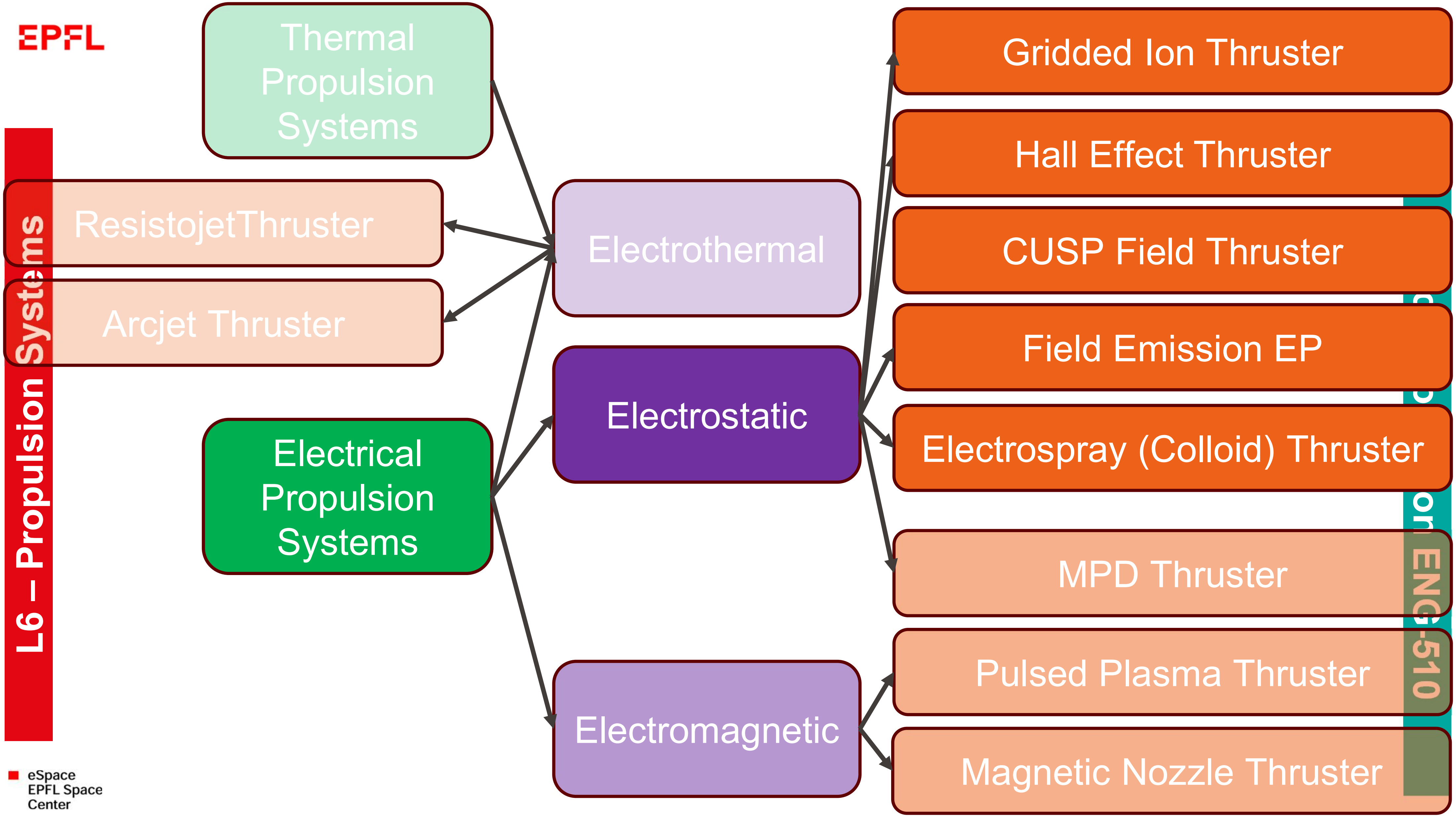
Particles which lost a few electrons from the normal state
=Positive charge

Which Electrical Propulsion Systems exist?

Electrical Propulsion Systems:

- Basics
  - What is Plasma? A combination of gas dynamics with electromagnetism
    - Interaction with E & B fields
    - Rarefied gas (basically not continuum modeling)
    - Mixture of particles of completely different nature

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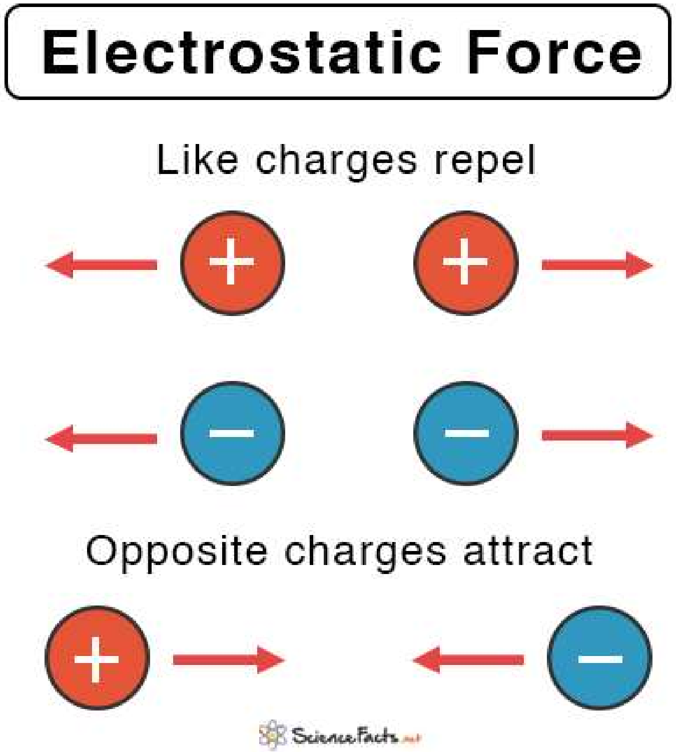
Magnetic Nozzle Thruster

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Electrostatic Force:
  - The electrostatic force is the force of attraction or repulsion between two charged particles
  - It is also called Coulomb's force or Coulomb's interaction



Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Electrostatic Force:
  - According to this law, the force between the two particles is,
    - Directly proportional to the product of the magnitude of the charges
    - Inversely proportional to the square of the distance between the two charge

$$F = k * \frac{q_1 * q_2}{r^2}$$

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Electrostatic Thruster - Operations and Performance
  - Thrust generated by acceleration of positive ions through an electrostatic field
  - Specific impulse primarily driven by the accelerating voltage V

$$v_e = \sqrt{2 * \frac{q}{m} * V}$$

  q/m…Ion charge / mass ratio

  - Specific impulse maximized for small ions for a given voltage, BUT …..
    - Ionization losses are greatest for small ions
    - Consequently thruster efficiencies are lowest with low atomic mass propellants –this outweighs the possible gains in maximizing the specific impulse

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Electrostatic Thruster - Operations and Performance
  - High atomic mass propellants are preferred
  - More complex molecules avoided as they can dissociate during ionization
  - Multiple charged ions are also avoided (as far as is possible), as their production and acceleration is less efficient than that for singly charged ions

Which Electrical Propulsion Systems exist?

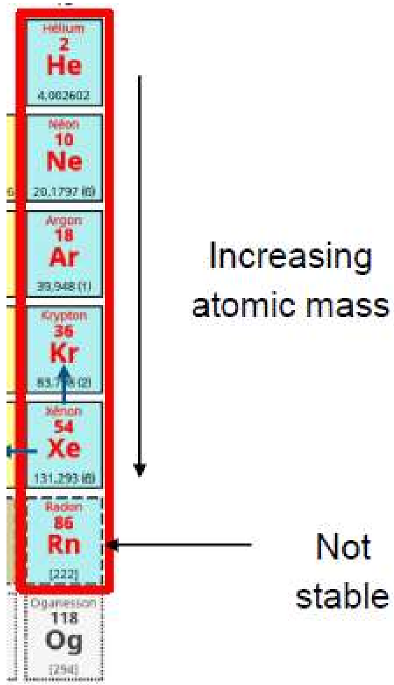
Electrostatic Propulsion Systems:

- Electrostatic Thruster - Operations and Performance
  - Xenon is the "industry standard" propellant for electrostatic systems
    - Noble gas (inert): no chemical reaction with the other parts of the system
    - High atomic mass (~131): high thrust
    - Low ionization energy: no too much energy lost for ionization
    - Gaseous at ambient temperature: no need to vaporize it to feed the thruster
    - High compression rate: not too big tanks at a reasonable pressure (150bar)
    - However it is present in low quantity on the Earth (0.08 ppm of the air) and is therefore very expensive (~ 3000 € / kg)

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Electrostatic Thruster - Operations and Performance
  - That is why alternate propellants are currently investigated (mainly Krypton, Argon and Iodine)
  - Xenon production and market:
    - Xenon (as well as Krypton) is made from air separation
    - World production: ≈ 70 t/year
    - Space industry is about 30 % of the need
    - Other industries are mainly lighting and electronics



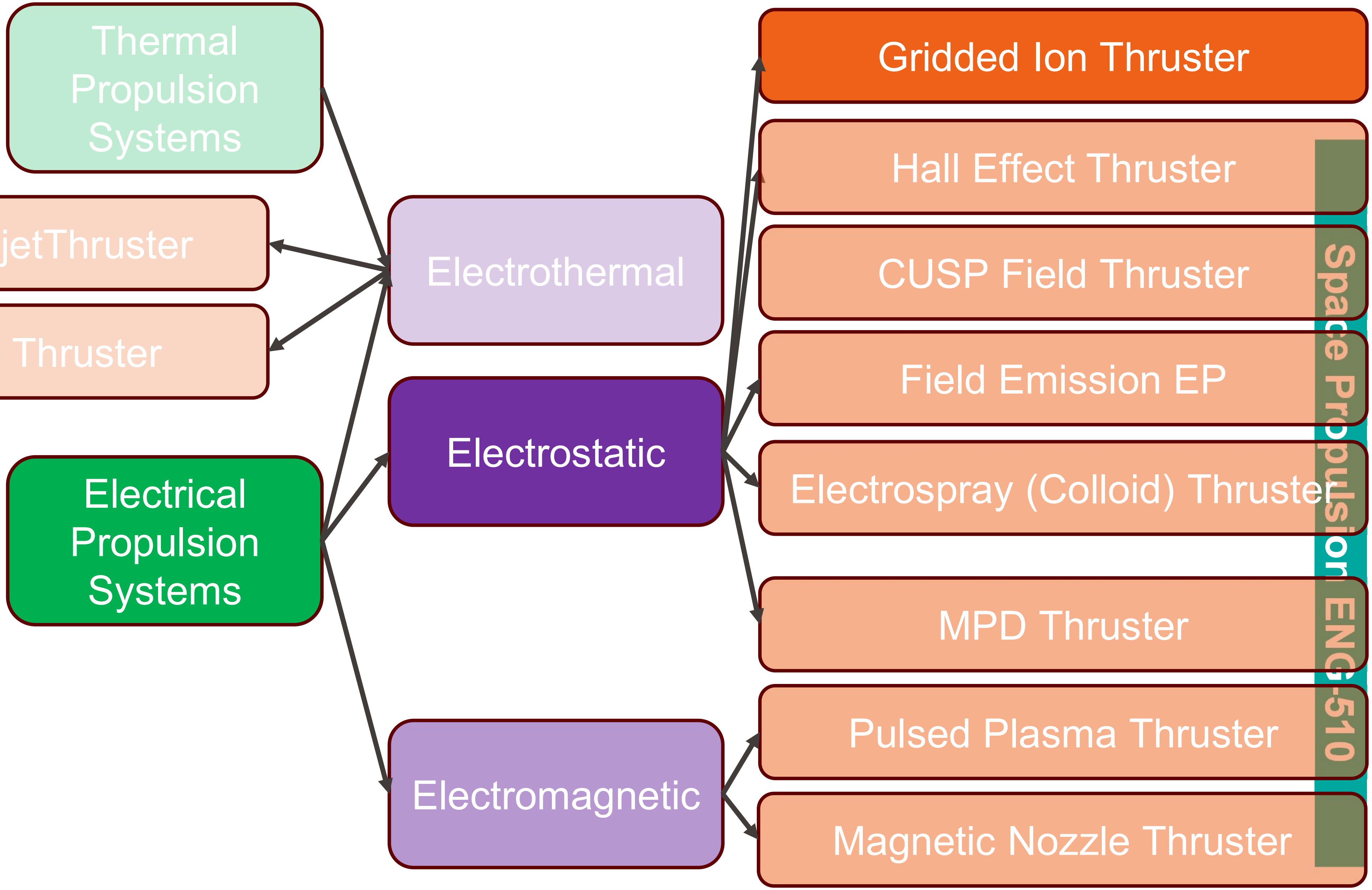
Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Electrostatic Thruster - Operations and Performance
  - Thrust is given by the ion current Ibeam for a given specific impulse

$$F = \frac{I_{beam}}{\frac{q}{m}} * V_e$$

  - Ion beam emitted by thruster requires neutralization, to avoid spacecraft charging
  - Power and flow rate to neutralizer have to be taken into account for overall thruster specific impulse and efficiency calculations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Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- (Gridded) Ion Thruster:
  - Gridded ion thrusters employ a variety of plasma generation techniques to ionize large fraction of the propellant
  - These thrusters then utilize biased grids to electrostatically extract ions from the plasma and accelerate them to high velocities at voltage up to and exceeding 10 kV
  - Ion thrusters feature the highest efficiency (from 60 % to > 80 %) and very high specific impulse (from 2.000 s to over 10.000 s) compared to other thruster types

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- (Gridded) Ion Thruster:
  - Basic principle of an ion thruster = ion production cost (power needed for creation of ions)

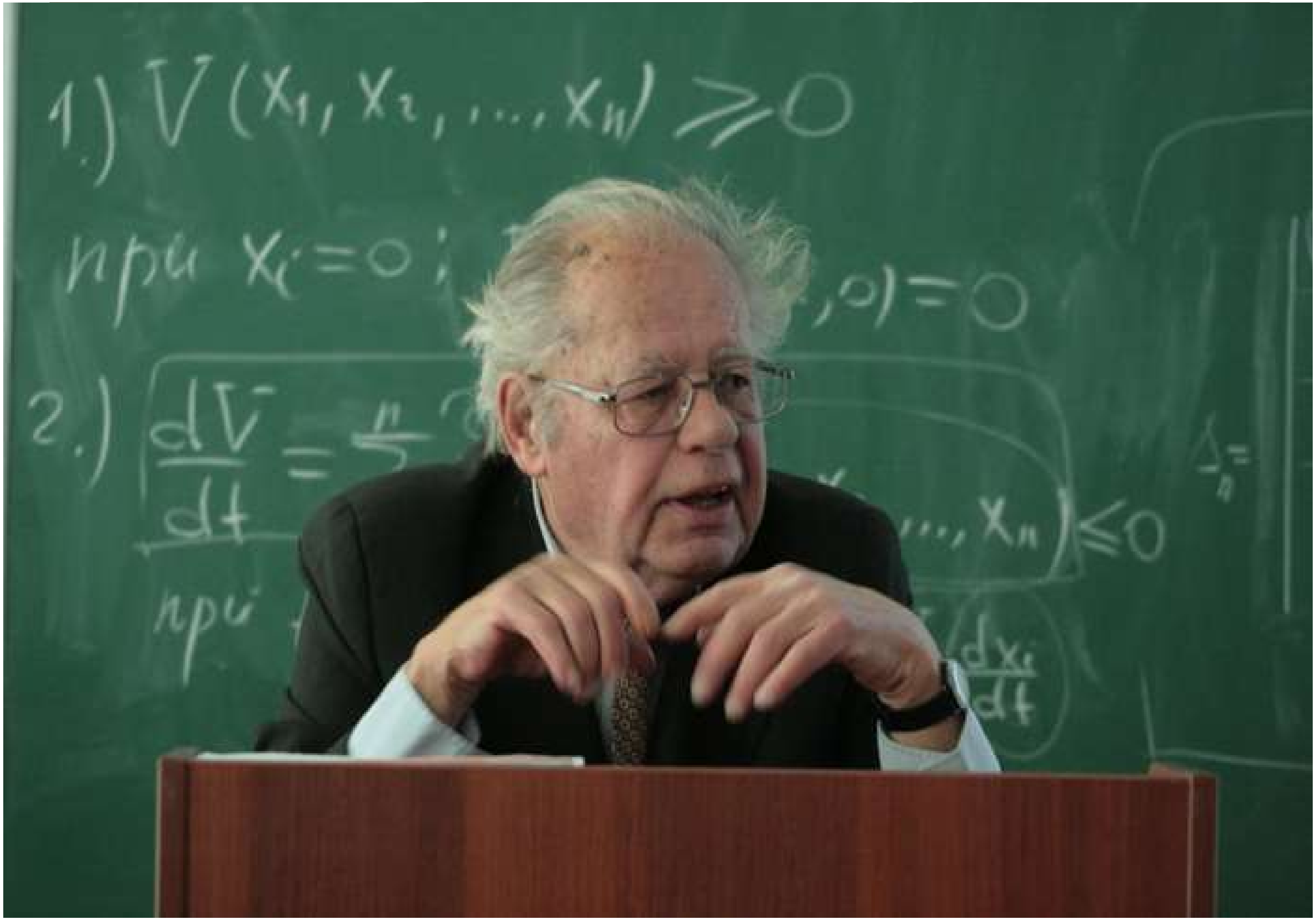
Generation + Acceleration + Neutralization

Not for thrust | For thrust | Not for thrust

Three staged are separated

$$P = P_{\text{plasma}} + P_{\text{beam}} + P_{\text{neut}}$$

$$= \left(\frac{P_{\text{palsma}}}{I_{\text{beam}}} + V_{\text{beam}} + \frac{P_{\text{neut}}}{I_{\text{beam}}} \right) I_{\text{beam}}$$


1.) V (x1, x2, ..., xn) ≥ 0

Which Electrical Propulsion Systems exist?

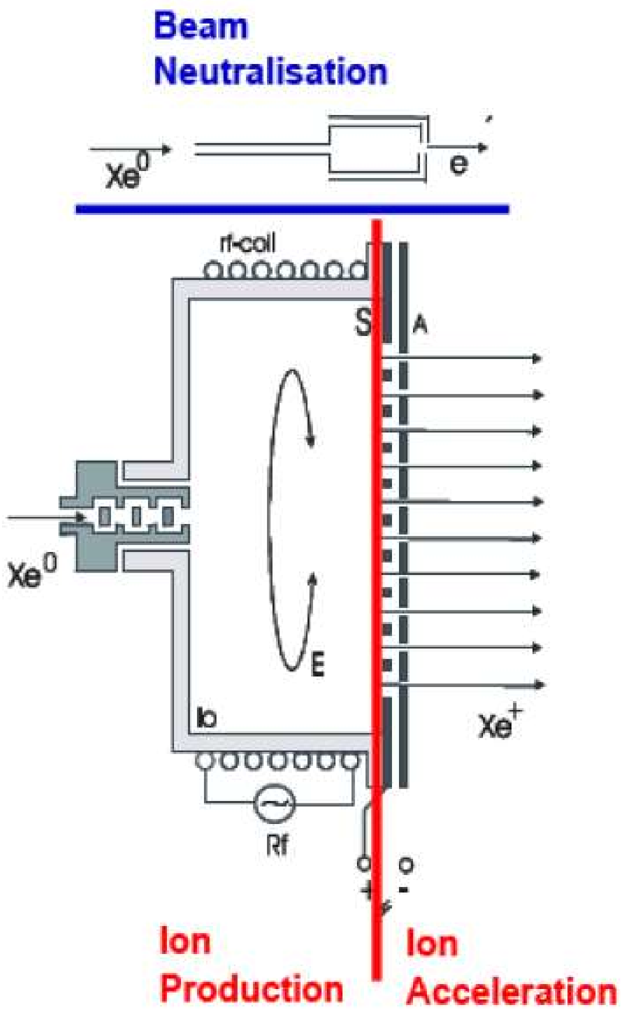
Electrostatic Propulsion Systems:

- Gridded Ion Thruster - Three main types of ion thruster, depending on the ionisation technique used:
  - Radio-Frequency (RF) Discharge:
    - Xenon flowed into discharge chamber
    - RF-current applied to coil; results in a primary axial magnetic field being induced inside the ioniser, which generates a secondary circular electric field (E)
    - Free electrons (from neutraliser) ionise the propellant
    - Once ionisation process is initially triggered the process is self-sustaining, with all electrons required for steady state operation being generated by this discharge process

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Gridded Ion Thruster - Two main types the ionisation technique used:
  - Radio-Frequency (RF) Discharge:



Which Electrical Propulsion Systems exist?

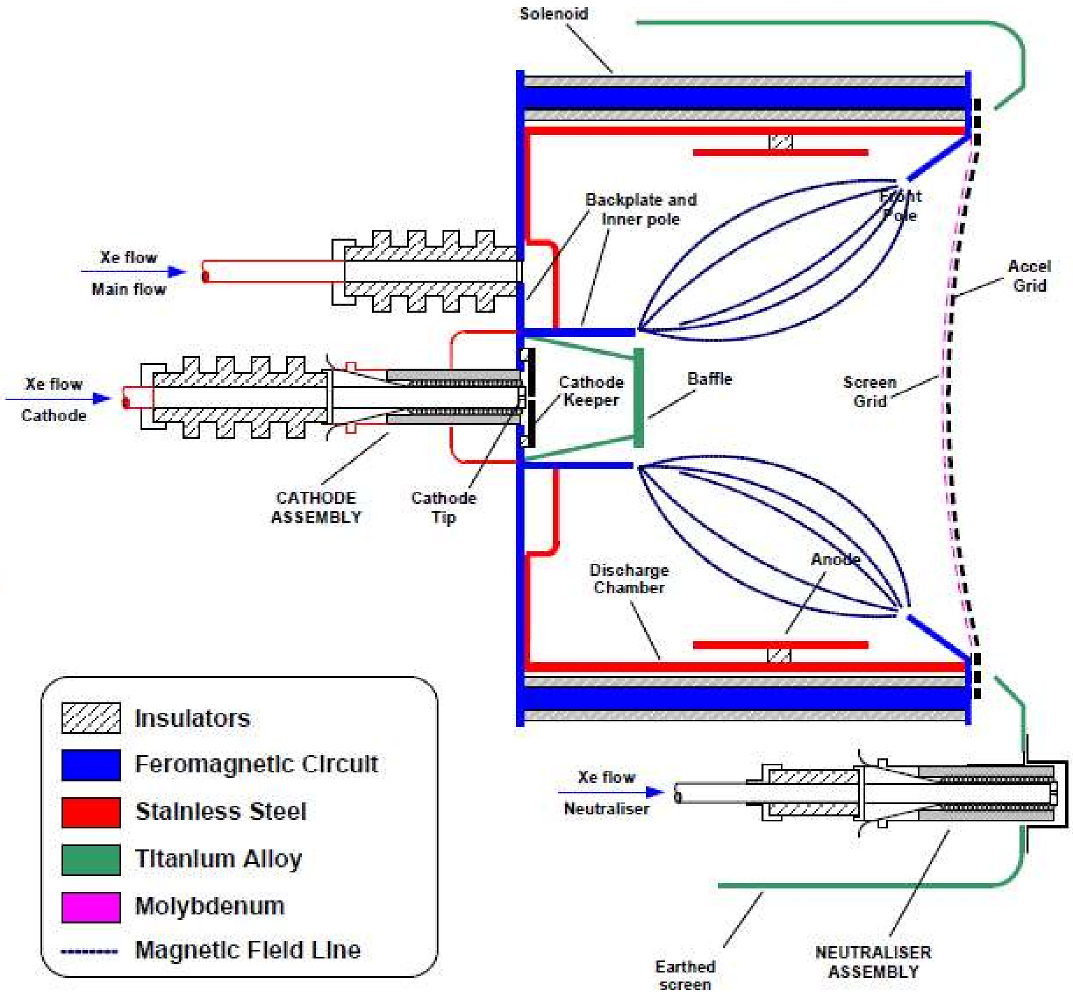
Electrostatic Propulsion Systems:

- Gridded Ion Thruster:
  - Electron-Bombardment (Kauffman type):
    - Cathode located at back of the discharge chamber provides electrons for discharge ionisation
    - Xenon ionised by bombardment by the electrons from the cathode as they are accelerated towards discharge chamber anode
    - Internal magnetic field forces electrons to follow spiral path, increasing ionisation efficiency
    - Thruster shown here uses solenoids to generate the internal magnetic field; some thrusters use permanent magnets instead

Which Electrical Propulsion System exist?

Electrostatic Propulsion Systems

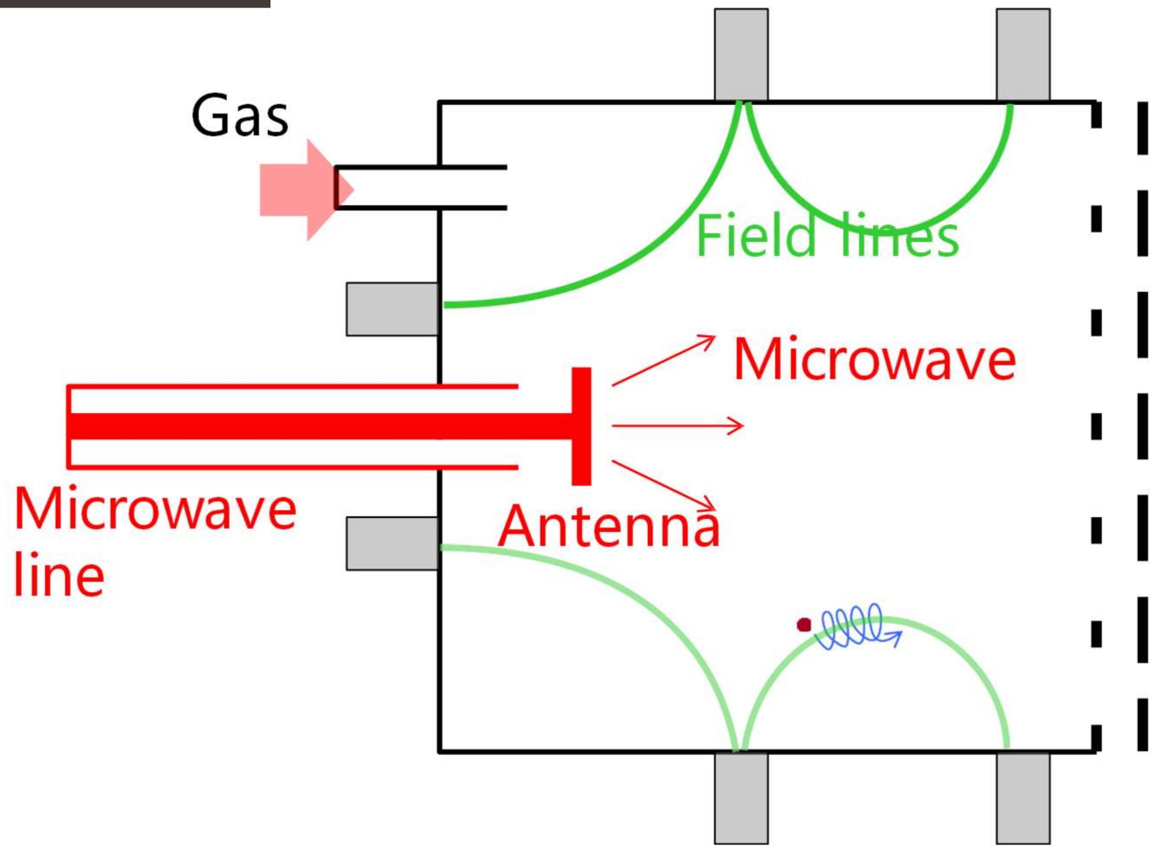
- Gridded Ion Thruster:
  - Electron-Bombardment (Kauffma



Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Sy

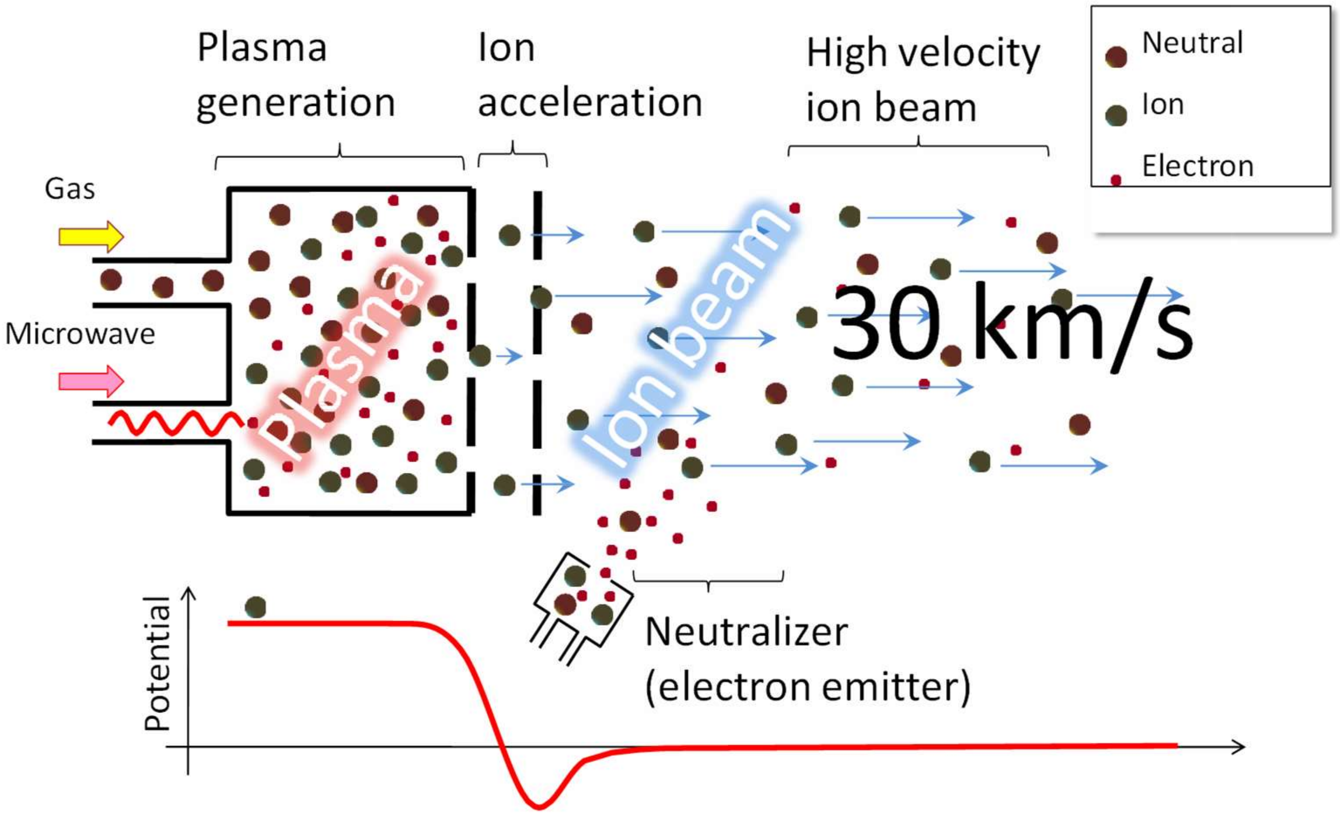
- Gridded Ion Thruster:
  - Microwave discharge:
    Emitting microwave ->
    Oscillating electric fields



Which Electrical Propulsion Systems exist?

Electrostatic Propuls

- Gridded Ion Thrust
  - Microwave dischar



Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Gridded Ion Thruster:
  - Xenon ions accelerated by potential difference between screen and accelerator grids, producing thrust
    - Neutralizer provides electrons to prevent spacecraft charging
  - Typically operate at beam voltages of 1 to 2 kV or higher, depending on the specific impulse required
    - Acceleration grid is normally negatively biased (a few hundred volts); this prevents external electrons from being attracted into the discharge chamber
  - Acceleration grid erodes due to ion impingement
    - Ion optics design avoids direct impingement; erosion caused by charge exchange between fast ions and slow neutrals in vicinity of grids
    - Grid life normally ~ > 25000 hours

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Gridded Ion Thruster:
  - High throttling range (~ 2:1 to 5:1)
  - Operation of a single thruster over a range of beam voltages (i.e. variable Isp) is possible but difficult
    - Grid ion optics are optimized for a given voltage (and hence Isp)
  - Ion thruster efficiencies ~ 35 % for small thrusters up to ~ 80 % for large thrusters
  - Low beam divergence (typically < 15 ° half cone angle)

Which Electrical Propulsion Systems exist?

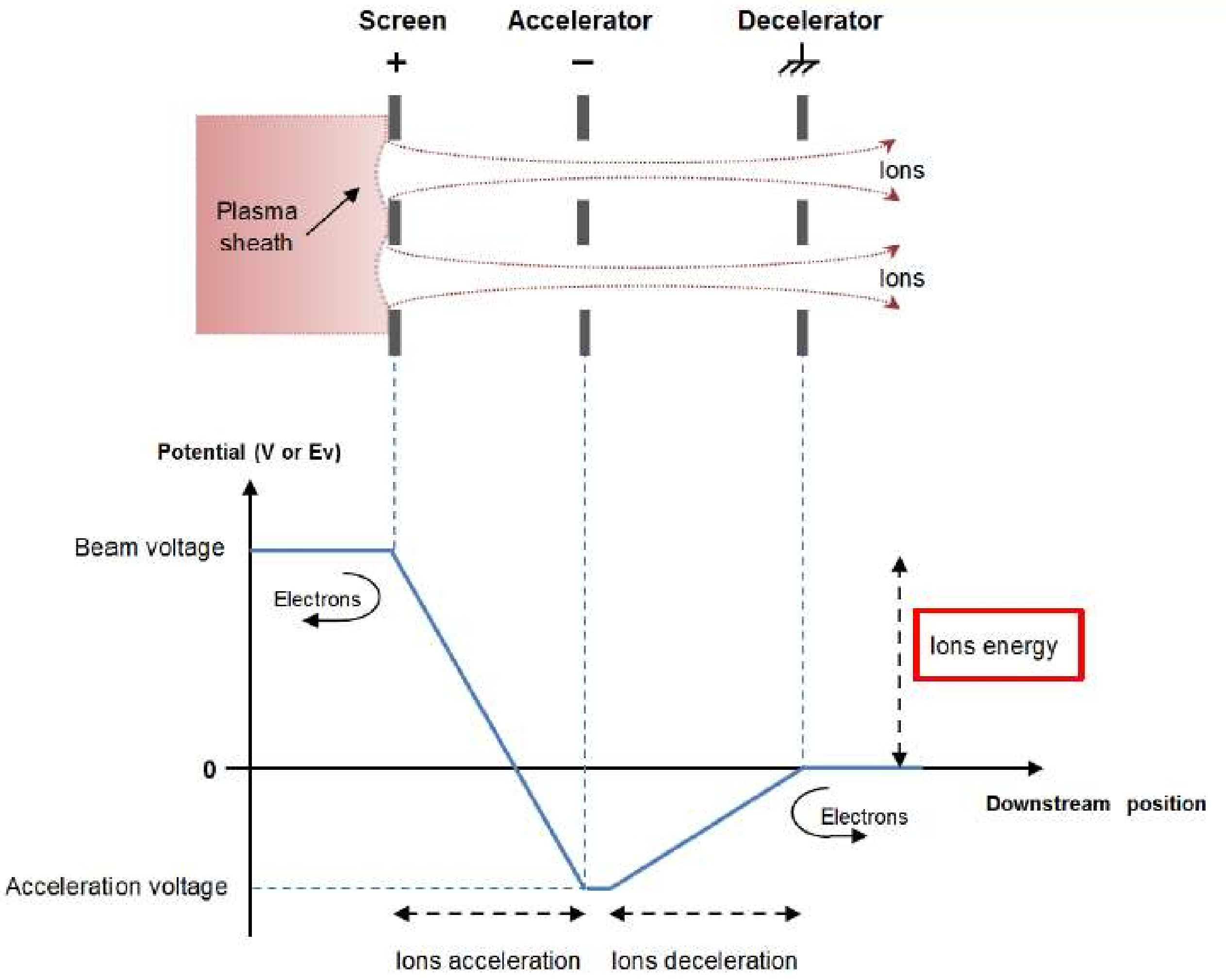
Electrostatic Propulsion Systems:

- Gridded Ion Thruster:
  - Ions Acceleration Principle:
    - Once the plasma (mix of ions and electrons) is created inside the ionization vessel, since it is a conductive medium, it is at the screen grid potential (several hundreds of volts)
    - Then the ions are accelerated due to the difference of potential between the screen grid and the plasma at infinity (i.e. 0V)

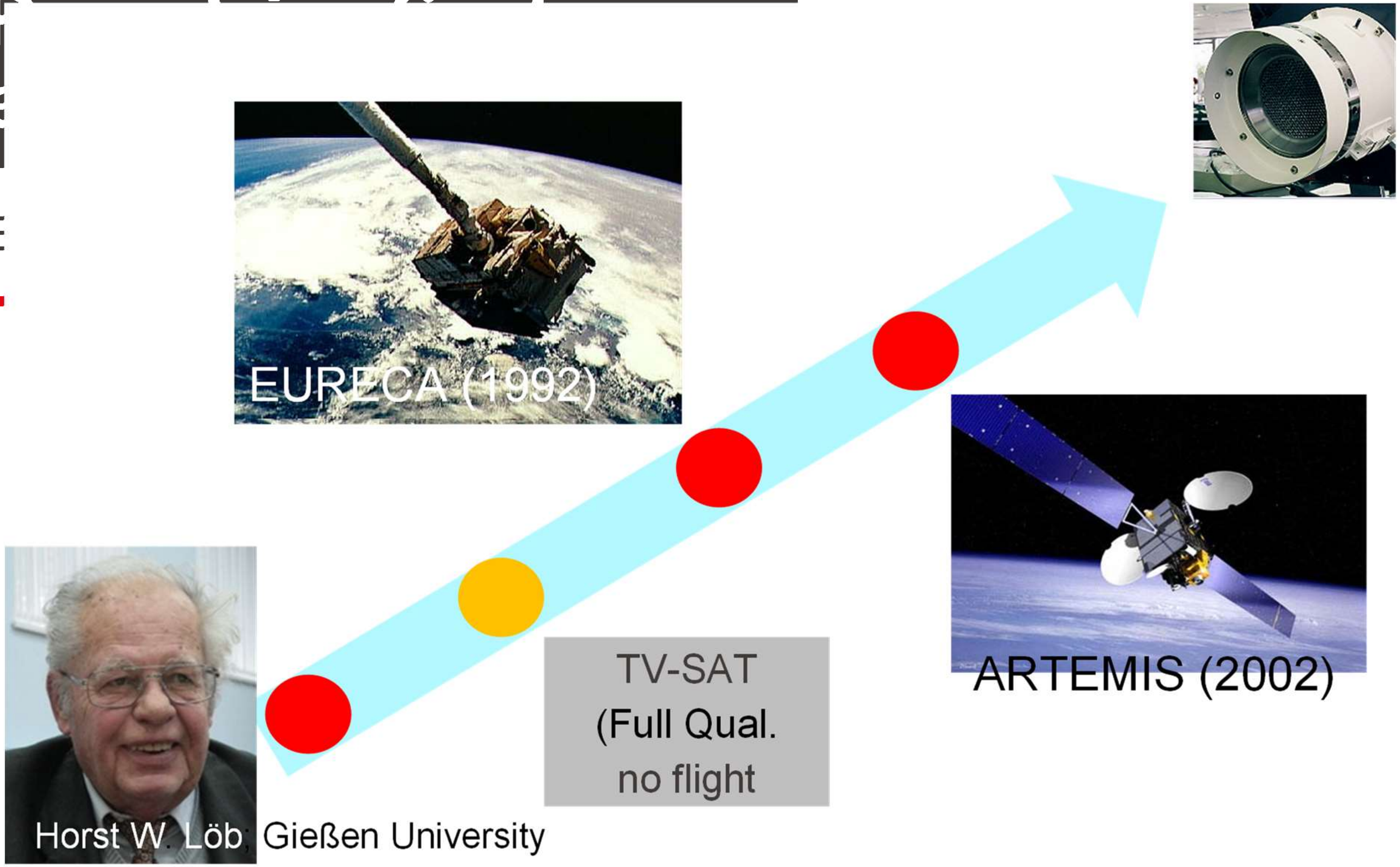
Which Electrical Propuls exist?

Electrostatic

- Gridded Ior
  - Ions Acce



Which Electrical



Which Electrical Propulsion Systems exist?

Elect

- Gr
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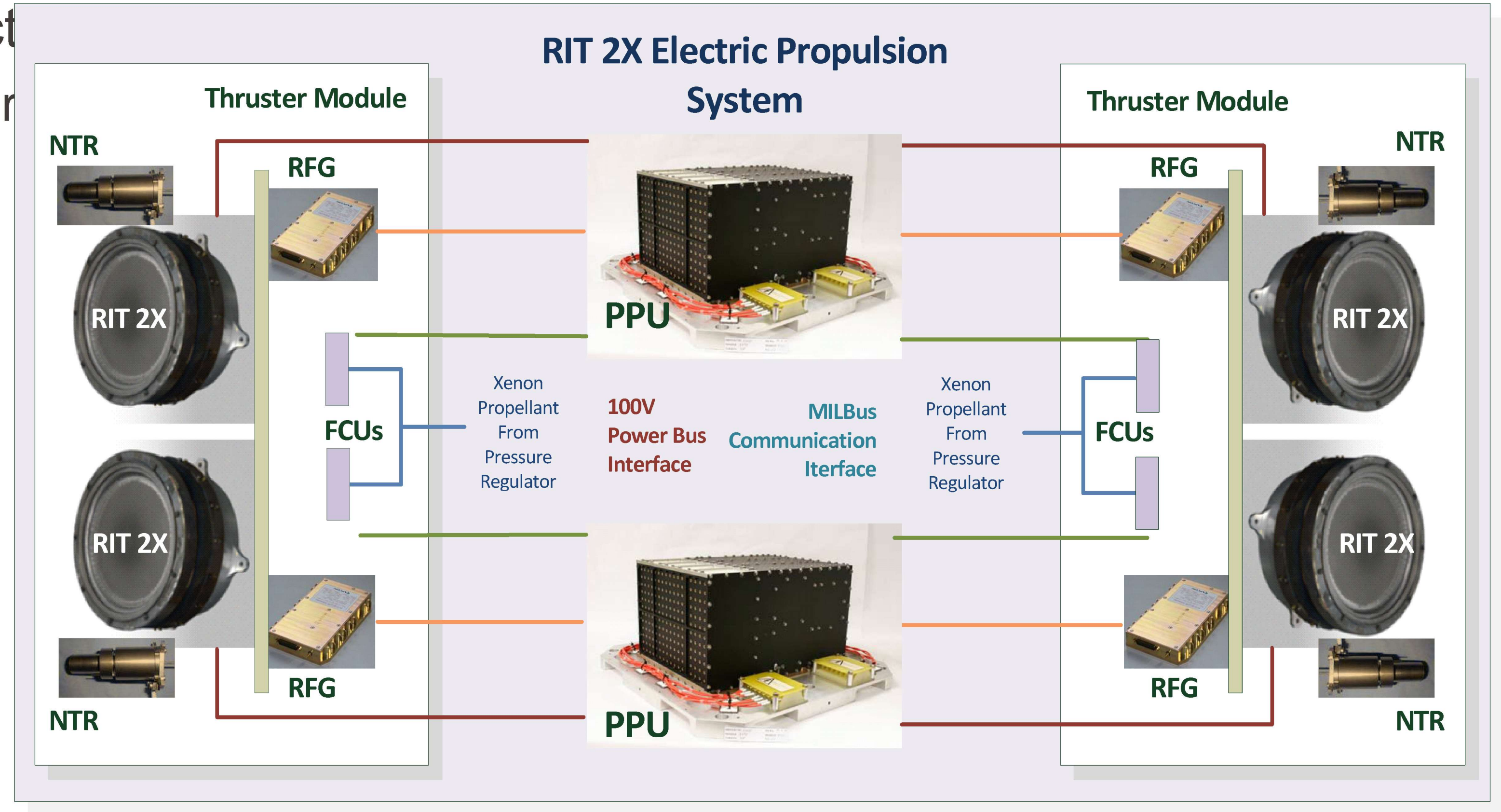
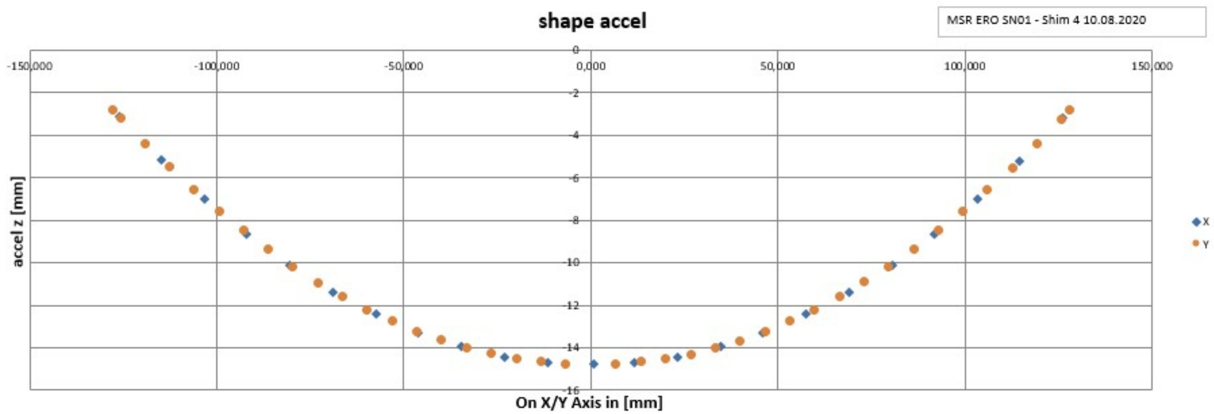


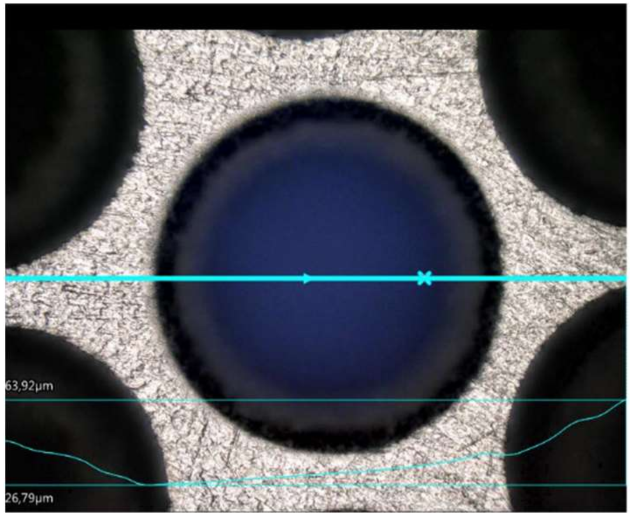

Huge thruster have the problem at
Grid systems

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Gridded Ion Thruster:
  - Manufacturing (number of holes, material, …)
  - Shape



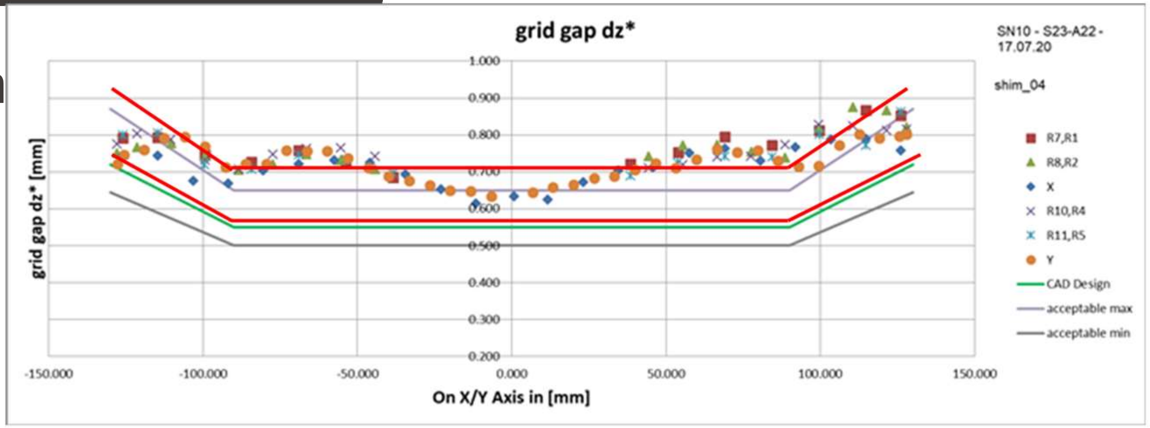


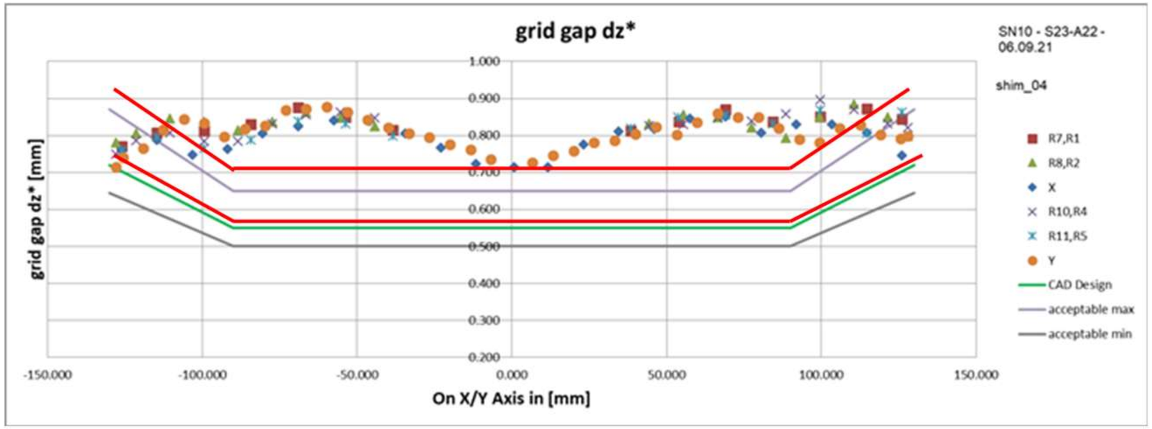
EPFL

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion

- Gridded Ion Thruster:
  - Alignment
  - Hot conditions





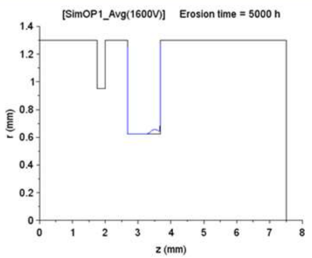
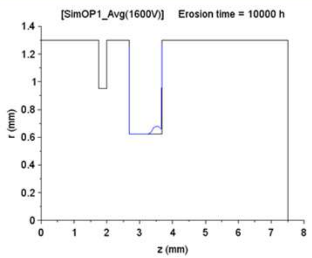
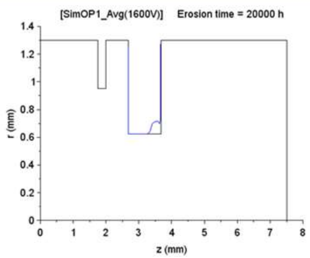
L6 – Propulsion Systems

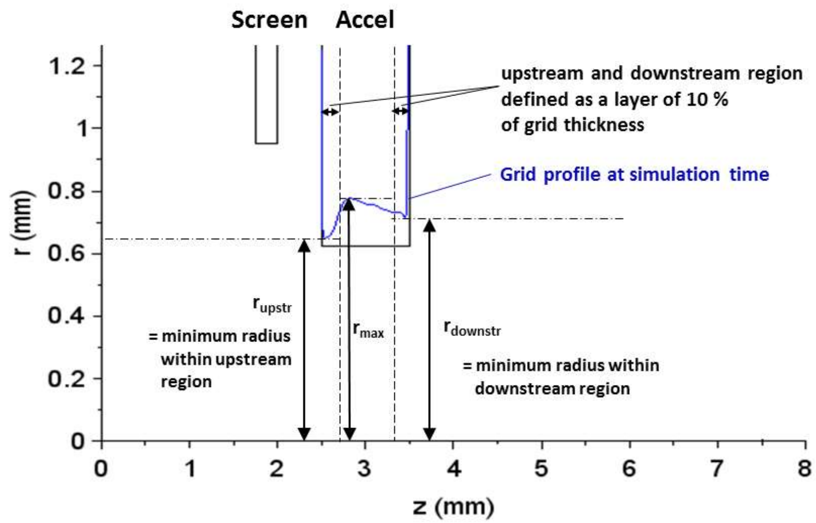
Space Propulsion ENG-510

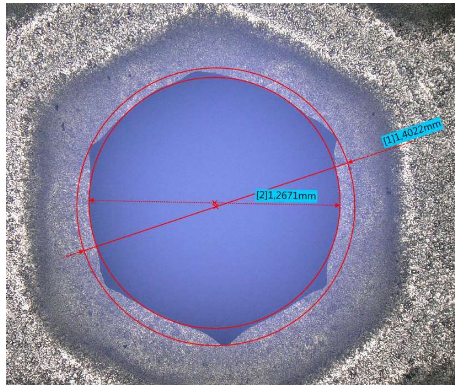
Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Gridded Ion Thruster:
  - Erosion

	5000h	10.000h	20.000h
OP1			

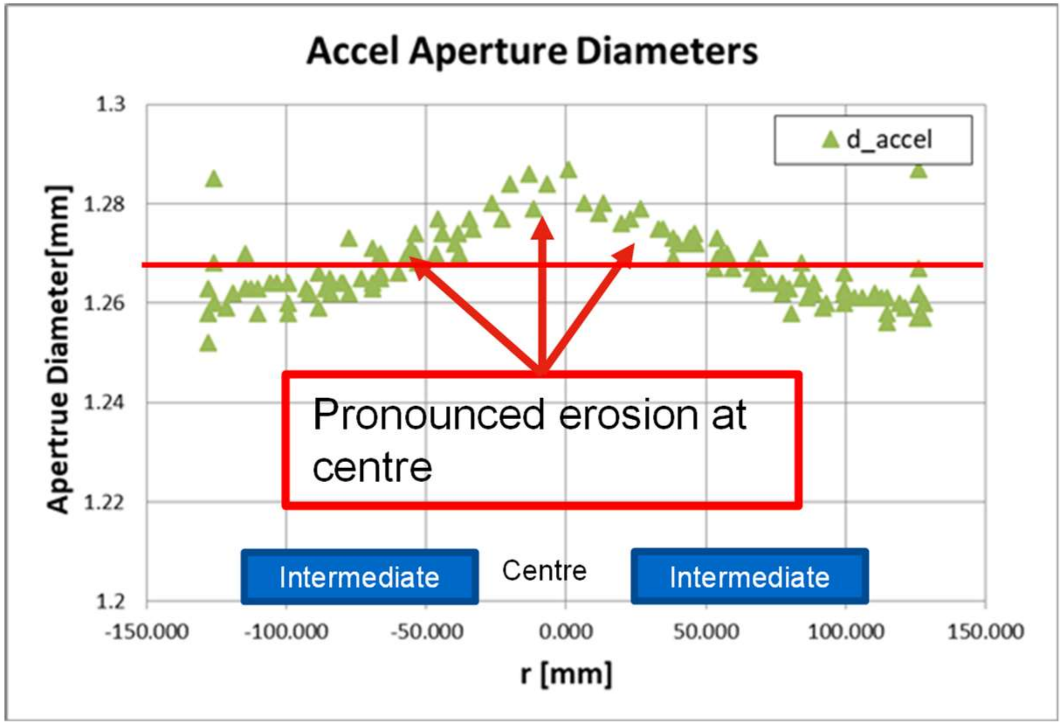




Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

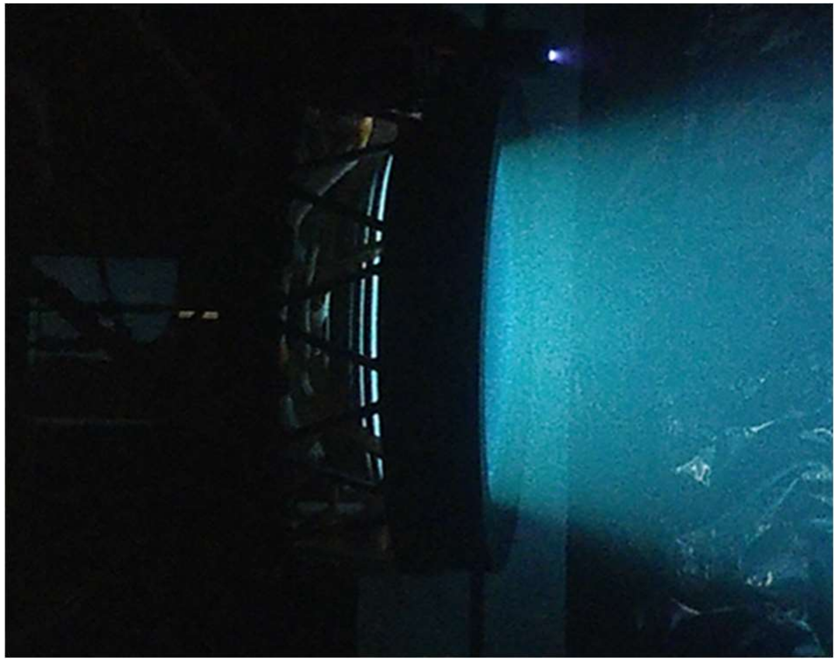
- Gridded Ion Thruster:
  - Erosion linked to position…

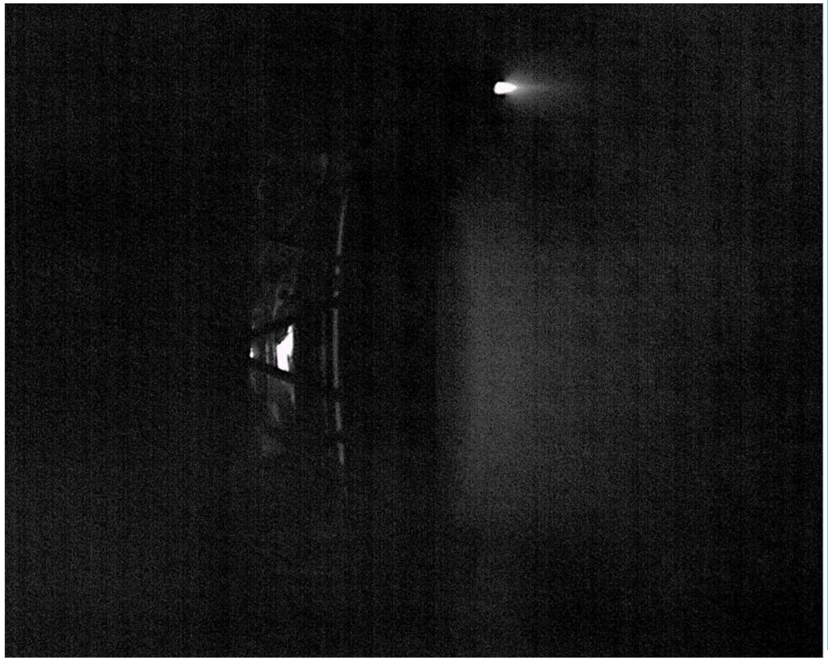


Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Gridded Ion Thruster:
  - Arcs



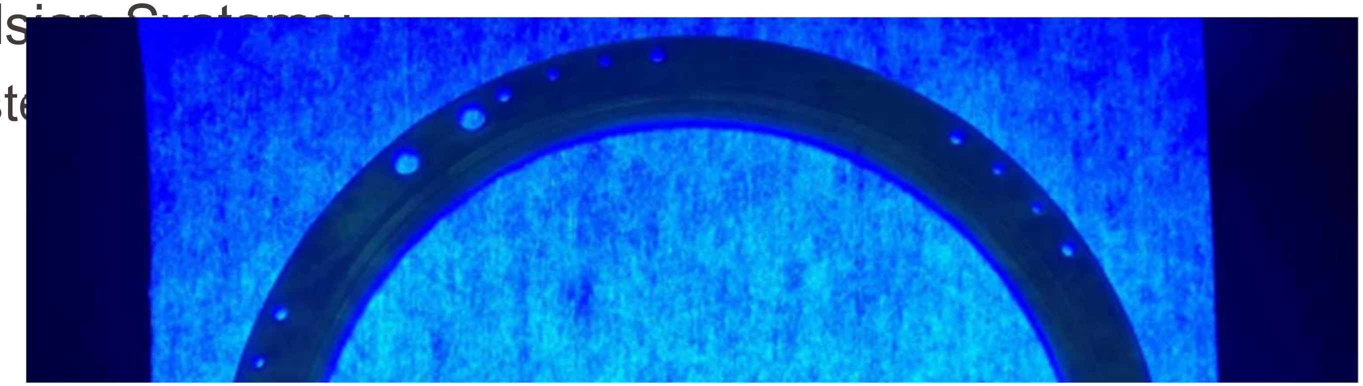



Huge thruster have the problem at
Grid systems
But not only as there is also

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

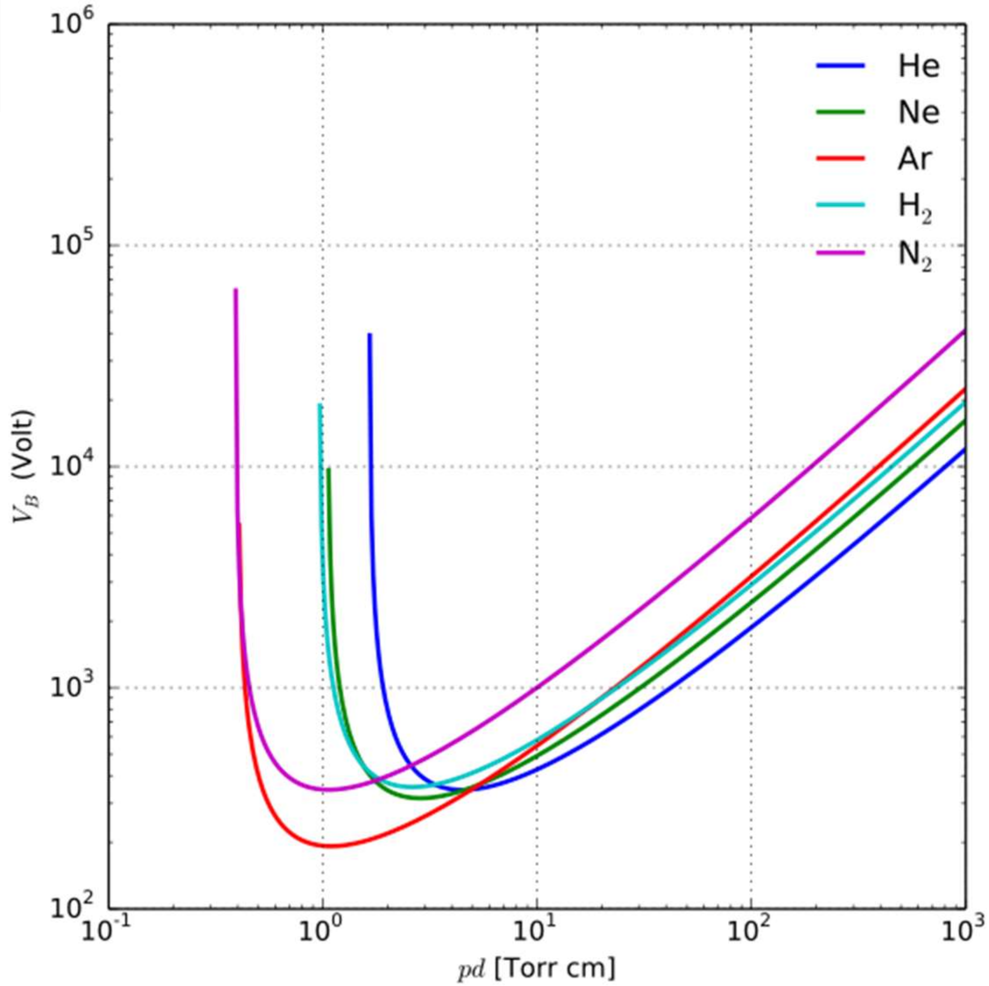
- Gridded Ion Thruste
  - Harness
  - RFG
  - Neutralizer
  - Ceramic
  - Testing on Ground (Vacuum level -> Paschen curve, sputter material)
  - Gas Inlet
  - …



Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

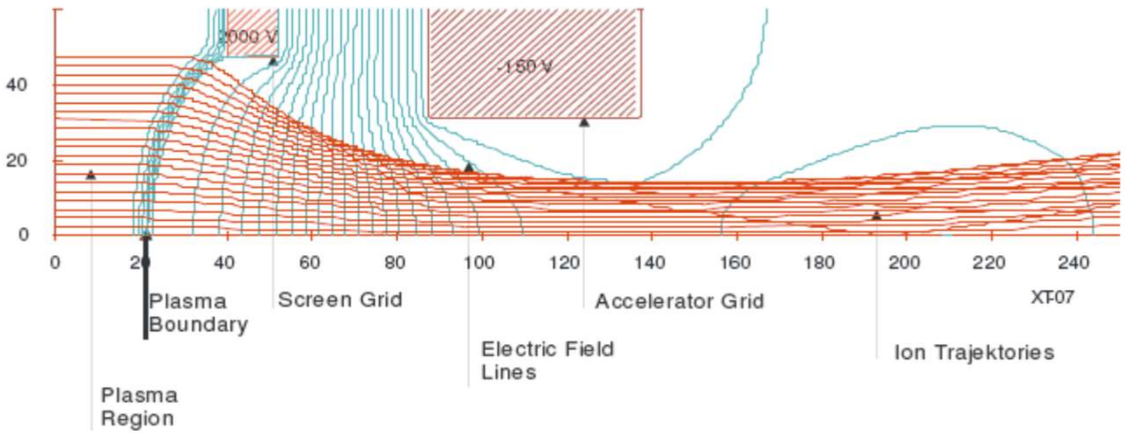
- Gridded Ion Thruster:
  - Testing on Ground
    (Vacuum level -> Paschen curve)



Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

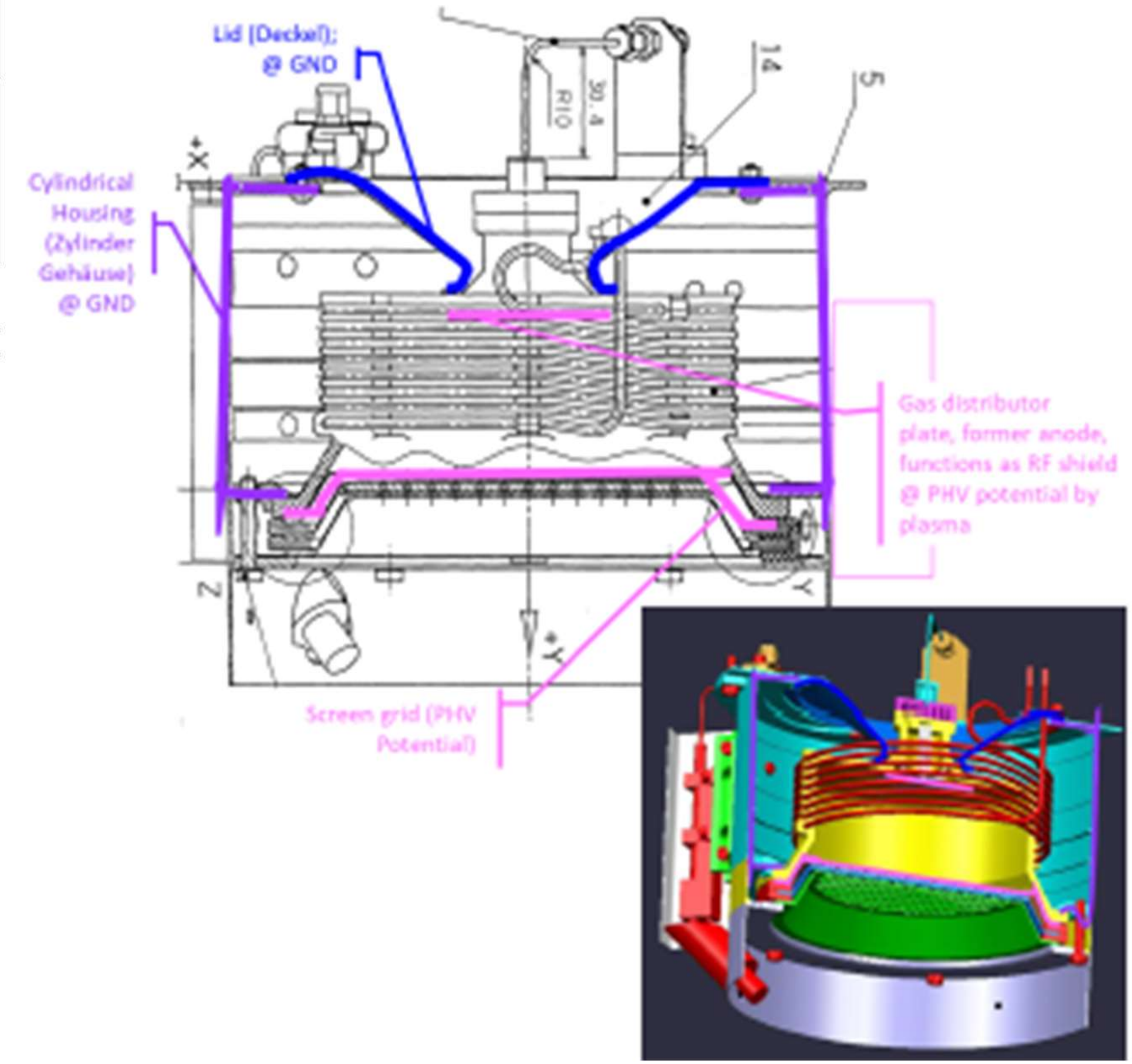
- Gridded Ion Thruster:
  - Testing on Ground (Sputter material)

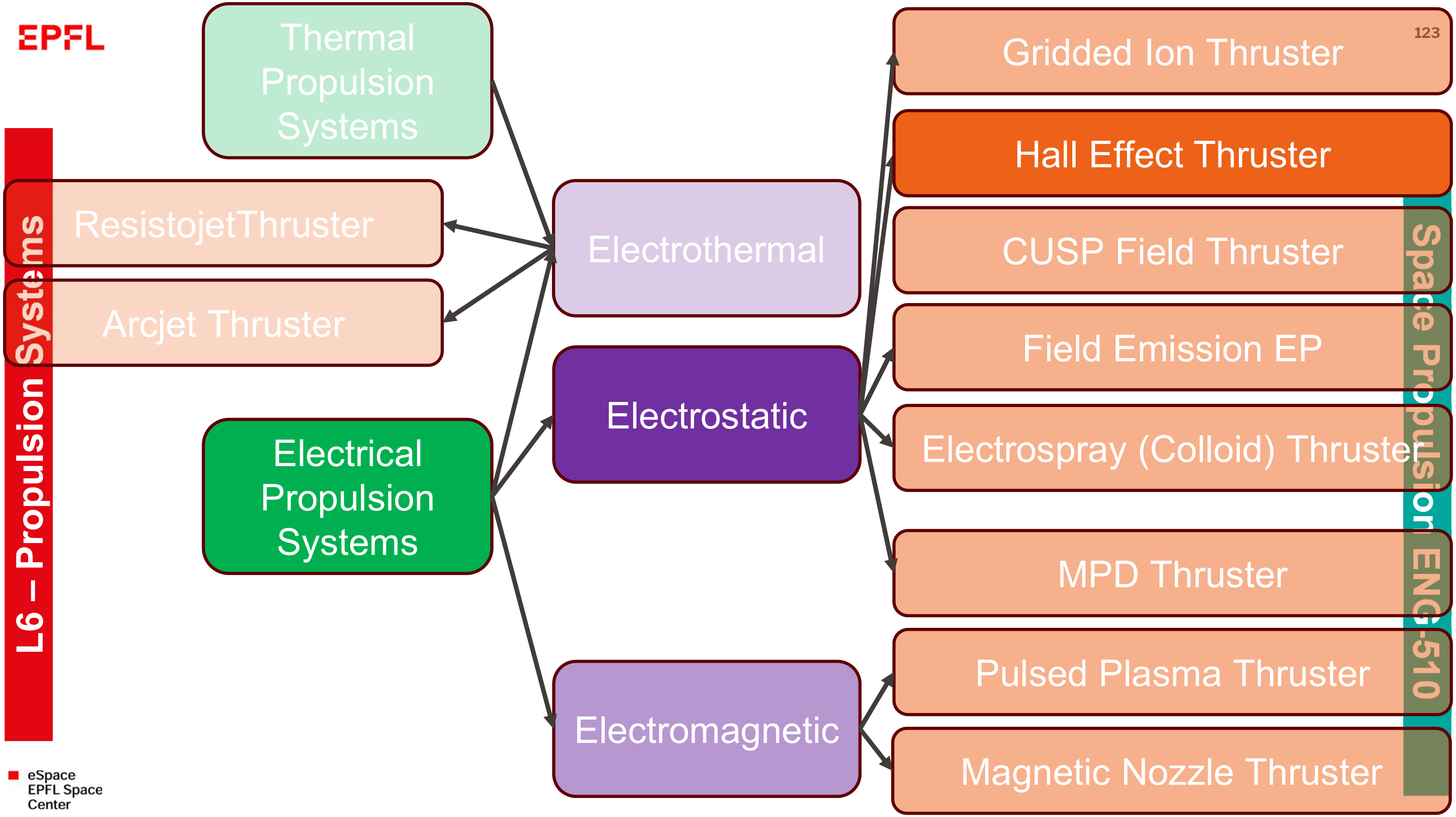


Which Electr
Propulsion S
exist?

Electrostatic Propulsic

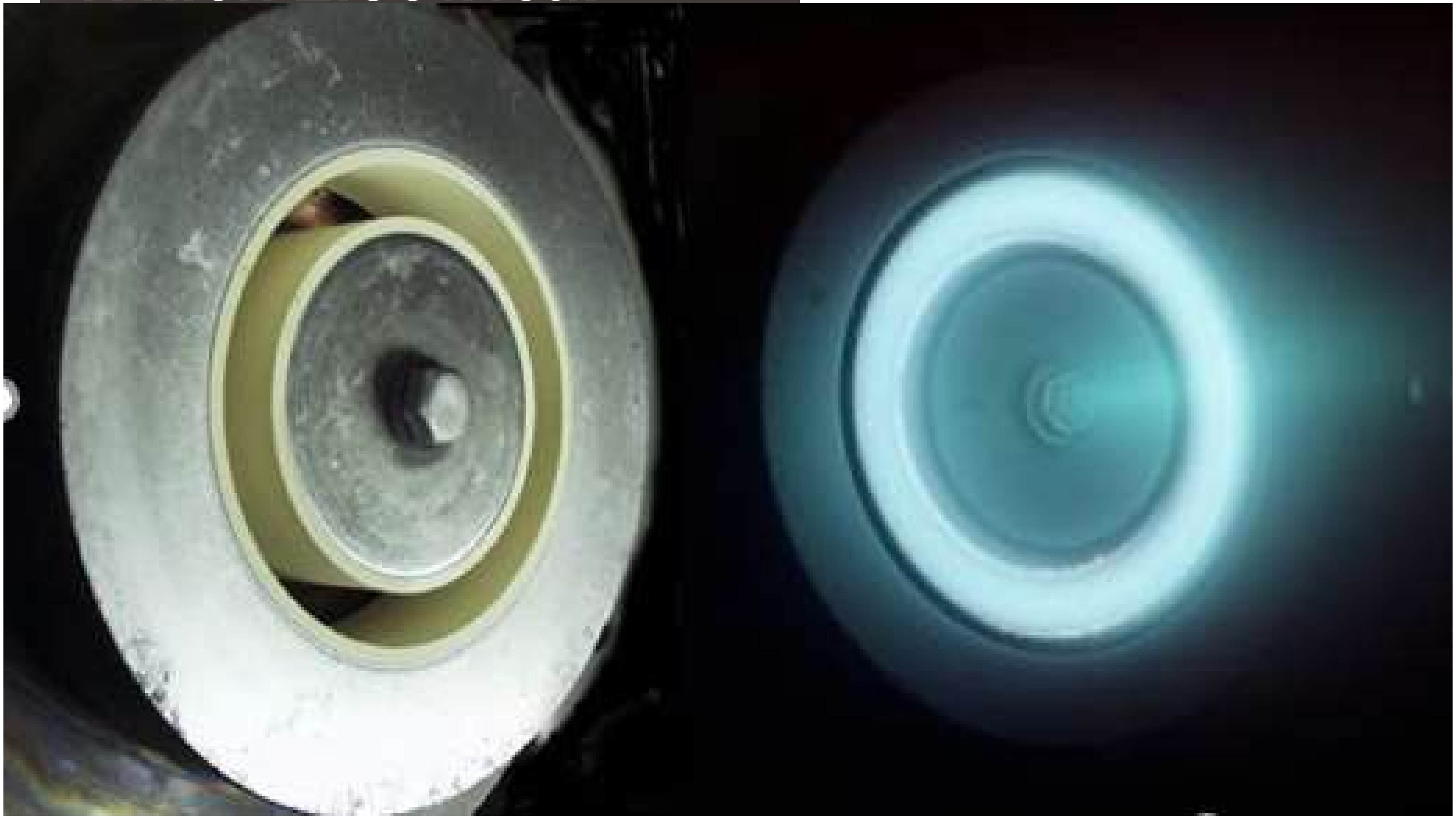
- Gridded Ion Thruster
  - Gas inlet




Thermal Propulsion Systems
ResistojetThruster
Arcjet Thruster
Electrical Propulsion Systems
Electrothermal
Electrostatic
Electromagnetic
Gridded Ion Thruster
Hall Effect Thruster
CUSP Field Thruster
Field Emission EP
Electrospray (Colloid) Thruster
MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster

EPFL

Which Electrical



Which Electrical Propulsion Systems exist?

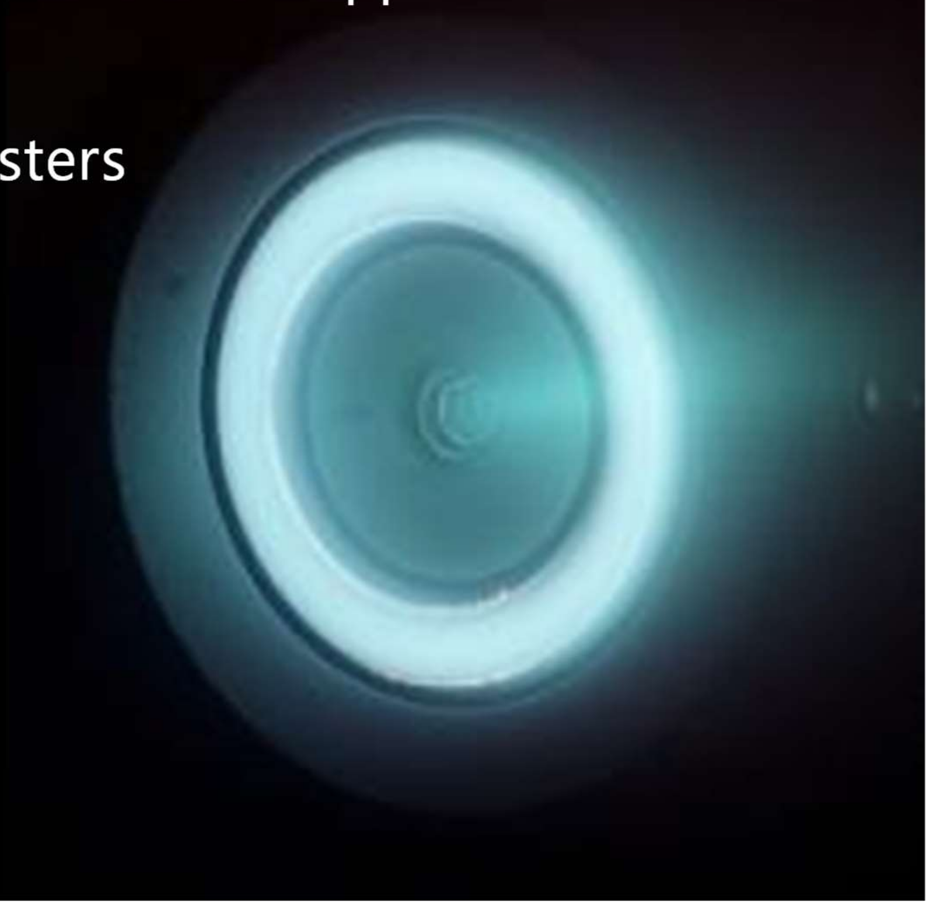
Electrostatic Propulsion Systems:

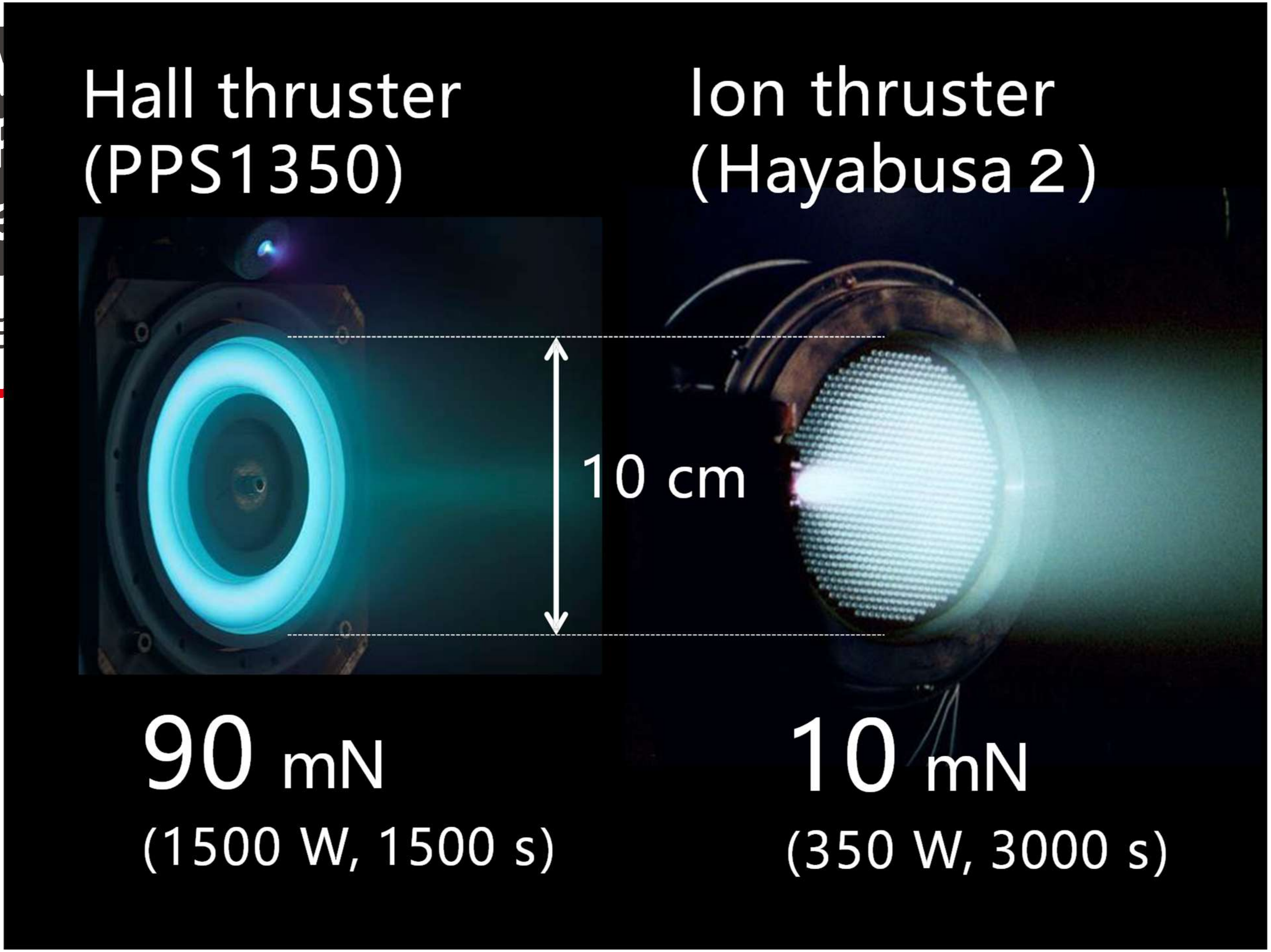
- Hall Effect Thruster:
  - This type of electrostatic thruster utilizes a cross-field discharge described by the Hall effect to generate the plasma
  - An electric field established perpendicular to an applied magnetic field electrostatically accelerates ions to high exhaust velocities, while transverse magnetic field inhibits electron motion that would tend to short out the electric field
  - Hall thruster efficiency and specific impulse is less compared to Gridded Ion thrusters, but the thrust at a given power is higher and the device is much simpler and requires fewer power supplies to operate

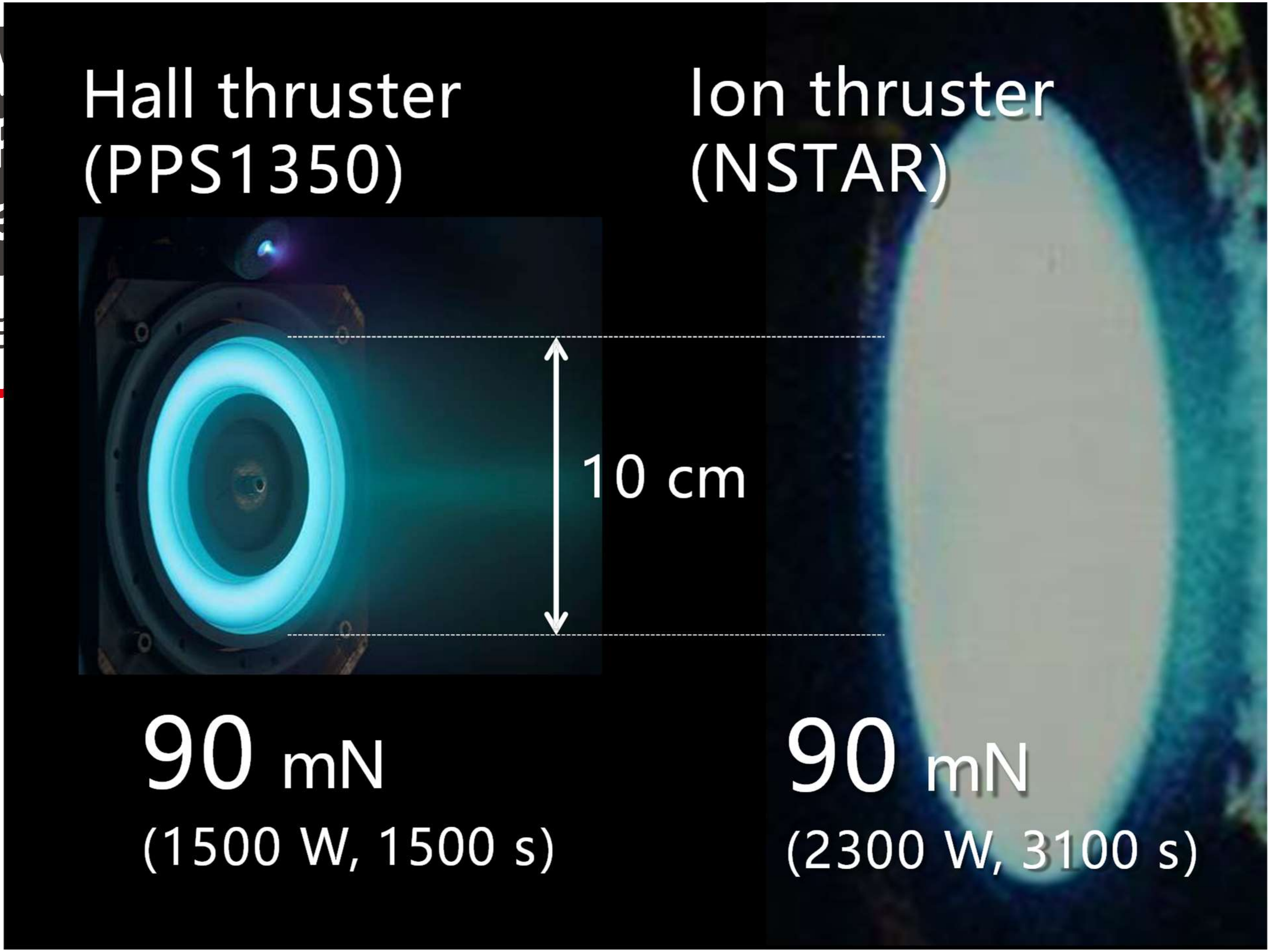
Hall-effect thruster

Ion electrostatic acceleration
in the region where electrons are trapped

Higher thrust density
compared with ion thrusters



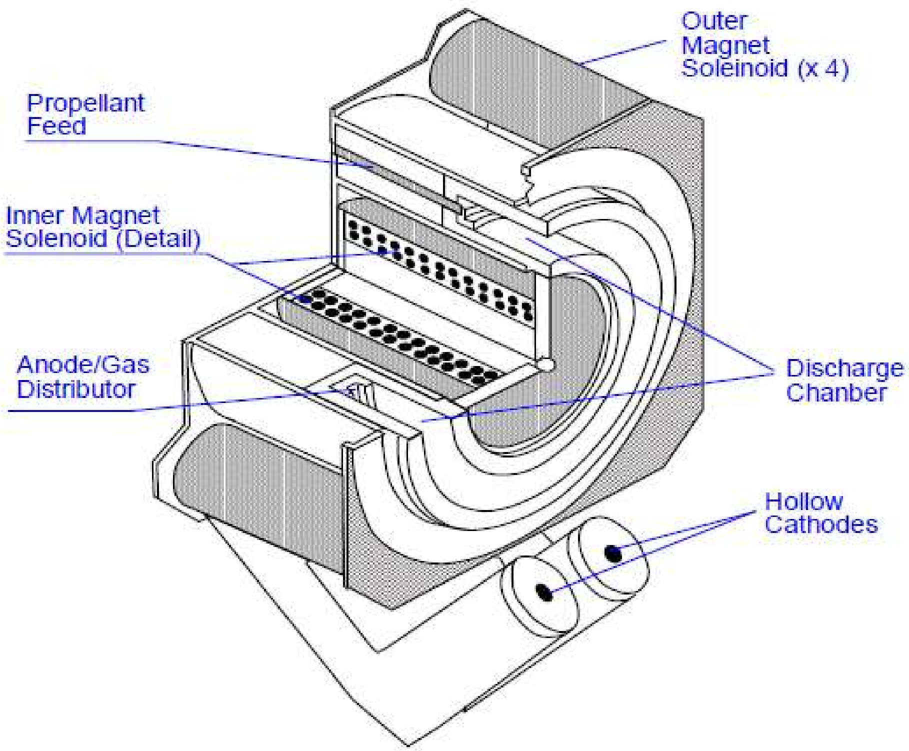

Hall thruster
(PPS1350)
Ion thruster
(Hayabusa 2)
10 cm
90 mN
(1500 W, 1500 s)
10 mN
(350 W, 3000 s)


Hall thruster
(PPS1350)
Ion thruster
(NSTAR)
10 cm
90 mN
(1500 W, 1500 s)
90 mN
(2300 W, 3100 s)

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Hall Effect Thruster:

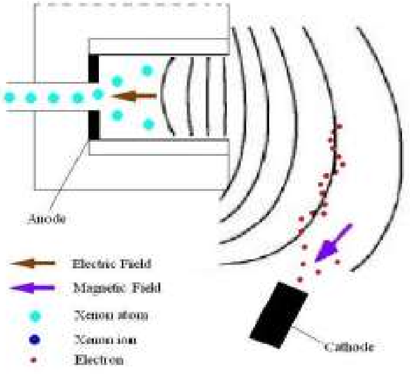


Which Electrical Propulsion Systems exist?

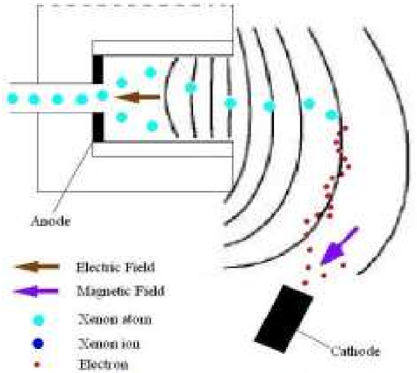
Electrostatic Propulsion Systems:

- Hall Effect Thruster:
  - Ions are produced within an annular discharge chamber by electron bombardment
    - Electrons provided by external cathode
    - Propellant flowed into discharge chamber through anode at rear of discharge chamber
    - Magnets trap the electrons, increasing ionization rate
  - Ions accelerated by electric field between anode and space
    - Cathodes also provide electrons for plume neutralization
  - HETs typically operate at 300 to 350 V
    - Higher voltages are used for higher specific impulse options
  - Beam divergence relatively high (45 ° half cone angle)

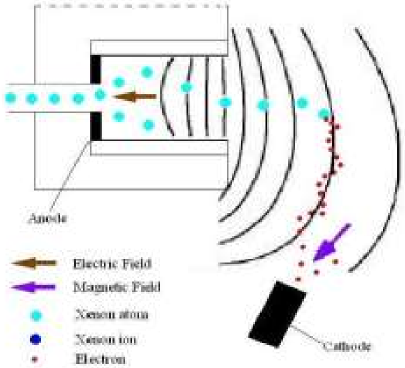
Which Electrical Propulsion Systems



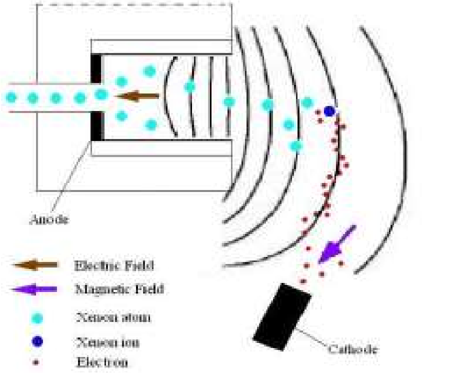
1/ Cathode electrons (e^-) are trapped in the magnetic field



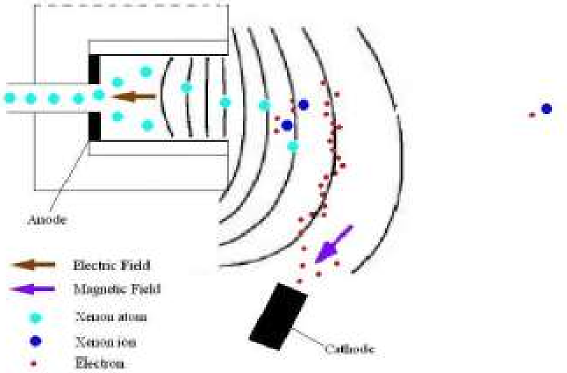
2/ Xenon (Xe) atoms are introduced in the anode



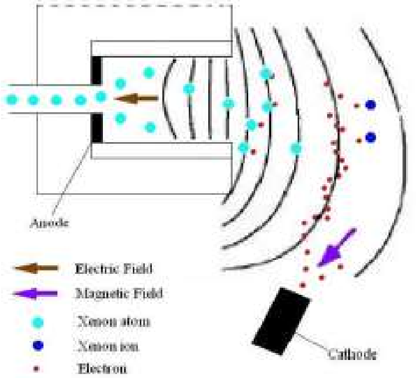
3/ One e^- collides with one Xe atom



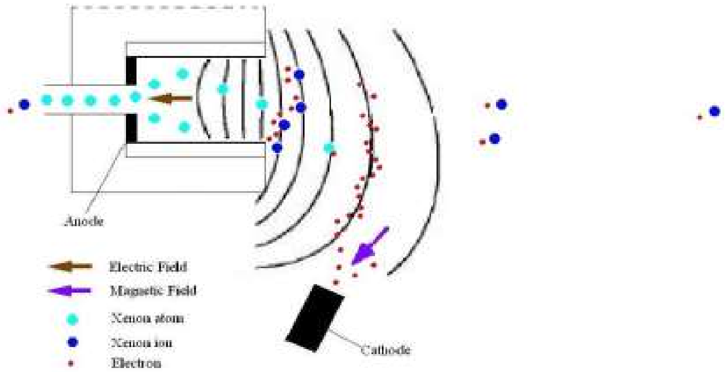
4/ When the colliding e^- has sufficient energy, the Xe atom is ionized: $Xe + e^- \rightarrow Xe^+ + 2e^-$



5/ Xe^+ is accelerated outwards by the electric field and attracts 1 e^-. The 2 e^- drift towards the anode and ionize 2 other Xe atoms



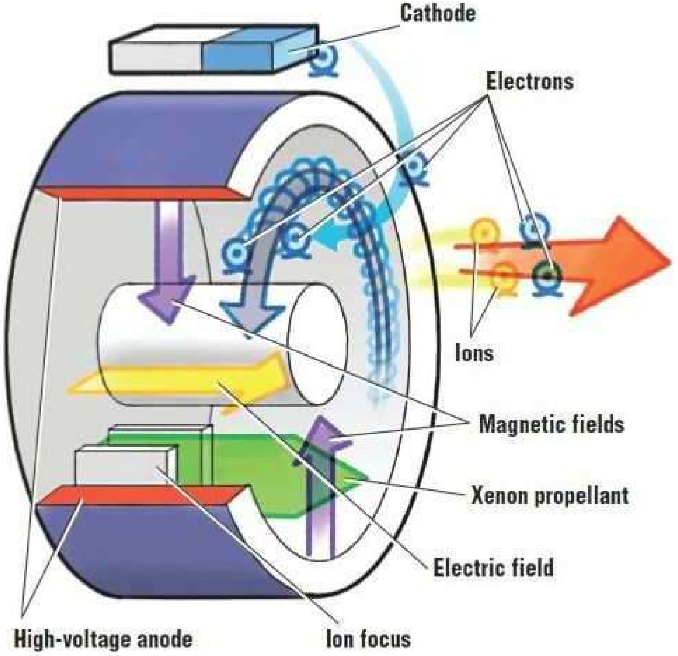
6/ The 2 new Xe^+ are accelerated and attract 2 e^- from the e^- cloud. The 4 e^- collide with 4 other Xe atoms and so on

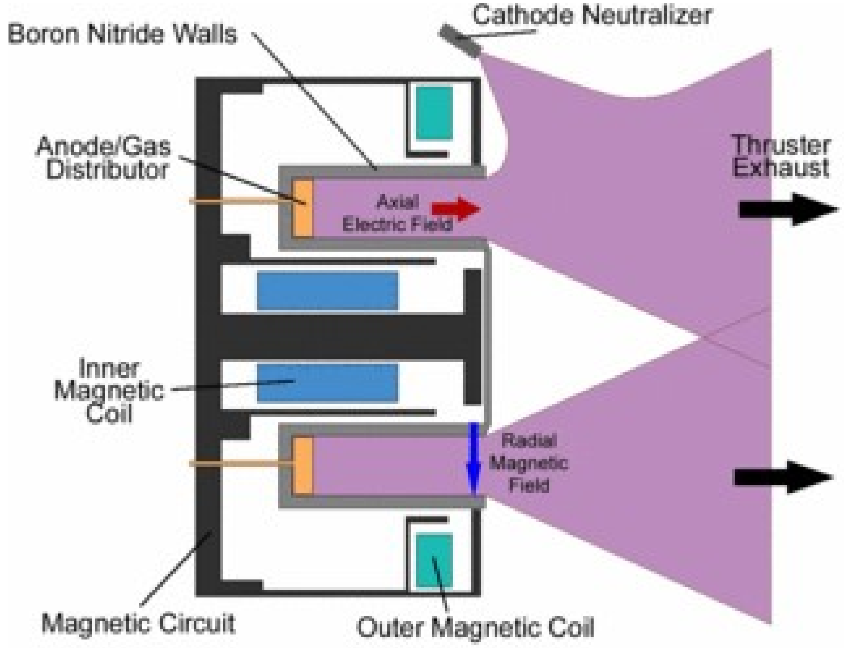


7/ The ionization process initiated by 1 e^- increases exponentially until the energy of generated e^- is insufficient to ionize Xe and they are collected by the anode

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:





Which Electrical Propulsion Systems exist?

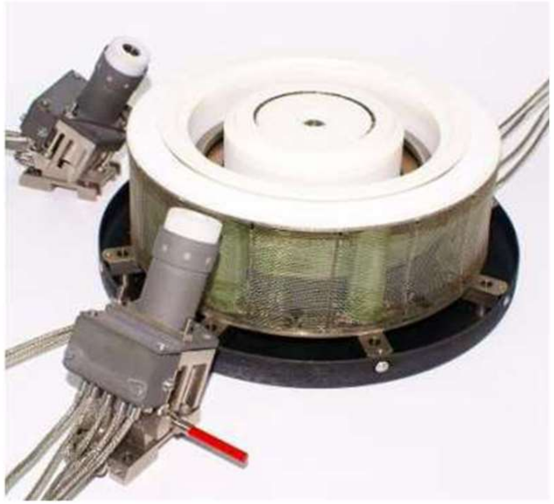
Electrostatic Propulsion Systems:

- Hall Effect Thruster:
  - This type of electrostatic thruster utilizes a cross-field discharge described by the Hall effect to generate the plasma
  - An electric field established perpendicular to an applied magnetic field electrostatically accelerates ions to high exhaust velocities, while transverse magnetic field inhibits electron motion that would tend to short out the electric field
  - Hall thruster efficiency and specific impulse is less compared to Gridded Ion thrusters, but the thrust at a given power is higher and the device is much simpler and requires fewer power supplies to operate

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Hall Effect Thruster:
  - Examples



SPT-140
(Fakel)

PPS-1350
(SNECMA)

Which Electrical Propulsion Systems exist?

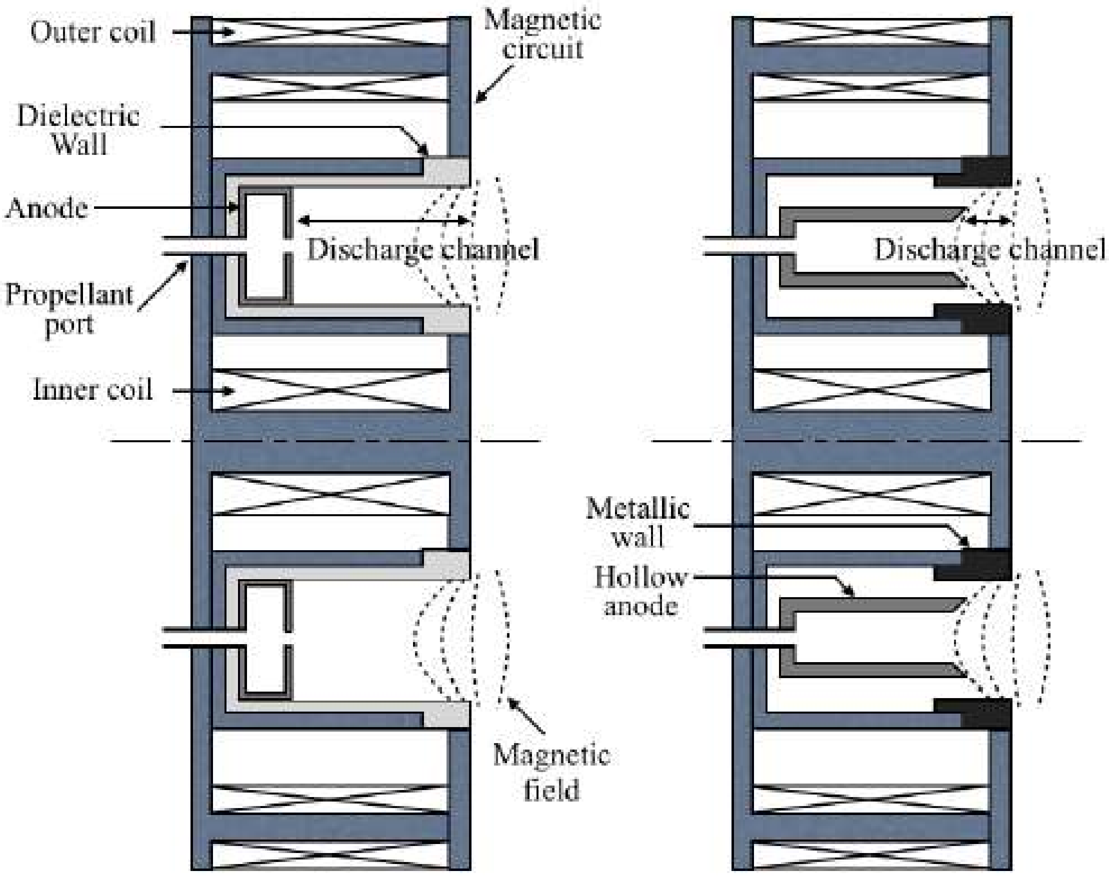
Electrostatic Propulsion Systems:

- Hall Effect Thruster:
  - Hall thrusters can be categorized into two primary types: the Thruster with Anode Layer (TAL) and the Stationary Plasma Thruster (SPT)
  - The distinguishing factor between the designs lies within the composition as well as the length of the discharge channel and, in many cases, by the position of the anode relative to the thruster body

Which Electrical Propulsion Systems exist?

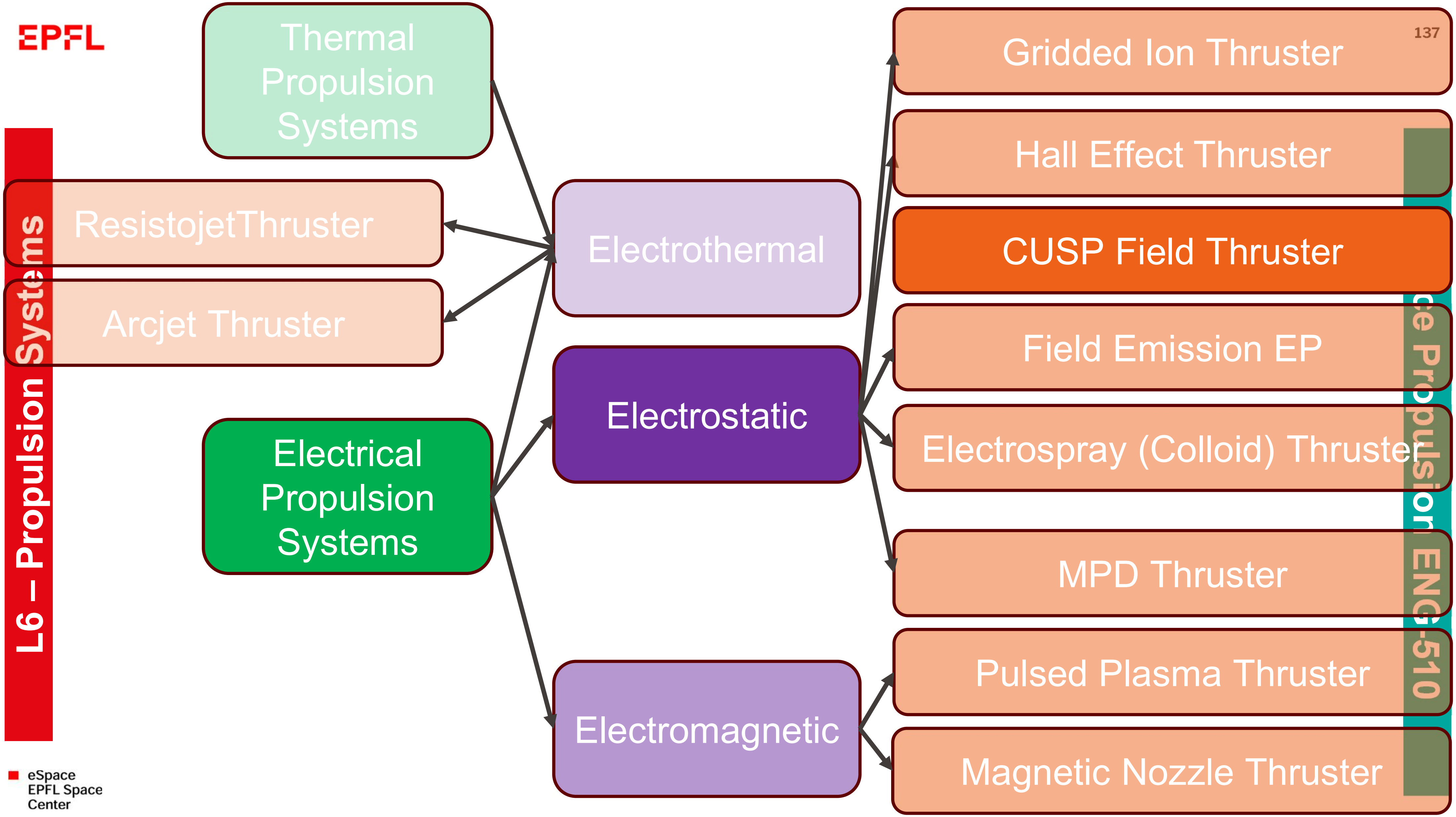
Electrostat

- Hall Effe



(a) Magnetic-layer type (SPT)

(b) Anode-layer type (TAL)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Hall Effect Thruster
CUSP Field Thruster
Field Emission EP
Electrospray (Colloid) Thruster
MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster

Which Electrical Propulsion Systems exist?

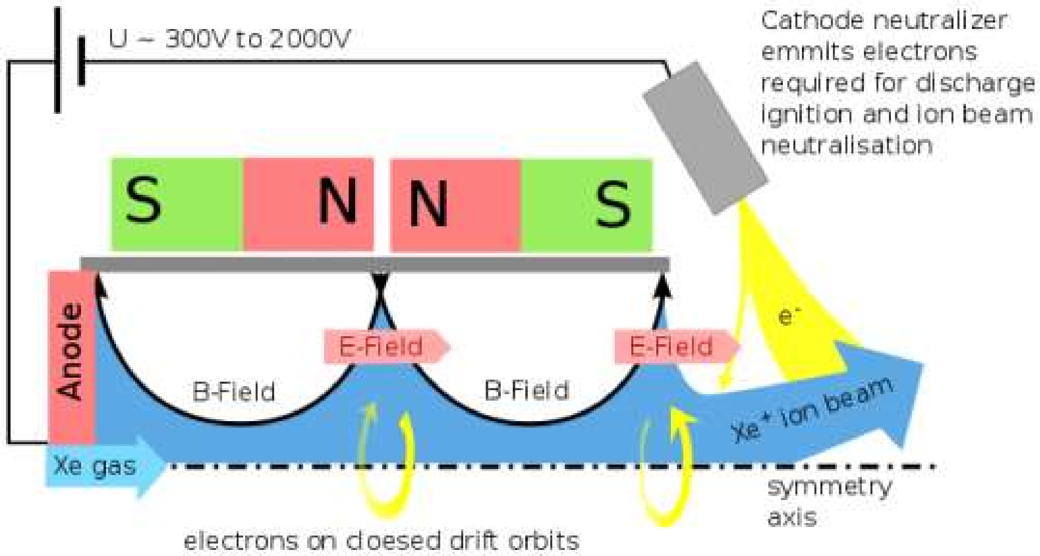
Electrostatic Propulsion System:

- ACFT (Advanced Cusp Field Thruster) / HEMPT (High Efficiency Multistage Plasma Thruster) EP
  - Cusp field thruster, also known as High Efficiency Multistage Plasma Thruster (HEMPT) and Advanced Cusp Field Thruster (ACFT), refers to the geometry of the magnetic field that influences the flow of electrons and ions
  - Similar in principle to a HET, but using a magnetic multistage cusp/mirror confinement of plasma

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- ACFT (Advanced Cusp Field Thruster) / HEMPT (High Efficiency Multistage Plasma Thruster) EP



Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- ACFT (Advanced Cusp Field Thruster) / HEMPT (High Efficiency Multistage Plasma Thruster) EP
  - Cusp field thruster comprise a dielectric, rotationally symmetric discharge channel with an anode located at the upstream end
  - The anode is connected to the power supply and represents the only high voltage electrode of the thruster
  - At the same position, the propellant inlet is located
  - The discharge channel is surrounded by a system of axially magnetized permanent magnet rings in opposite magnetization

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- ACFT (Advanced Cusp Field Thruster) / HEMPT (High Efficiency Multistage Plasma Thruster) EP
  - At the downstream end of the discharge channel, a cathode / neutraliser is placed to provide the starter electrons for igniting the plasma discharge and for neutralizing the ion beam emitted by the thruster in space
  - The electrodes create with their applied potentials inside the chamber an essentially axial electric field, which accelerates positive ions towards the chamber exit to produce thrust

Which Electrical Propulsion Systems exist?

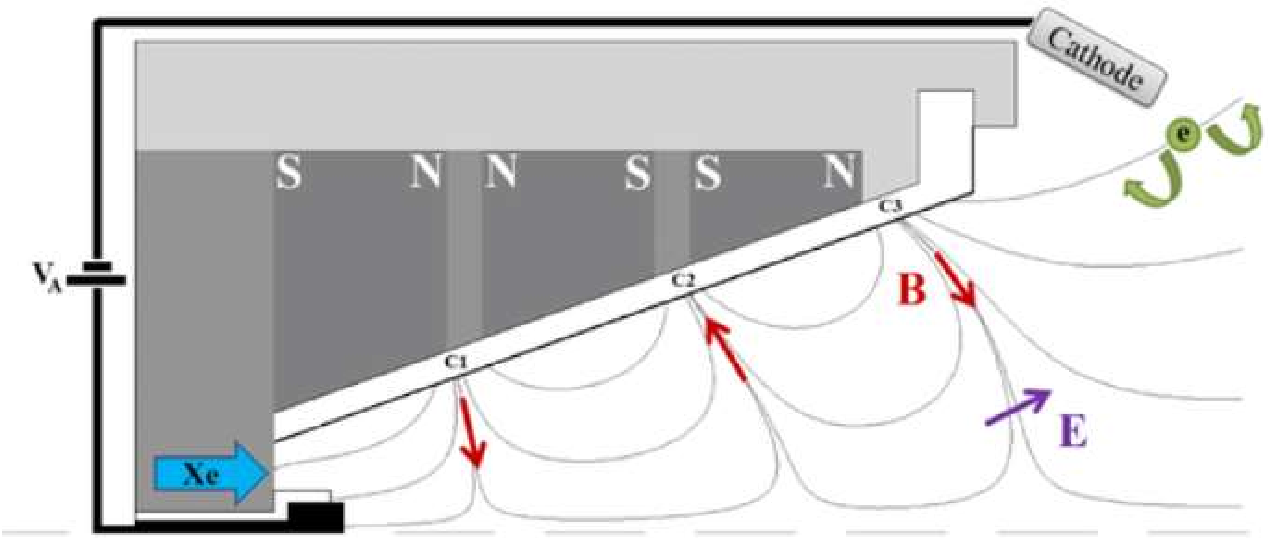
Electrostatic Propulsion System:

- ACFT (Advanced Cusp Field Thruster) / HEMPT (High Efficiency Multistage Plasma Thruster) EP
  - The magnetic rings create a magnetic field almost perpendicular to the electric field, which forces the electrons towards the anode in spiral trajectories which allows more propellant atoms to be ionised, thereby increasing efficiency
  - The magnetic field concentrates the plasma on the axis and reducing losses to the ionization chamber walls, increasing the lifetime and efficiency of the thruster
  - Their advantages are performance stability, compatibility with any noble gas, low cost and short lead-time

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- ACFT (Advanced Cusp Field Thruster) / HEMPT (High Efficiency Multistage Plasma Thruster) EP



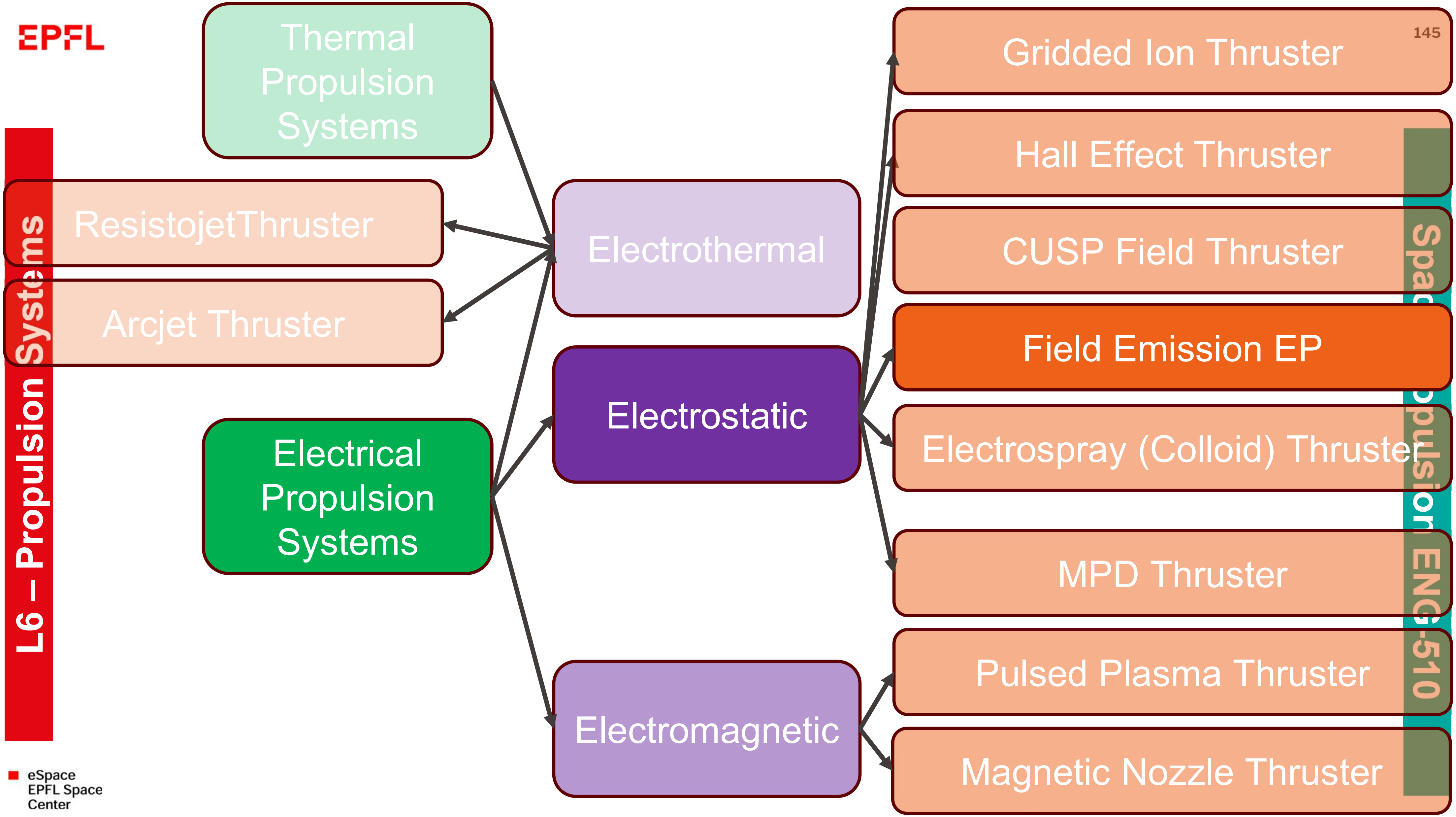
Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- ACFT (Advanced Cusp Field Thruster) / HEMPT (High Efficiency Multistage Plasma Thruster) EP

300 W Iodine CFT

10 W and 1 mN CFT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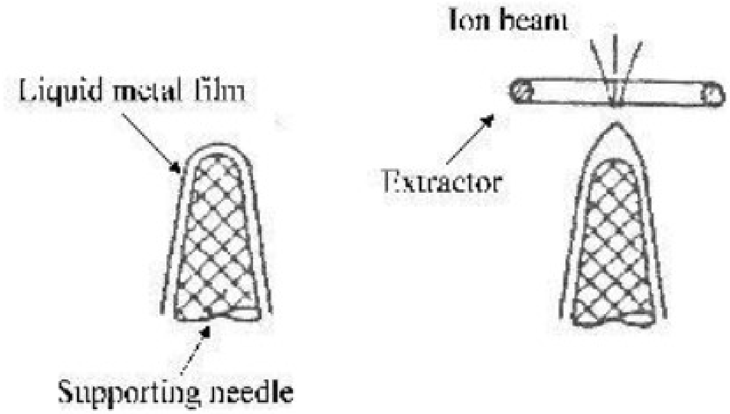
CUSP Field Thruster
Field Emission EP
Electrospray (Colloid) Thruster
MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- Field Emission Electric Propulsion
  - FEEP thruster is a type of electrostatic EP device that generate very low thrust (< 1 mN) like electrospray thruster
  - FEEP thrusters wick or transport liquid metals (typically indium or cesium) along needles, extracting ions from the sharp tip by field emission processes
  - Due to their very low thrust, these devices will be used for precision control of spacecraft position or attitude in space
  - Use of metallic propellants raises unique concerns regarding contamination of spacecraft

Which Electrical Propulsion Systems exist?



Electrostatic Propulsion System:

- Field Emission Electric Propulsion
  - Ions extracted from liquid metal surface by evaporation, and accelerated by electrostatic field
  - With strong electric field, liquid metal surface deforms into Taylor cones
    - Shape is determined by balance between electrostatic and surface tension forces
    - Above ~ 109 V/m, ions ripped from cone; these ions are then accelerated by the electric field
  - Needle effectively forms anode, with neutralizer as cathode
  - Propellant reservoir embedded within overall thruster design; propellant feed is by capillary effects

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

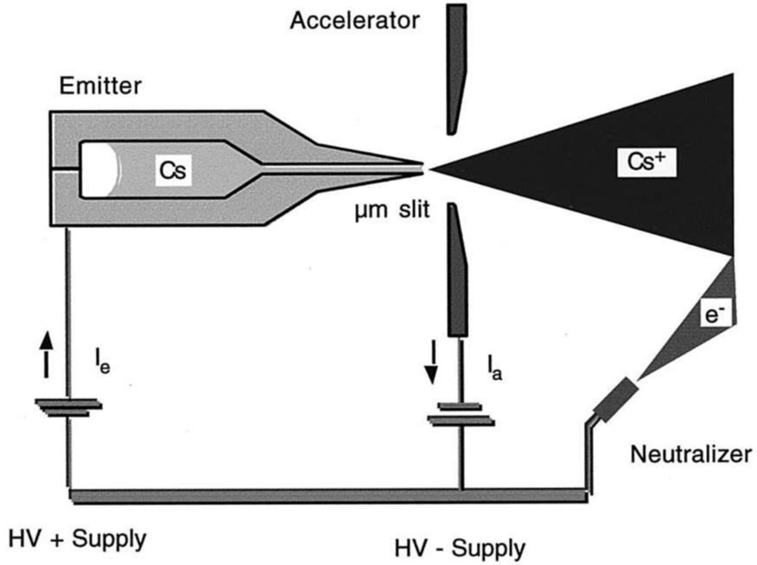


FIGURE 6 Schematic of a field emission electric propulsion

Jahn, Robert G. and Choueiri, Edgar Y., "Electric Propulsion," Encyclopedia of Physical Science and Technology, Vol.5, pp.125-141, 2001.

Which Electrical Propulsion Systems exist?

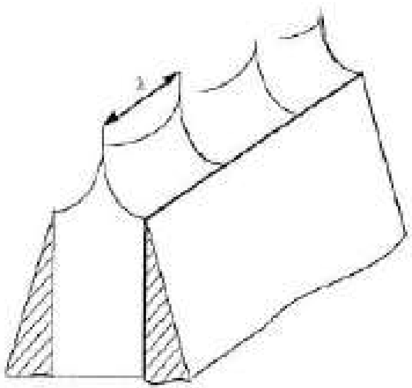
Electrostatic Propulsion System:

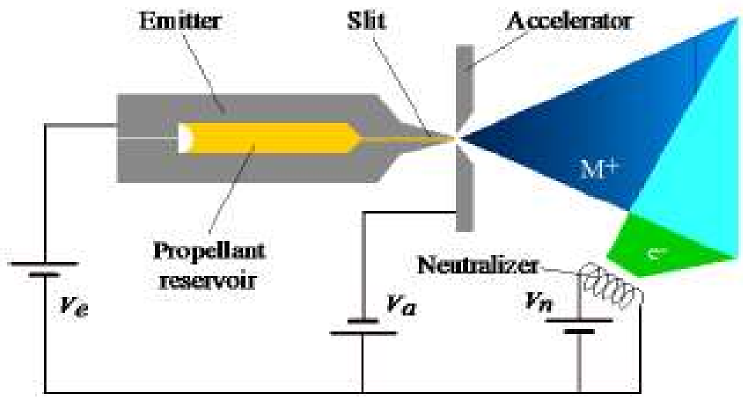
- Field Emission Electric Propulsion
  - Single needle can provide thrust levels up to around 10 µN
    - Above this level ion current is so large that emission geometry is disrupted, and droplets are emitted at lower efficiency
  - 2 main developments aimed at increasing thrust level up to > 100 µN:
    - Clustering of needles
    - Slit thruster (For the slit thruster, a series of Taylor cones is generated along the length of the slit)

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- Field Emission Electric Propulsion
  - Single needle can provide thrust levels up to around 10 μN

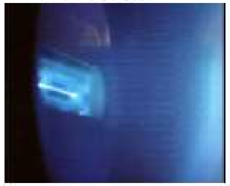
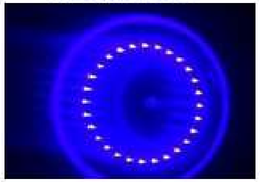


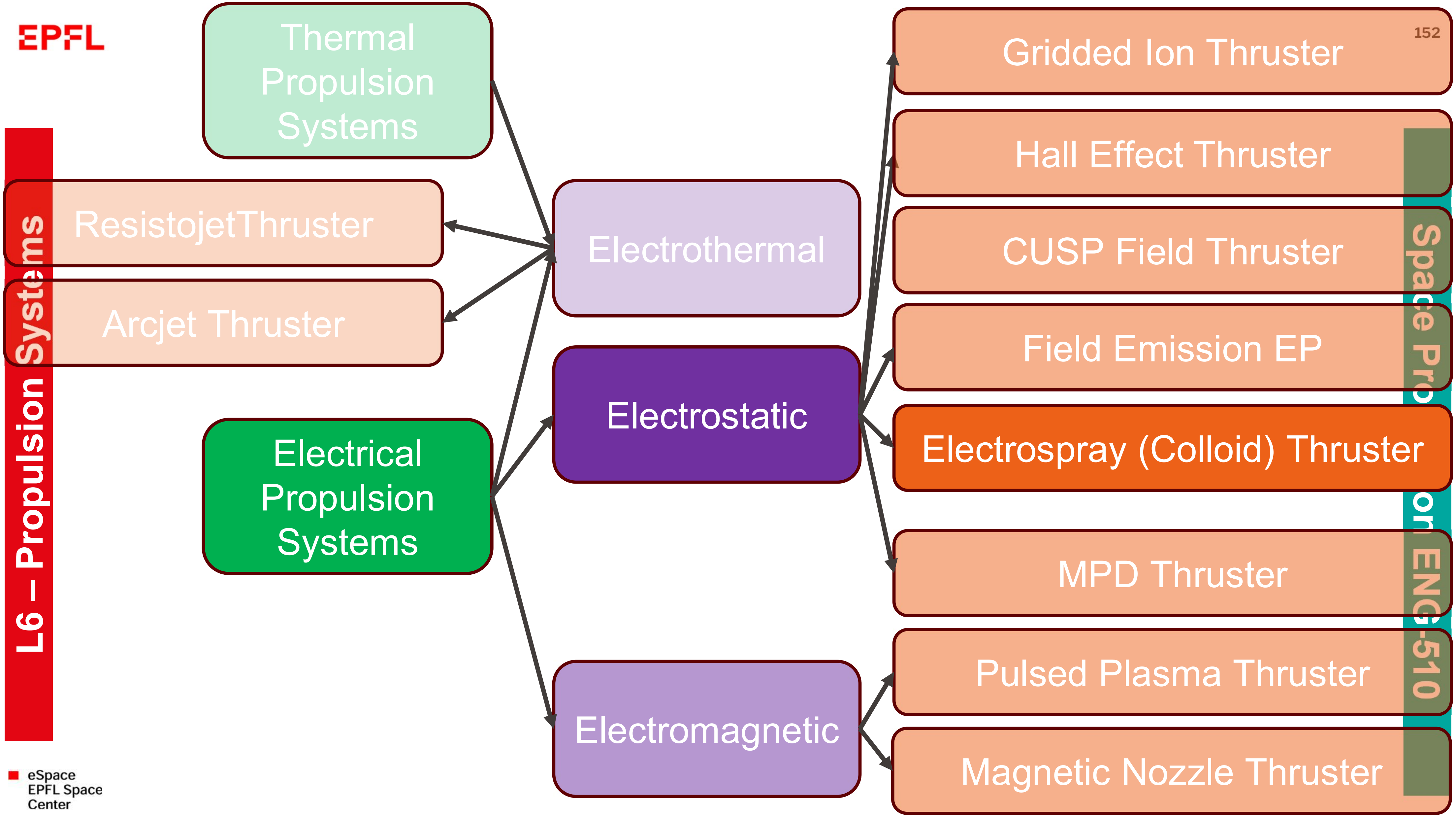


Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- Field Emission Electric Propulsion
  - Performance summary:
    - Overall voltage levels of around 7 to 9 kV

	Slit FEEP 	Needle FEEP 
Propellant	Caesium	Indium
Thrust range	0.1 to >150 μN	10 to 400 μN
Thrust resolution	50 nN	-
Thrust noise	<0.1 μN/√Hz	-
Specific Impulse	4000 to 7000 s	2000 to 6000 s
Power	51 W (4 thrusters at 100μN)	40 W at 350 μN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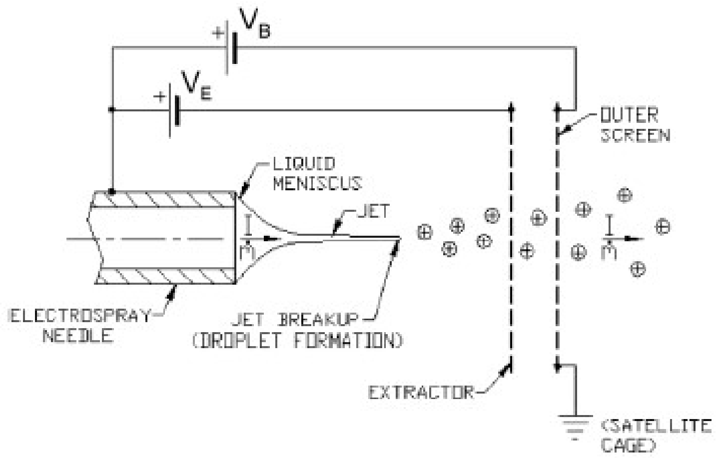
Pulsed Plasma Thruster
Magnetic Nozzle Thruster

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- Electrospray Thruster
  - Electrospray thruster is a type of electrostatic EP device that generate very low thrust (< 1 mN) like FEEP
  - Electrospray thrusters extract ions or charged droplets from conductive liquids fed through small needles and accelerate them electrostatically with biased, aligned apertures to high energy
  - Due to their very low thrust, these devices will be used for precision control of spacecraft position or attitude in space

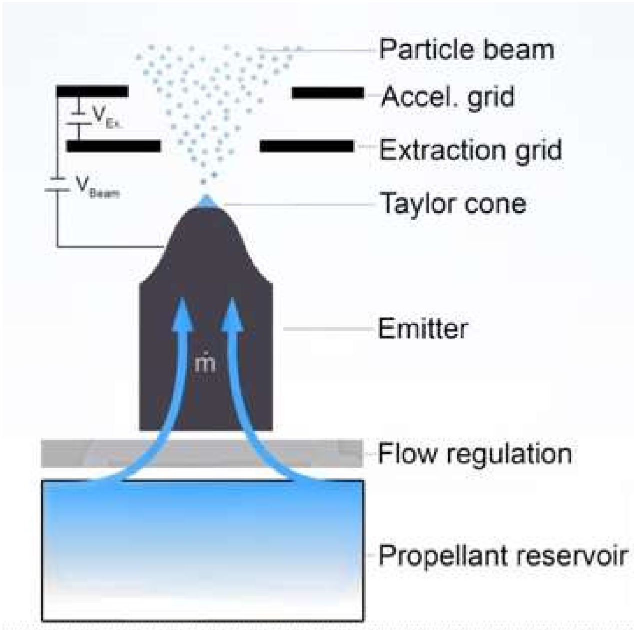
Which Electrical Propulsion Systems exist?



Electrostatic Propulsion System:

- Electrospray Thruster
  - Balance of surface tension and electrostatic forces create microscopic droplets
    - Droplet size is typically 10 to 100 nm diameter
  - Semi-conductive liquid used
  - Droplets are extracted and accelerated by either:
    - The same applied voltage, or
    - Separate extractor and accelerator voltages
  - DC operation - needle effectively forms anode, with neutralizer as cathode
    - Alternatively, needles can be separately biased +ve and –ve within an array, so no neutraliser needed

Which Electrical Propulsion Systems exist?



Electrostatic Propulsion System:

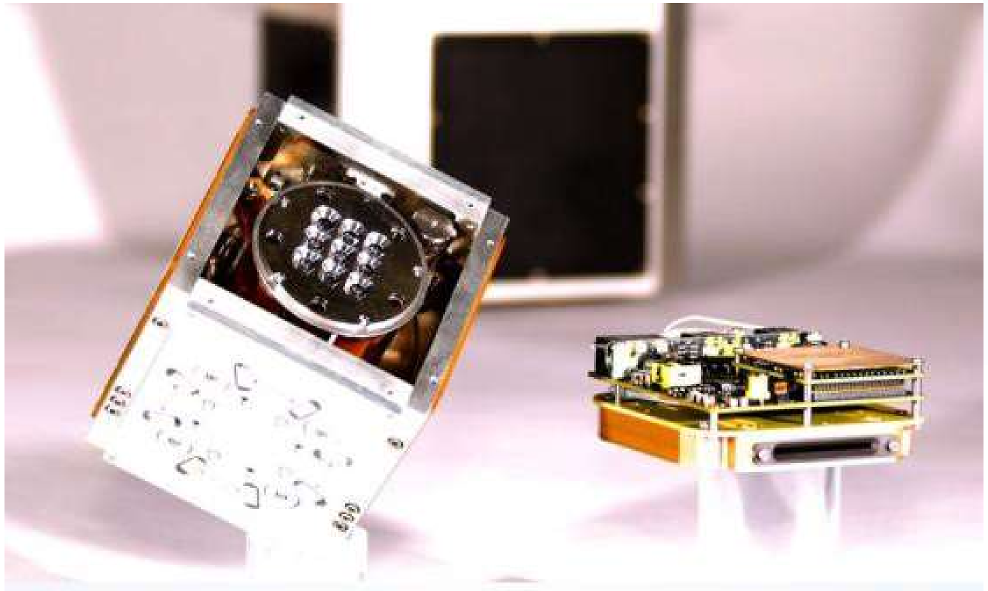
- Electrospray Thruster
  - Single needle can provide only a few µN
    - Array of needles used to provide higher thrust levels
  - Thrust controlled by acceleration voltage and / or propellant flow rate
    - Propellant feed is typically at constant pressure
  - Beam voltages up to 10 kV
  - Typical performance summary

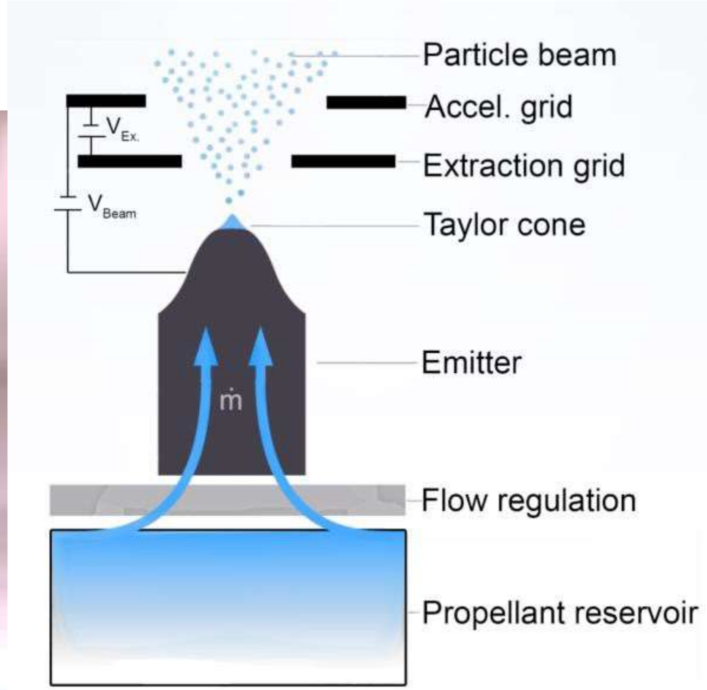
Requirement	Performance
Thrust range	4.5 to 35 µN
Thrust resolution	<0.1 µN
Thrust noise	<0.1 µN/√Hz
Specific Impulse	500 to 1500 s
Power at 35 µN	1.75 W

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- Electrospray Thruster



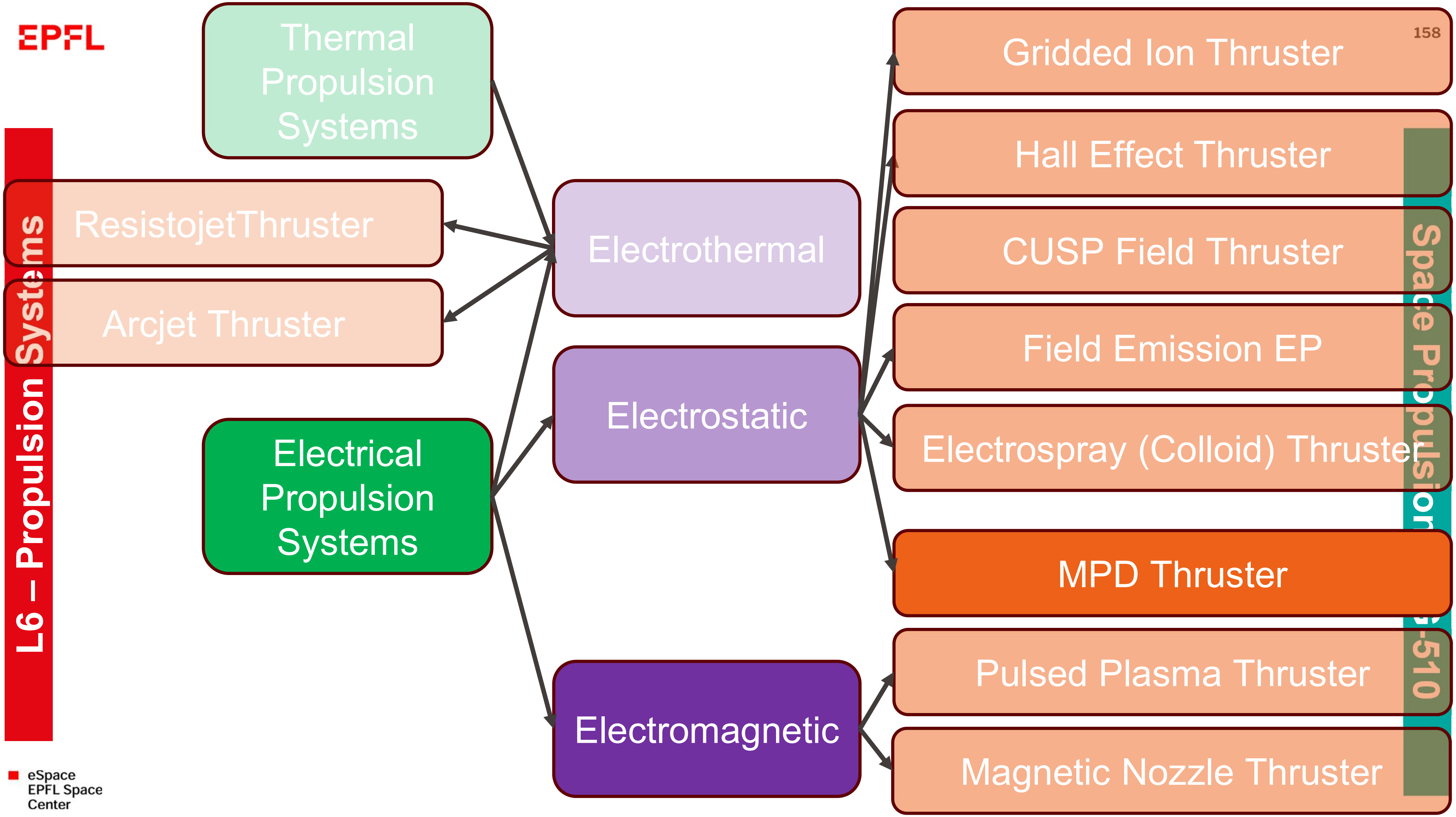


EPFL

Back-up 1

Brief overview on all space propulsion systems

eSpace
EPFL Space
Center


Thermal Propulsion Systems
Electrical Propulsion Systems
ResistojetThruster
Arcjet Thruster
Electrothermal
Electrostatic
Electromagnetic
Gridded Ion Thruster
Hall Effect Thruster
CUSP Field Thruster
Field Emission EP
Electrospray (Colloid) Thruster
MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster

Which Electric Propulsion Systems exist (32/40)?

Objective: To develop the basics of electrical propulsion

- Magnetoplasmadynamic Thruster
  - MPD thrusters are electromagnetic devices that use a very high current arc to ionize a significant fraction of the propellant and then electromagnetic forces (Lorentz J x B forces) in the plasma discharge to accelerate the charged propellant
  - Since both the current and the magnetic field are usually generated by the plasma discharge, MPD thrusters tend to operate at very high powers in order to generate sufficient force for high specific impulse operation and thereby also generate high thrust compared to the other EP systems

Which Electric Propulsion Systems exist (33/40)?

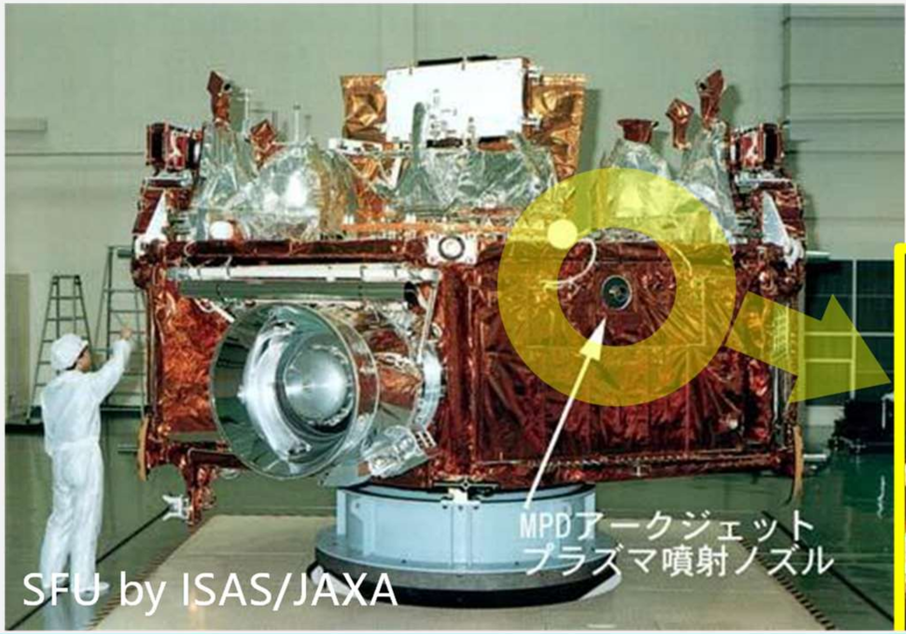
Objective: To develop the basics of electrical propulsion

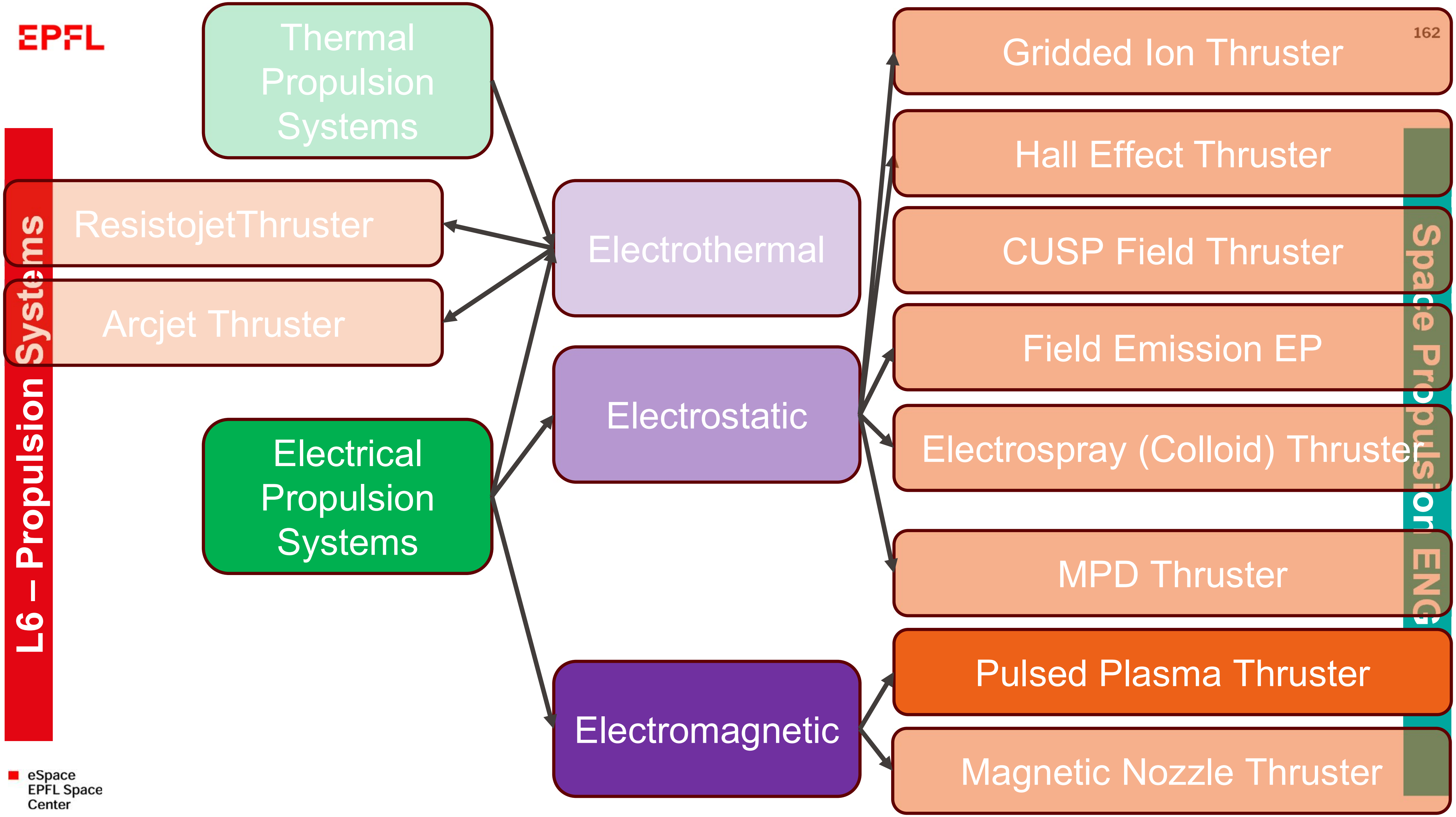
- Magnetoplasmadynamic Thruster
  - Application: only a pulsed demonstration
  - Working fluid: plasma
  - Working fluid generation: arc discharge
  - Acceleration: electromagnetic, 100 V
  - Exhaust velocity (typical): 1-20? km/s
  - Power (typical): 100 kW?

Which Electric Propulsion Systems exist (34/40)?

Objective: To develop the basics of electrical propulsion

- Magnetoplasmadynamic Thruster

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MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster

Which Electric Propulsion Systems exist (35/40)?

Objective: To develop the basics of electrical propulsion

- Pulsed Plasma Thruster
  - A PPT is an electromagnetic thruster that utilizes a pulsed discharge to ionize a fraction of a solid propellant ablated into a plasma arc and electromagnetic effects in the pulse to accelerate the ions to high exit velocity
  - The pulse repetition rate is used to determine the thrust level

Which Electric Propulsion Systems exist (36/40)?

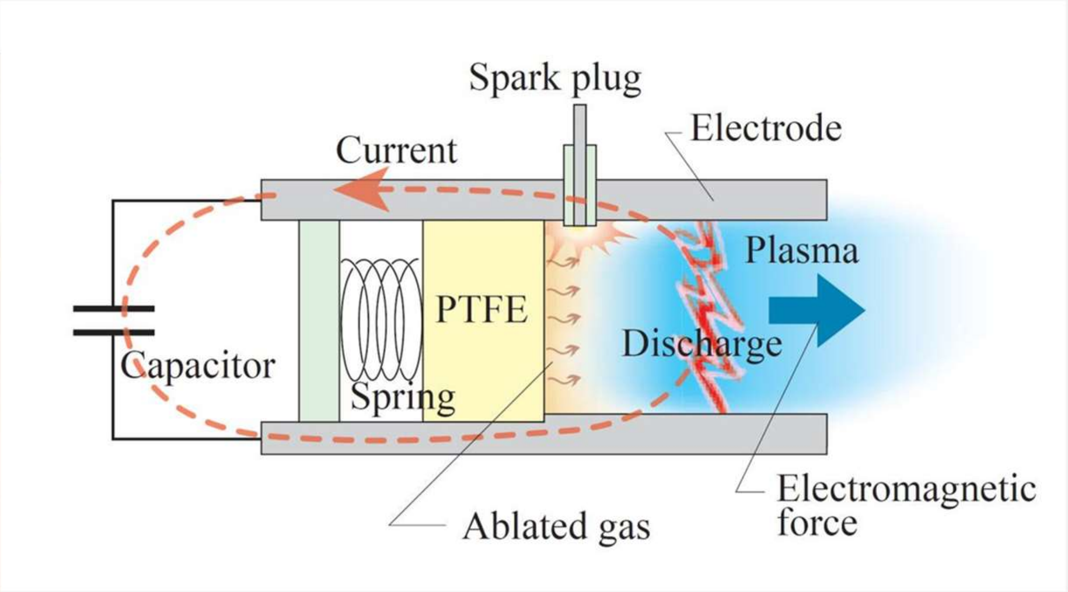
Objective: To develop the basics of electrical propulsion

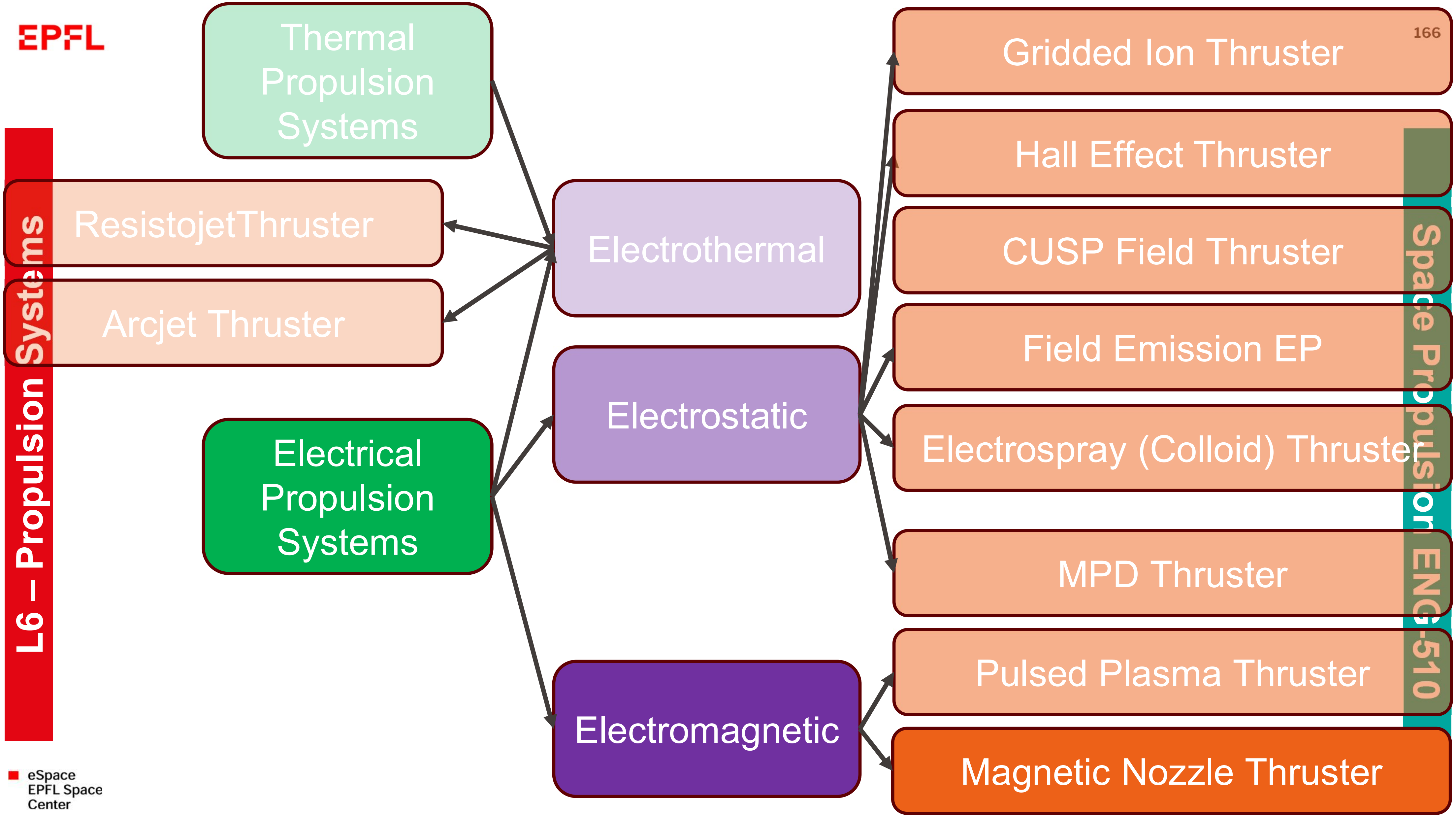
- Pulsed Plasma Thruster
  - Application: several demonstrations
  - Working fluid: plasma
  - Working fluid generation: pulsed arc discharge
  - Acceleration: electromagnetic / electrothermal, 1-3 kV
  - Exhaust velocity (typical): 5-20 km/s
  - Power (typical): 10 W

Which Electric Propulsion Systems exist (37/40)?

Objective: To develop the basics of electrical propulsion

- Pulsed Plasma Thruster

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Magnetic Nozzle Thruster

Which Electric Propulsion Systems exist (38/40)?

Objective: To develop the basics of electrical propulsion

- Magnetic Nozzle Thruster
  - A magnetic nozzle is a convergent-divergent magnetic field that guides, expands and accelerates a plasma jet into vacuum
  - The magnetic field in a magnetic nozzle plays a similar role to the convergent-divergent solid walls in a Laval nozzle, wherein a hot neutral gas is expanded first sub sonically and then supersonically to increase the thrust
  - A magnetic nozzle converts the internal energy of the plasma into directed kinetic energy due to interaction of the applied magnetic field with the electric charges
  - The main advantage of a magnetic nozzle over a solid one is that it can operate contactless, i.e. avoiding the material contact with the hot plasma

Which Electric Propulsion Systems exist (39/40)?

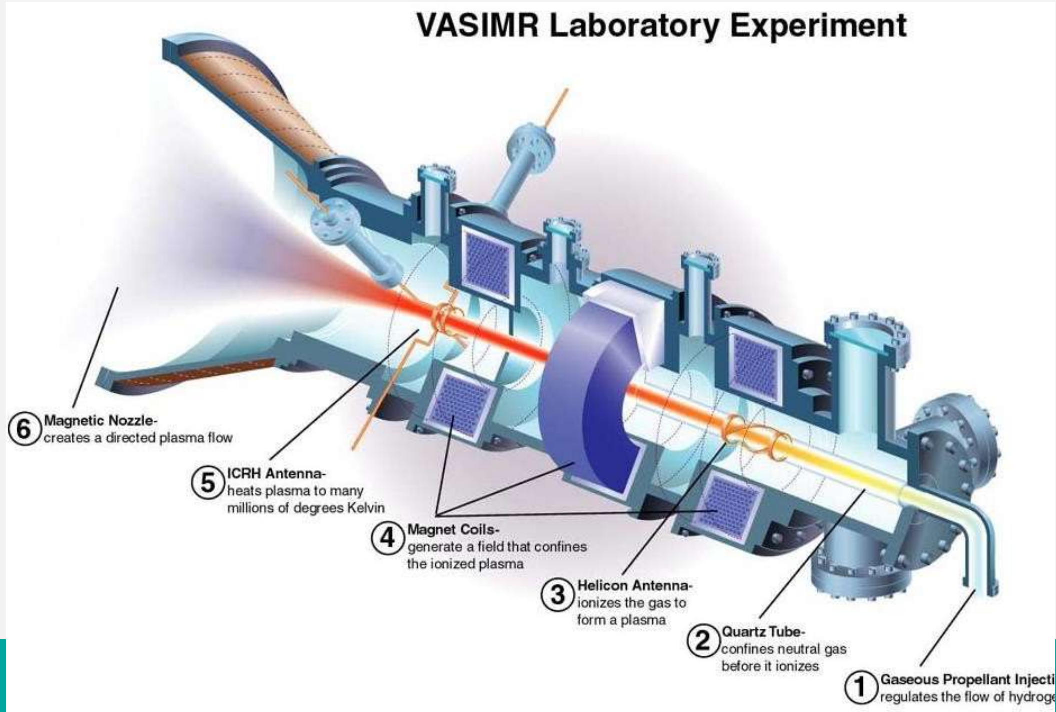
Objective: To develop the basics of electrical propulsion

- Magnetic Nozzle Thruster
  - Application: not yet
  - Working fluid: plasma
  - Working fluid generation: RF, Helicon, etc
  - Acceleration: plasma potential, magnetic mirror, ion heat
  - Exhaust velocity (typical): 1-20? km/s
  - Power (typical): 1 MW?

Which Electric Propulsion Systems exist (40/40)?

Objective: To develop the basics of electrical propulsion

- Magnetic Nozzle Thruster



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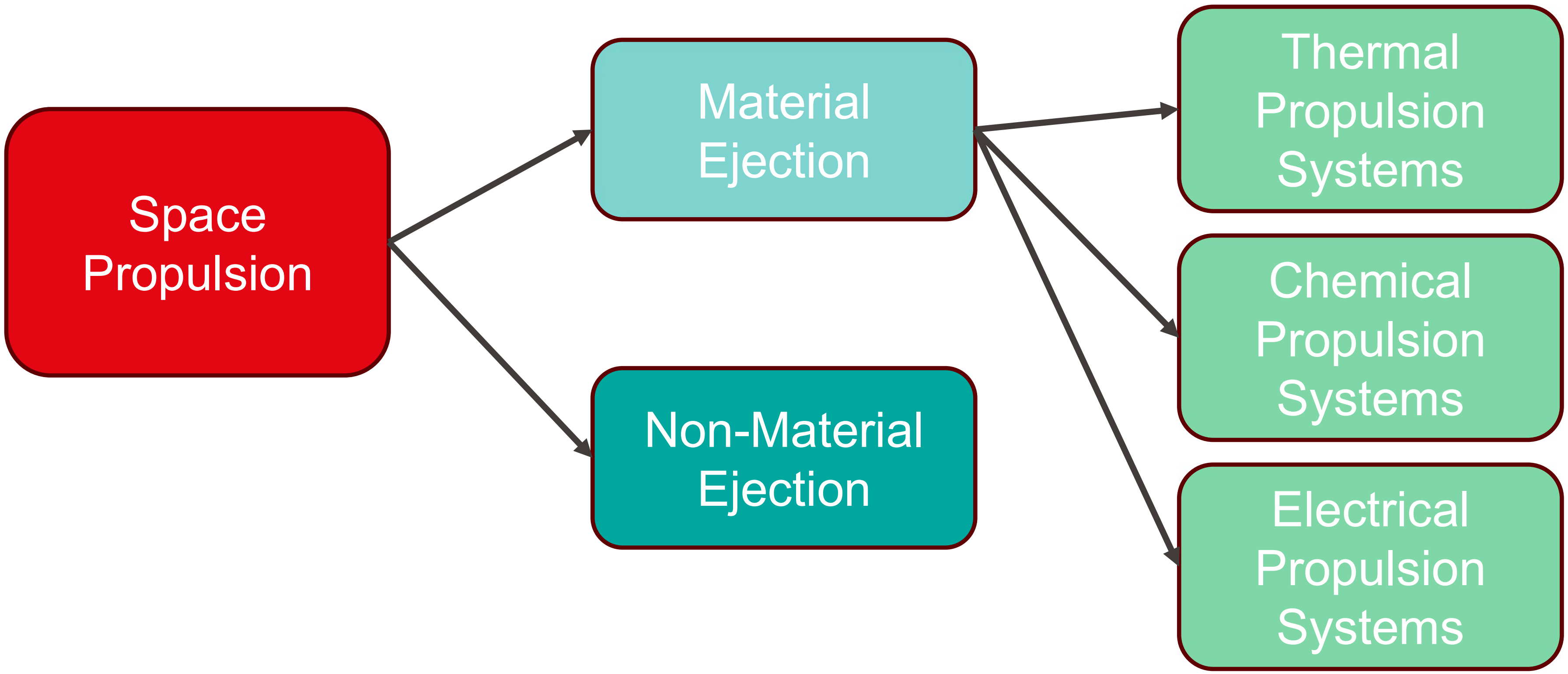
Back-up 2

Brief overview on all space propulsion systems

Which Electrical Propulsion Systems exist?

Electrical Propulsion Systems:



Which Propulsion Systems do we know (1/3)?

Objective: To categorize different space propulsion systems

- Energy type and propulsion systems:
  - Nuclear fusion -> Not applicable
  - Nuclear fission -> Nuclear thermal propulsion and nuclear electric propulsion
  - Chemical reaction -> Chemical propulsion
  - Pressure release -> Pneumatic propulsion
  - Electrical battery -> See solar power
  - Solar power -> Solar (radiant) electric propulsion
  - Others… -> To be discussed

Which Propulsion Systems do we know (2/3)?

Objective: To categorize different space propulsion systems

- Propulsion System categorization linked to energy conversion type:
  - Pneumatical Propulsion Systems (e.g. cold gas systems)
  - Chemical (Combustion) Propulsion Systems
  - Electrical Propulsion Systems (including Nuclear Electrical Propulsion)
  - Thermal Propulsion Systems
  - Others…like nuclear energy / radiant energy

Recap: It is difficult to categorize space propulsion systems

Which Propulsion Systems do we know (3/3)?

Objective: To categorize different space propulsion systems

- Propulsion System categorization linked to energy conversion type:
  - ~~Pneumatical Propulsion Systems (e.g. cold gas systems)~~
  - ~~Chemical (Combustion) Propulsion Systems~~
  - ~~Electrical Propulsion Systems (including Nuclear Electrical Propulsion)~~
  - ~~Thermal Propulsion Systems (including Nuclear Thermal Propulsion)~~
  - Others…like nuclear energy / radiant energy

  - Classical space propulsion systems are today limited as delta v is linked to propellant mass

Recap: It is difficult to categorize space propulsion systems

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What is the future of Space Propulsion (1/x)?

Overview

- Air-augmented rockets (e.g. ramjet, scramjet)
- Rocket advancements
  - High energy chemical fuels
  - Nuclear rockets
  - Propulsion by annihilating antimatter
  - Magnetic thrust chambers

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What is the future of Space Propulsion (2/x)?

Overview

- Non-rocket advancements
  - Solar power
  - External beamed power (e.g. Laser)
  - Catapult launch (e.g. spin launch)
  - Tether propulsion systems
- Interstellar flight
  - ???

What is the future of Space Propulsion (3/x)?

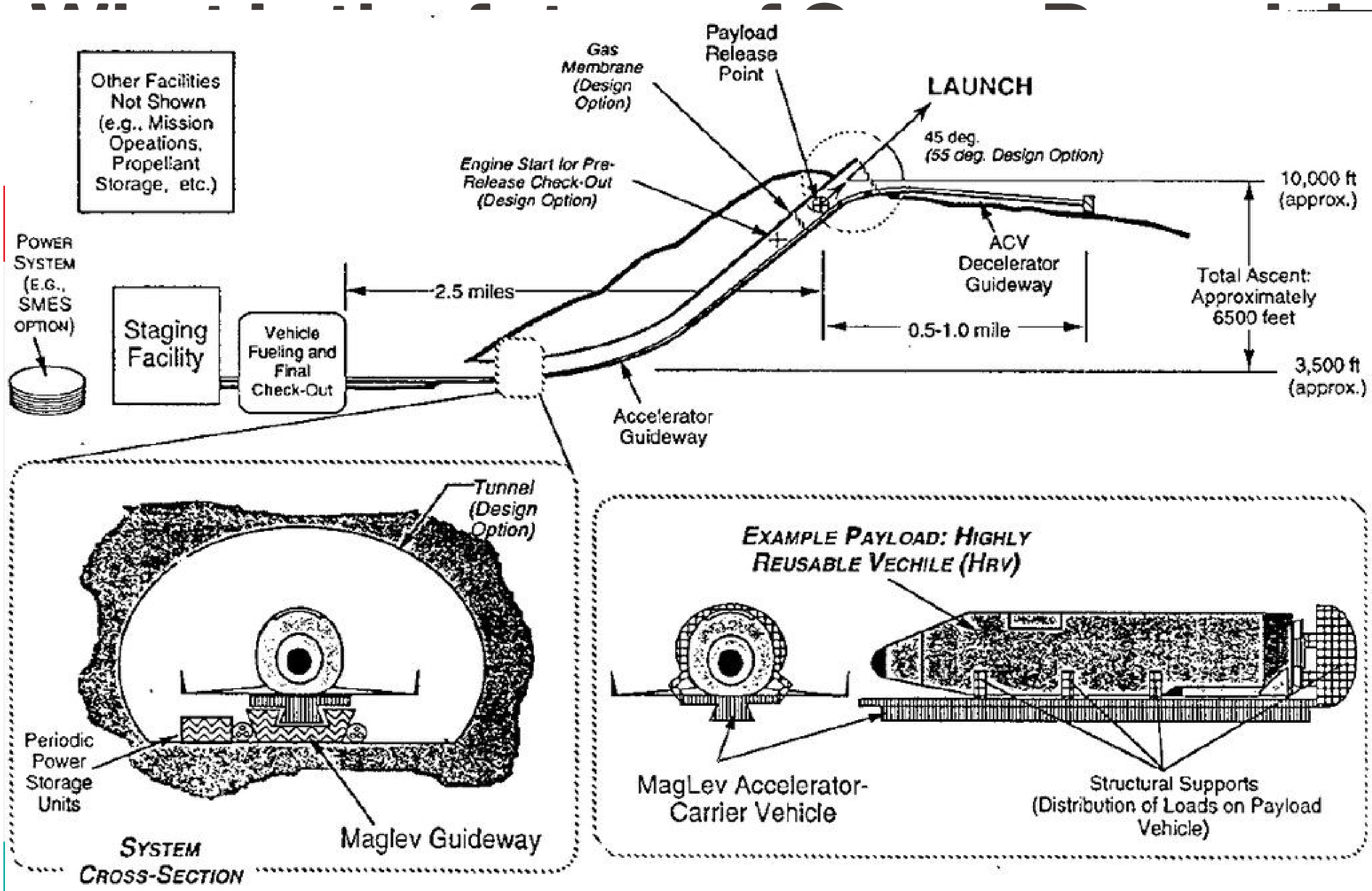
Overview

- Non-rocket advancements
  - Spin launch

What is the future of Space Propulsion (4/x)?

Overview

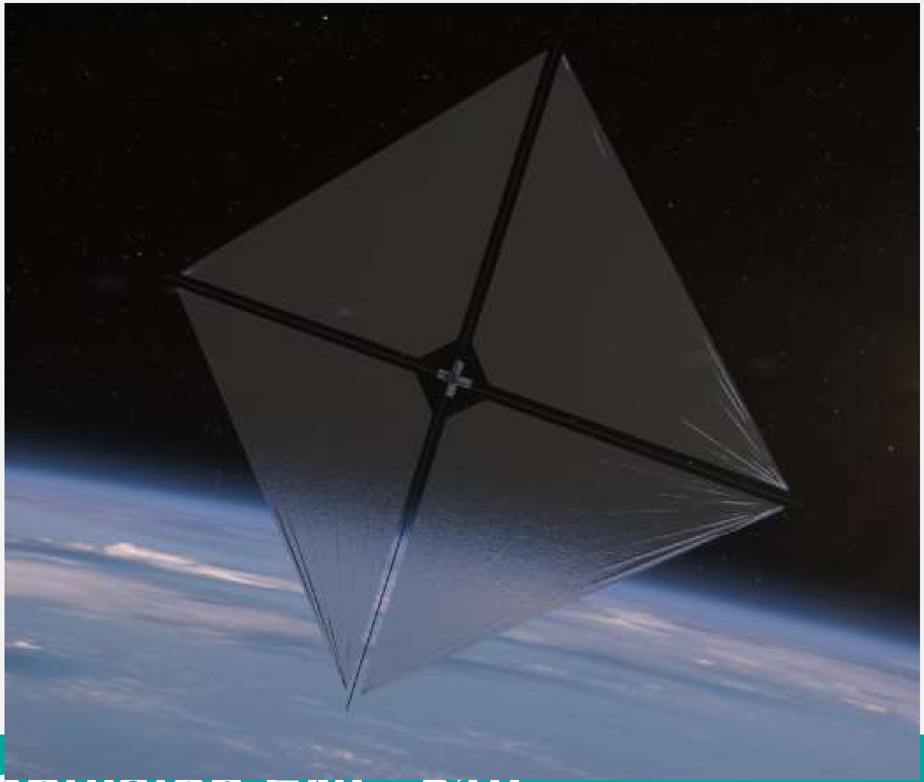
- Non-rocket advancements
  - Space gun
    - In Project HARP, a 1960s joint United States and Canada defence project, a 410 mm gun was used to fire a 180 kg projectile at 3,600 m / s (12,960 km / h), reaching an apogee of 180 km, hence performing a suborbital spaceflight
    - However, a space gun has never been successfully used to launch an object into orbit or out of Earth's gravitational pull


Other Facilities Not Shown (e.g., Mission Opeations, Propellant Storage, etc.)
Gas Membrane (Design Option)
Payload Release Point
LAUNCH
45 deg. (55 deg. Design Option)
Engine Start for Pre-Release Check-Out (Design Option)
10,000 ft (approx.)
POWER SYSTEM (E.G., SMES OPTION)
Staging Facility
Vehicle Fueling and Final Check-Out
2.5 miles
ACV Decelerator Guideway
0.5-1.0 mile
Total Ascent: Approximately 6500 feet
3,500 ft (approx.)
Accelerator Guideway
Tunnel (Design Option)
Periodic Power Storage Units
Maglev Guideway
SYSTEM CROSS-SECTION
EXAMPLE PAYLOAD: HIGHLY REUSABLE VECHILE (HRV)
MagLev Accelerator-Carrier Vehicle
Structural Supports (Distribution of Loads on Payload Vehicle)

What is the future of Space Propulsion (5/x)?

Overview

- Non-rocket advancements
  - Solar sail



What is the future of Space Propulsion (6/x)?

Overview

- Non-rocket advancements
  - Solar sail
    - Solar sails use the pressure of sunlight for propulsion, angling toward or away from the Sun so that photons bounce off the reflective sail to push a spacecraft
    - This eliminates heavy propulsion systems and could enable longer duration and lower-cost missions
    - Although mass is reduced, solar sails have been limited by the material and structure of the booms, which act much like a sailboat's mast
    - But NASA is about to change the sailing game for the future.
    - In April, a next-generation solar sail technology – known as the Advanced Composite Solar Sail System – was launched aboard Rocket Lab's Electron rocket
    - The technology could advance future space travel and expand our understanding of our Sun and solar system

What is the future of Space Propulsion (7/x)?

Overview

- Non-rocket advancements
  - Solar sail
    - The Advanced Composite Solar Sail System demonstration uses a twelve-unit (12U) CubeSat built by NanoAvionics to test a new composite boom made from flexible polymer and carbon fiber materials that are stiffer and lighter than previous boom designs
    - The mission's primary objective is to successfully demonstrate new boom deployment, but once deployed, the team also hopes to prove the sail's performance
    - Like a sailboat turning to capture the wind, the solar sail can adjust its orbit by angling its sail
    - After evaluating the boom deployment, the mission will test a series of maneuvers to change the spacecraft's orbit and gather data for potential future missions with even larger sails

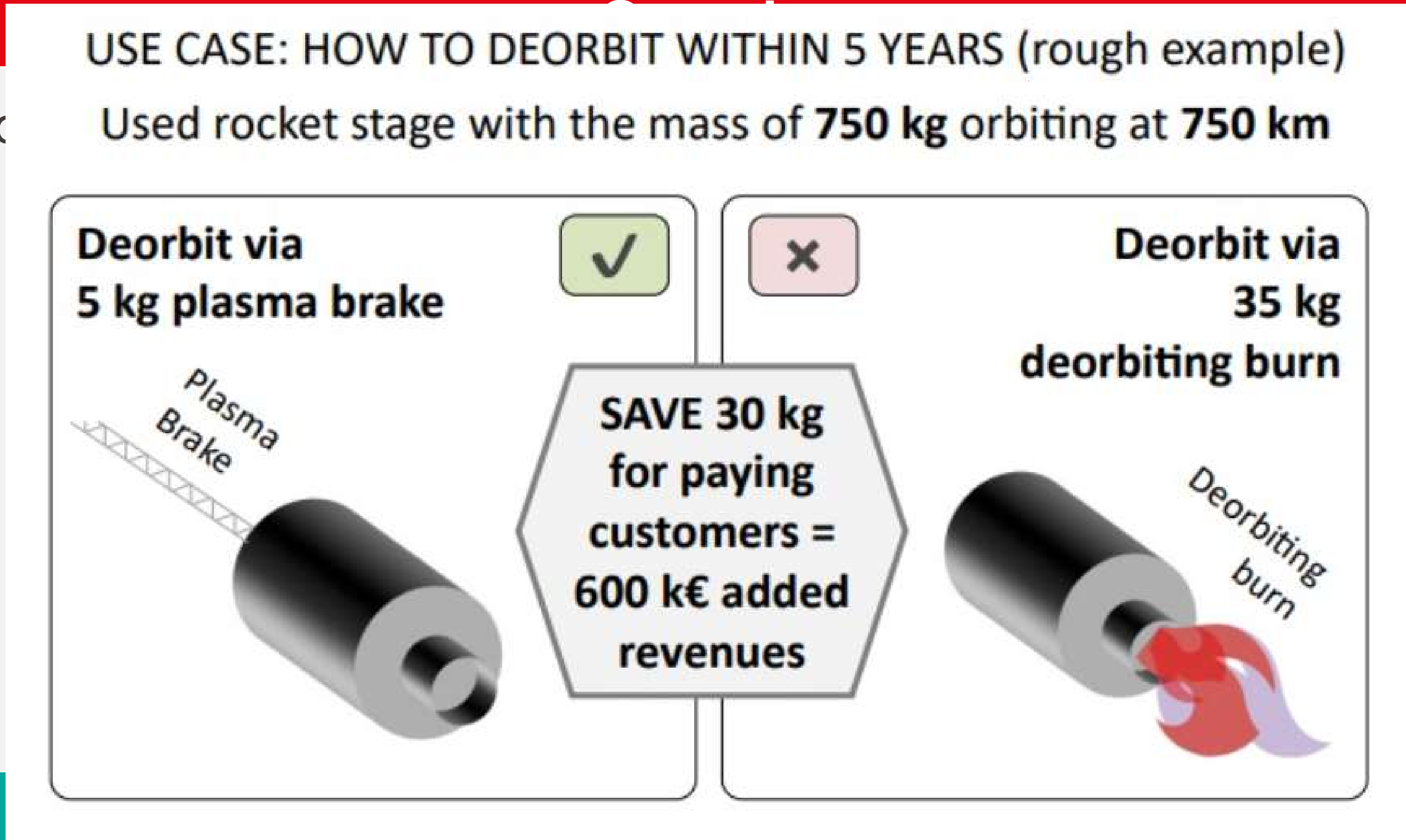
What is the future of Space Propulsion (8/x)?

Overview

- Non-rocket advancements
  - Tether – Plasma Brake
    - Plasma brake does not use any propellant, instead it utilizes the interaction of ionospheric plasma and a charged micro-tether to generate Coulomb drag
    - This is similar to atmospheric drag-based devices, but unlike them, micro-tether is safe to other spacecraft and the Coulomb drag is orders of magnitude stronger than atmospheric drag
    - This difference in deaccelerating forces is even larger as the orbital altitude increases

What is the future of Space Propulsion (9/x)?

- Nc

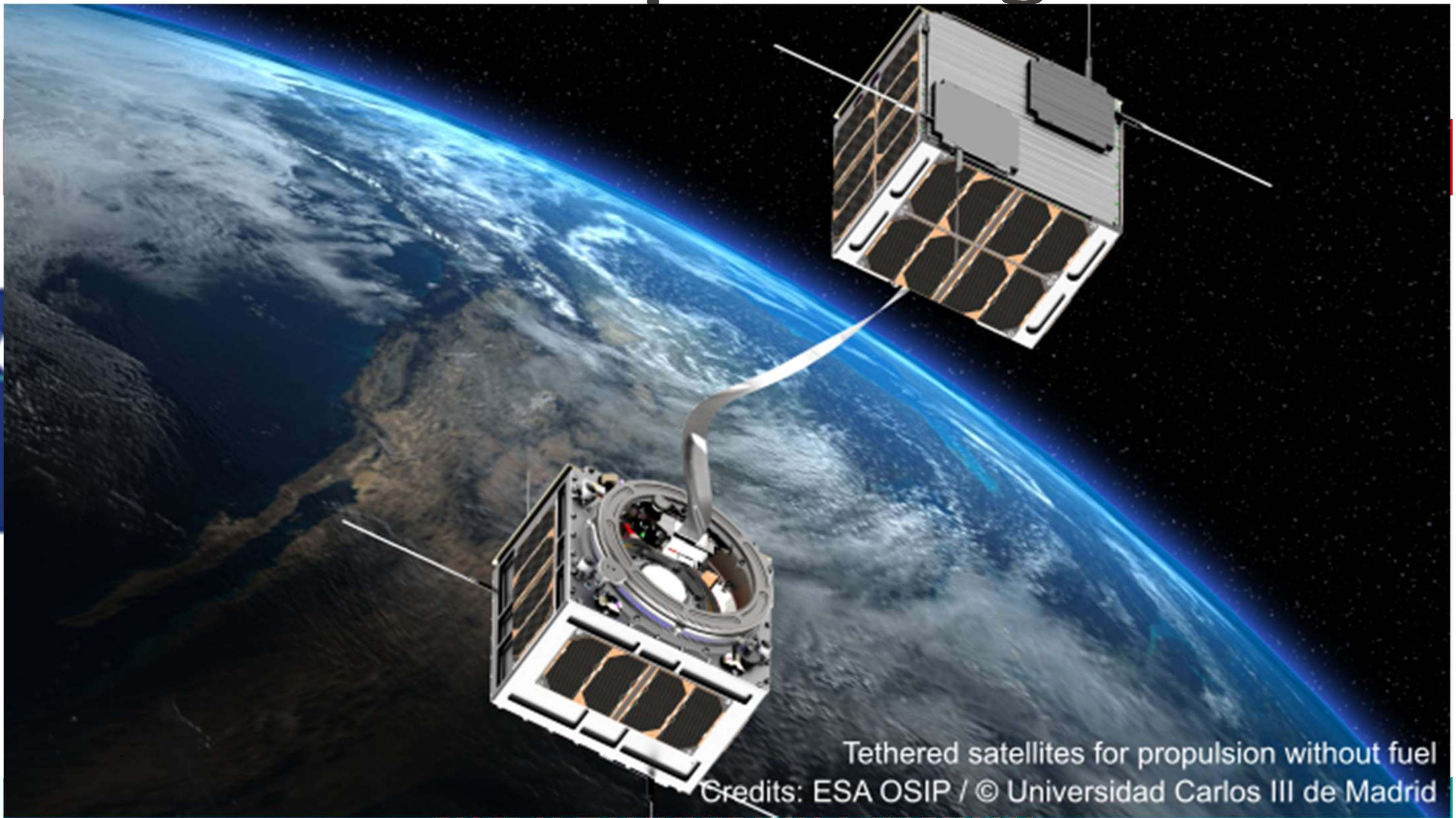


ESA Innovative Propulsion – Cross Cutting Initiative (32/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 8 - Space Tethers
  - Space tethers are long, strong, charged cables which can be used for propulsive maneuvers in space thanks to their interaction with charged particles present in the high layers of the atmosphere and in the solar wind
  - Their working principle allows for propellant-less orbital transfers or de-orbiting satellites at the end of their life

Which Future Aspects are given for



ESA Innovative Propulsion – Cross Cutting Initiative (33/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - A variety of different concepts for space transportation systems with Beamed Energy Propulsion (BEP) engines were proposed in past studies by several different authors
  - They can be roughly grouped in the following categories:
    - Plasma: The incoming beamed energy is focused by a mirror system. In the focal point on-board propellant or ambient air is converted into plasma
    - The ejected plasma propels the vehicle by momentum exchange
    - Laser ablative propulsion, where the target spacecraft or space debris is ablated to create an impulse, also falls in this category

ESA Innovative Propulsion – Cross Cutting Initiative (34/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Thermal: A heat exchanger in the vehicle is heated by beamed energy
    - The heat is transferred to on-board propellant, which is ejected in a classical convergent-divergent nozzle
    - A special form of thermal beamed energy propulsion is the solar thermal propulsion stage, where the beam source is the sun
    - Sail: The beamed energy is reflected by a sail
    - The resulting radiation pressure exacts a force on the vehicle
    - The Solar Sail is a specific concept of this category, using the pressure of the solar light for propellant less propulsion

ESA Innovative Propulsion – Cross Cutting Initiative (35/54)?

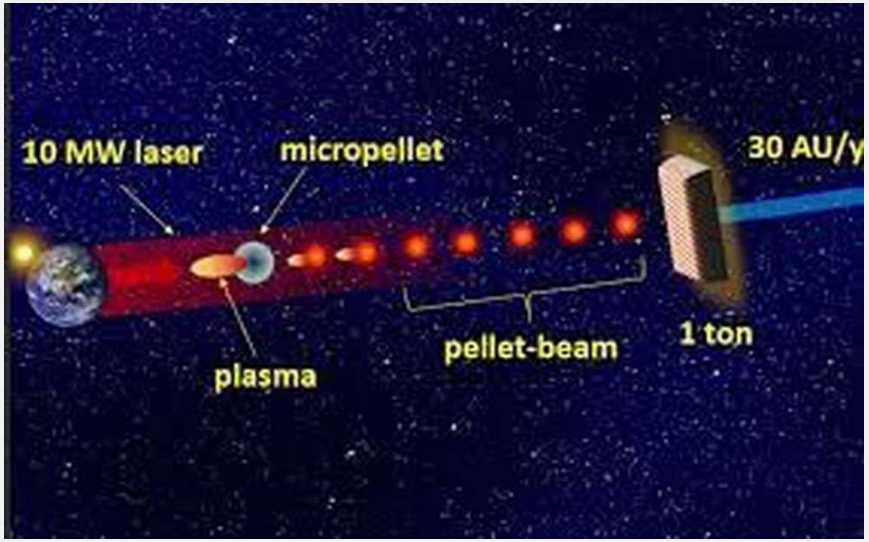
Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Climber: The climber type is a vehicle for a space elevator type transportation system
    - The climber will convert beamed energy into mechanical energy used for climbing the tether to the orbital destination station
  - While the Sail is a feasible approach for in-space applications only, the Climber is a radically different concept and difficult to compare with other propulsion systems
  - And now the pellet beam…out of NASA Innovative Advanced Concepts (NIAC)

ESA Innovative Propulsion – Cross Cutting Initiative (36/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Pellet beam:



ESA Innovative Propulsion – Cross Cutting Initiative (37/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Pellet beam: The pellet-beam concept requires two spacecraft – one that sets off for interstellar space, and one that goes into orbit around Earth
    - The spacecraft orbiting Earth would shoot a beam of tiny microscopic particles at the interstellar spacecraft
    - Those particles would be heated up by lasers, causing part of them to melt into plasma that accelerates the pellets further, a process known as laser ablation

ESA Innovative Propulsion – Cross Cutting Initiative (38/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Those pellets could reach 120 km / s and either hit the sail of the interstellar spacecraft or repel a magnet within it, helping to propel the spacecraft to huge speeds that would let it whizz out of our heliosphere – the bubble of the solar wind around our Solar System
    - The NIAC proposal examines a new propulsion architecture for fast transit of heavy (1 ton and more) payloads across the Solar System and to the interstellar medium

Which Future Aspects are given for Propulsion (26/x)?

Introduction into Propulsion Future Development

- Beamed Energy Propulsion
  - A variety of different concepts for space transportation systems with Beamed Energy Propulsion (BEP) engines were proposed in past studies by several different authors
  - They can be roughly grouped in the following categories

Which Future Aspects are given for Propulsion (27/x)?

Introduction into Propulsion Future Development

- Beamed Energy Propulsion
  - Plasma:
    - The incoming beamed energy is focused by a mirror system
    - In the focal point on-board propellant or ambient air is converted into plasma
    - The ejected plasma propels the vehicle by momentum exchange
    - Laser ablative propulsion, where the target spacecraft or space debris is ablated to create an impulse, also falls in this category

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Which Future Aspects are given for Propulsion (28/x)?

Introduction into Propulsion Future Development

- Beamed Energy Propulsion
  - Thermal:
    - A heat exchanger in the vehicle is heated by beamed energy
    - The heat is transferred to on-board propellant, which is ejected in a classical convergent-divergent nozzle
    - A special form of thermal beamed energy propulsion is the solar thermal propulsion stage, where the beam source is the sun

Which Future Aspects are given for Propulsion (29/x)?

Introduction into Propulsion Future Development

- Beamed Energy Propulsion
  - Sail:
    - The beamed energy is reflected by a sail
    - The resulting radiation pressure exacts a force on the vehicle
    - The Solar Sail is a specific concept of this category, using the pressure of the solar light for propellantless propulsion
  - Climber:
    - The climber type is a vehicle for a space elevator type transportation system
    - The climber will convert beamed energy into mechanical energy used for climbing the tether to the orbital destination station

Which Future Aspects are given for Propulsion (30/x)?

Introduction into Propulsion Future Development

- Beamed Energy Propulsion
  - While the Sail is a feasible approach for in-space applications only, the Climber is a radically different concept and difficult to compare with other propulsion systems

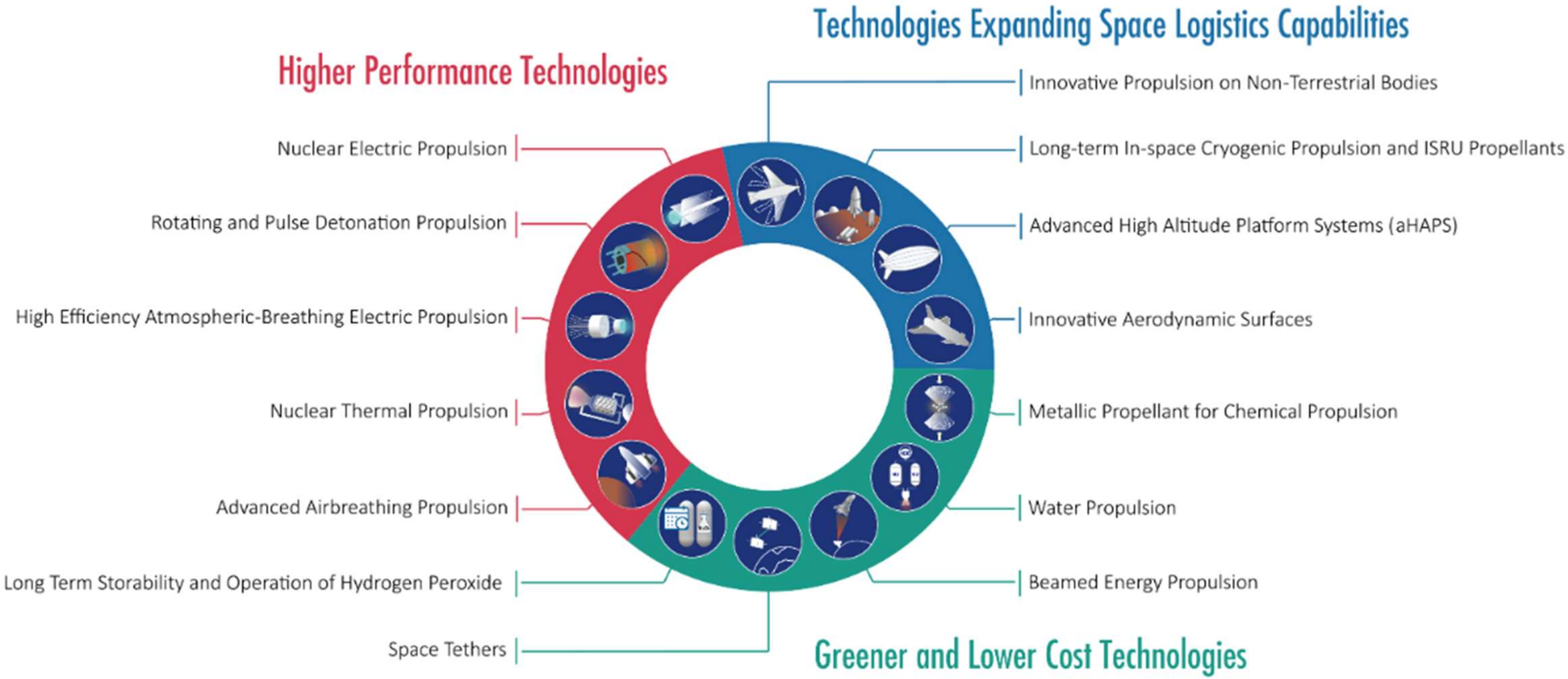
Back-up 3

Brief overview on all space propulsion systems

Lecture # 6 Cross Cutting Initiative – Innovative Propulsion

Describe objectives of ESA cross cutting initiative linked to propulsion

ESA Innovative Propulsion – Cross Cutting Initiative (1/54)?



ESA Innovative Propulsion – Cross Cutting Initiative (2/54)?

Objective: To describe ideas of cross cutting initiative

- Innovative Propulsion, by definition, shall:
  - Bring significant positive benefit in terms of mass, performance, cost and flexibility
  - Be at low TRL yet enough (> TRL 2) to be engineered and demonstrated in a medium term
  - Enable new missions or applications
  - Facilitate the creation of new markets
  - Enhance reliability and competitiveness

ESA Innovative Propulsion – Cross Cutting Initiative (3/54)?

Objective: To describe ideas of cross cutting initiative

- The objectives of the IP–CCI are:
  - To identify and support the strategic interest of ESA member states, industry and academia
  - To stimulate the propulsion ecosystem of the ESA member states
  - To increase the technology readiness, implement IOV / IOD missions, foster the research, development and testing capabilities and demonstrate the applications and services
  - To provide an increased visibility of innovative propulsion activities for space

ESA Innovative Propulsion – Cross Cutting Initiative (4/54)?

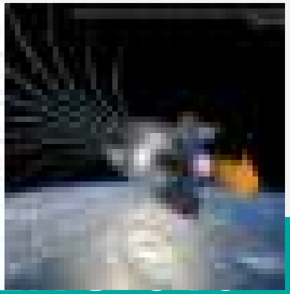
Objective: To describe ideas of cross cutting initiative

- Objective of the Workshops:
  - The workshops are organized by the Propulsion, Aerothermodynamics, and Flight Vehicles Engineering Division of ESA
- The workshops will serve to the collection of future vision, needs and requirements for the development of Innovative Propulsion systems and technologies in order to consolidate the ESA Innovative Propulsion roadmap

ESA Innovative Propulsion – Cross Cutting Initiative (5/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 1 - High Efficiency Atmospheric-Breathing Electric Propulsion
  - Atmospheric-breathing electric propulsion systems are defined by their capability to generate thrust using as propellant the gases of the atmosphere, which are collected by an intake installed on the same platform
  - They are capable of operating with variable atmospheric gas mixtures and densities, and resilient to long term operation in a challenging environment
  - This topic targets innovative electric propulsion systems with high thrust-to-power and high-specific-impulse capability



ESA Innovative Propulsion – Cross Cutting Initiative (6/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 2 - Advanced Airbreathing Propulsion
  - Generating lift by means of atmospheric flight while ingesting the atmospheric oxidizer into the airbreathing engine results into an overall lighter flight vehicle: there is no need to carry the oxidizer and the related storage system on board and the high aerodynamic efficiency L/D > 1 lowers further the required thrust with respect to classical non-lifting vehicles
  - The main applications are to first stages of launchers, replacing the booster function and potentially performing some of the duty of subsequent stages, or suborbital point-to-point transports

ESA Innovative Propulsion – Cross Cutting Initiative (7/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 2 - Advanced Airbreathing Propulsion
  - Owing to a wide flight regime, potentially from Mach 0 to about 12, the vehicle and its propulsion must perform in an ample operational range
  - This challenges the design of the propulsion system, which may incorporate variable geometry elements to enlarge the operational regime of the:
    - Air intake and isolator
    - Compressor: ram- or turbo based
    - Combustor and injectors
    - Nozzle and thrust vectoring

ESA Innovative Propulsion – Cross Cutting Initiative (8/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 2 - Advanced Airbreathing Propulsion
  - As an alternative to the multi-mode variable cycle engine, an engine integrating different propulsion elements can also be considered, e.g. a turbine- or rocket-based combined cycle engine and a (sc)ramjet which provides the required operational range
  - In either case of a variable cycle engine or a combination of propulsion systems, the following design aspects have a critical impact in the overall performance of the vehicle:
    - The transition between modes of operation, e.g. turbo to ramjet or ram to scramjet
    - The overall integration of the propulsion system in the vehicle
    - The combined aerothermal and aerodynamic loads throughout the mission

ESA Innovative Propulsion – Cross Cutting Initiative (9/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 2 - Advanced Airbreathing Propulsion
  - In either case of a variable cycle engine or a combination of propulsion systems, the following design aspects have a critical impact in the overall performance of the vehicle:
    - The overall thrust-to-drag (aero-propulsive) balance to assure net thrust and acceleration
    - The various combustion regimes
    - The internal flow path design from an aero-thermo-mechanical-structural point of view
    - The design and integration of the variable geometry components, e.g. intakes, throats and nozzles, by translation, deflection or morphing of the structural elements

ESA Innovative Propulsion – Cross Cutting Initiative (10/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 2 - Advanced Airbreathing Propulsion

ESA Innovative Propulsion – Cross Cutting Initiative (11/54)?

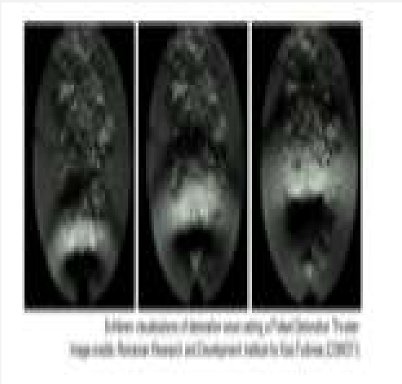
Objective: To describe ideas of cross cutting initiative

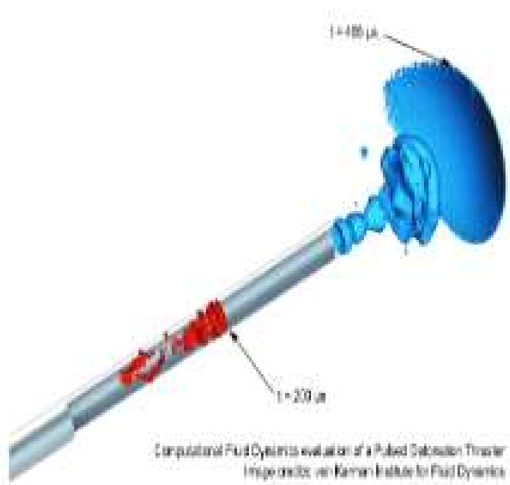
- Topic # 3 - Rotating and Pulse Detonation Propulsion
  - Detonative propulsion engines exhibit superior performance in terms of specific impulse than conventional liquid, hybrid or solid rocket engines
  - In addition, the pressure gain combustion offers the advantage of lowering the required injection pressure, thus potentially benefiting from an overall reduction in system mass
  - There are two approaches to realize detonative combustion in a propulsive system: pulse detonation and rotating detonation
  - Both concepts have the potential of simplifying and reducing the weight of the current propulsion systems

ESA Innovative Propulsion – Cross Cutting Initiative (12/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 3 - Rotating and Pulse Detonation Propulsion
  - Although the research on detonative combustion started more than half a century ago, the needs of more affordable and efficient propulsion system justify this breakthrough





Computational Fluid Dynamics evaluation of a Pulsed Detonation Thruster
Image credits: von Karman Institute for Fluid Dynamics

Space Pr

ESA Innovative Propulsion – Cross Cutting Initiative (13/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 3 - Rotating and Pulse Detonation Propulsion
  - RTE (Rotating Detonation Engine)
    - A rotating detonation engine (RDE) uses a form of pressure gain combustion, where one or more detonations continuously travel around an annular channel
    - Computational simulations and experimental results have shown that the RDE has potential in transport and other applications
    - In a detonative combustion, the flame front expands at supersonic speed
    - It is theoretically more efficient than conventional deflagrative combustion by as much as 25% which would provide major fuel savings
    - Disadvantages include instability and noise

ESA Innovative Propulsion – Cross Cutting Initiative (14/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 3 - Rotating and Pulse Detonation Propulsion
  - RTE (Rotating Detonation Engine)
    - The basic concept of an RDE is a detonation wave that travels around a circular channel (annulus)
    - Fuel and oxidizer are injected into the channel, normally through small holes or slits
    - A detonation is initiated in the fuel / oxidizer mixture by some form of igniter
    - After the engine is started, the detonations are self-sustaining
    - One detonation ignites the fuel / oxidizer mixture, which releases the energy necessary to sustain the detonation
    - The combustion products expand out of the channel and are pushed out of the channel by the incoming fuel and oxidizer

ESA Innovative Propulsion – Cross Cutting Initiative (15/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 3 - Rotating and Pulse Detonation Propulsion
  - RTE (Rotating Detonation Engine)
    - Although the RDE's design is similar to the pulse detonation engine (PDE), the RDE is superior because the waves cycle around the chamber, while the PDE requires the chambers to be purged after each pulse

ESA Innovative Propulsion – Cross Cutting Initiative (16/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 3 - Rotating and Pulse Detonation Propulsion
  - PTE (Pulse Detonation Engine)
    - A pulse detonation engine (PDE) is a type of propulsion system that uses detonation waves to combust the fuel and oxidizer mixture
    - The engine is pulsed because the mixture must be renewed in the combustion chamber between each detonation wave and the next
    - Theoretically, a PDE can operate from subsonic up to a hypersonic flight speed of roughly Mach 5
    - Key issues for further development include fast and efficient mixing of the fuel and oxidizer, the prevention of autoignition, and integration with an inlet and nozzle

ESA Innovative Propulsion – Cross Cutting Initiative (17/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 4 - Water Propulsion
  - Water propulsion systems are currently being developed for various applications
  - In the search for non-toxic, non-carcinogenic and in general non-hazardous replacements of hydrazine, water is the ultimate green propellant
  - While the specific impulse can be better than that of other monopropellants, the main advantage is the removal of hazards, such as toxicity and adiabatic decomposition of hydrazine
  - The water is not toxic nor carcinogenic and therefore handling is by definition as safe as, or even safer, than that of any other conceivable green propellant

ESA Innovative Propulsion – Cross Cutting Initiative (18/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 4 - Water Propulsion
  - The main advantages of water propulsion are thus on the one hand the safe storability of the propellant in form of the stable reaction product, water
  - Water is however also a substance which can be found, in solid state, in various places in the solar system (comets, lunar poles, Martian soil, etc.)
  - The concept of water propulsion is therefore, beyond the immediate applications as hydrazine replacement in LEO satellites, potentially very useful in future exploration missions, employing a simple form of In-Situ Resource Utilization (ISRU), with only limited propellant processing equipment required

ESA Innovative Propulsion – Cross Cutting Initiative (19/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 4 - Water Propulsion
  - Several different types of water propulsion exist, with possibly the most common current application being Water-Resistojets (WR)
  - This type of thermo-electric propulsion uses the water itself as propellant
  - In contrast Water Electrolysis Propulsion (WEP) employs an electrolyser to generate the actual propellants oxygen and hydrogen from the stored water
  - The two gases are then used to operate conventional chemical propulsion thrusters
  - Other concepts, like water electrolysis Hall Effect Thrusters (HET) using oxygen and hydrogen for electric propulsion, are also currently under development

ESA Innovative Propulsion – Cross Cutting Initiative (20/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 5 - Long Term Storability and Operation of Hydrogen Peroxide
  - Hydrogen peroxide was developed as a propellant for missiles in the 1940s and 1950s until it was replaced by higher performing combinations of propellants, such as hydrazine in the case of satellites, or cryogenically stored liquid hydrogen / liquid oxygen for launchers
  - Since the 1990s, hydrogen peroxide development for thrusters (in particular small thrusters in the 5N class) has enjoyed a renaissance of activity, as the desire for non-toxic propellants for spacecraft has increased
  - Pure hydrogen peroxide will naturally decompose into water (steam) and oxygen given the right catalyst

ESA Innovative Propulsion – Cross Cutting Initiative (21/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 5 - Long Term Storability and Operation of Hydrogen Peroxide
  - Stabilizers are added to the hydrogen peroxide to facilitate the storage and allow the safe use as propellant, thus reducing the purity
  - These additives have the undesirable effect of reducing the propulsive efficiency, hence their use needs to be minimized wherever possible
  - In launch vehicle and other short-term applications, a cumulative increase of pressure can be vented overboard to prevent over pressurization of the storage tanks
  - Nonetheless, this is not desirable, or even nor possible in some cases, for multi-year mission satellites

ESA Innovative Propulsion – Cross Cutting Initiative (22/54)?

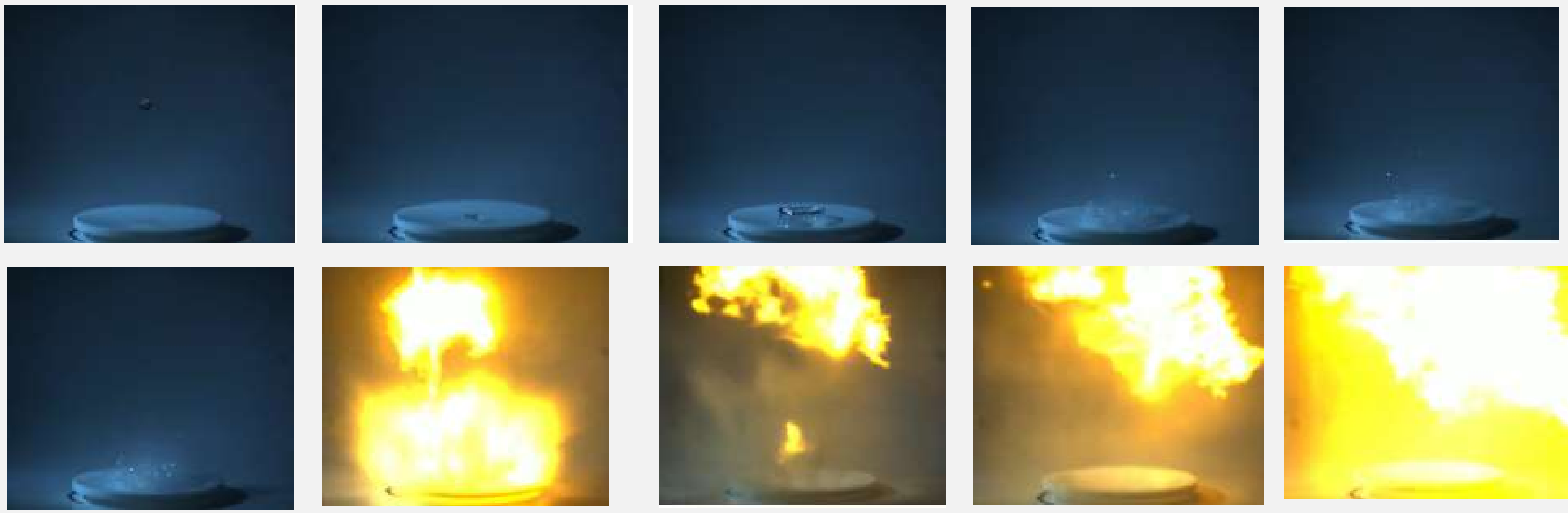
Objective: To describe ideas of cross cutting initiative

- Topic # 5 - Long Term Storability and Operation of Hydrogen Peroxide
  - The traditional materials used on satellites, such as titanium alloys and some stainless steels, facilitate the decomposition of hydrogen peroxide and therefore are not suitable in their current form for the long-term storage of hydrogen peroxide-based propellants
  - In order to use hydrogen peroxide for long term applications, alternative materials for components and / or alternative stabilizing additives need to be used

ESA Innovative Propulsion – Cross Cutting Initiative (23/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 5 - Long Term Storability and Operation of Hydrogen Peroxide



ESA Innovative Propulsion – Cross Cutting Initiative (24/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 6 - Innovative Aerodynamic Surfaces
  - The topic of innovative aerodynamic surfaces comprises ailerons, elevons, flaps, rudders, or panels that modify the aerodynamic characteristics of a vehicle and produce lift and drag forces
  - Several categories of aerodynamic surfaces are envisaged, subdivided between primary surfaces and complementary surfaces
  - Primary surfaces are ailerons, elevators, and rudders
  - Ailerons are mounted on the trailing edge of the flying vehicle and move in opposite directions

EPFL

ESA Innovative Propulsion – Cross Cutting Initiative (25/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 6 - Innovative Aerodynamic Surfaces
  - Elevators are a moveable part of the horizontal stabilizers, hinged to the back of the tail of the flying vehicle
  - Rudders are mounted on the trailing edge of the vertical stabilizer, part of the empennage
  - Complementary surfaces are spoilers, flaps, slats, and airbrakes
  - Spoilers are used to disrupt the airflow and reduce the lift whereas flaps and slats are used to increase the lift of the flying vehicle. Airbrakes are used to increase drag

ESA Innovative Propulsion – Cross Cutting Initiative (26/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 6 - Innovative Aerodynamic Surfaces
  - This topic focus on the conception, architecture design, technical analysis, development, and operations of Innovative Aerodynamic Surfaces as propulsive mean for a flight vehicle

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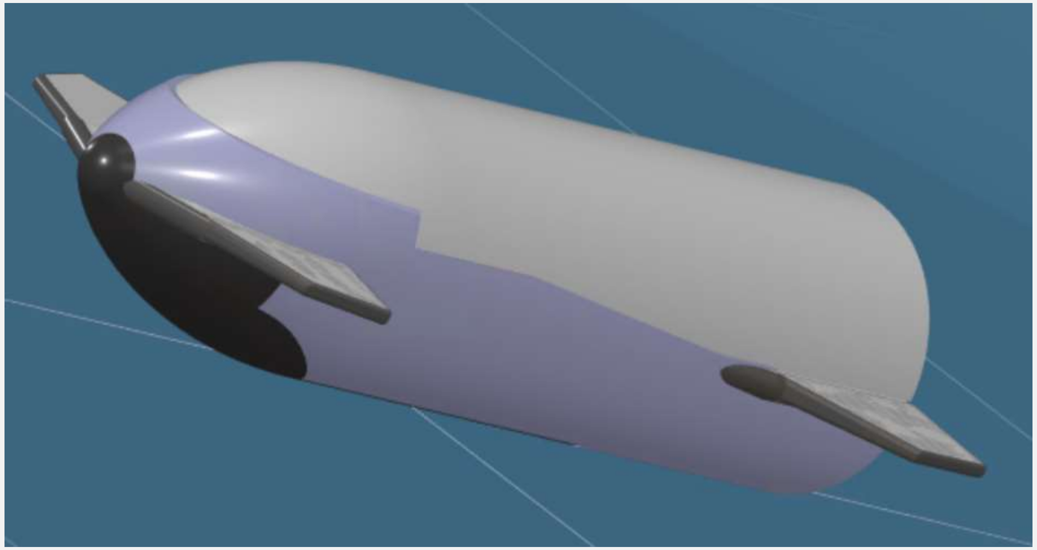
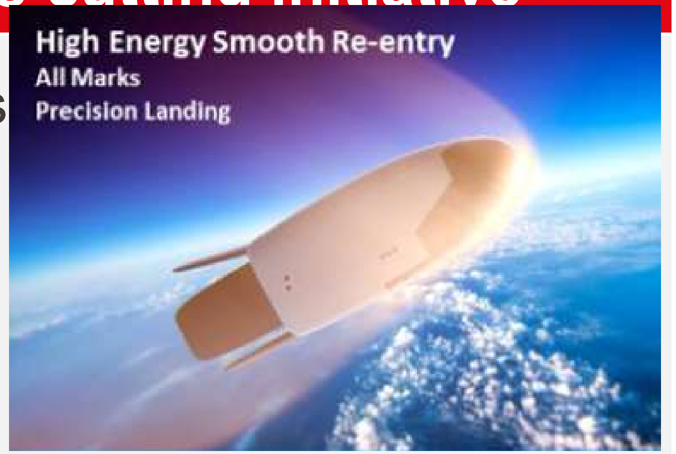
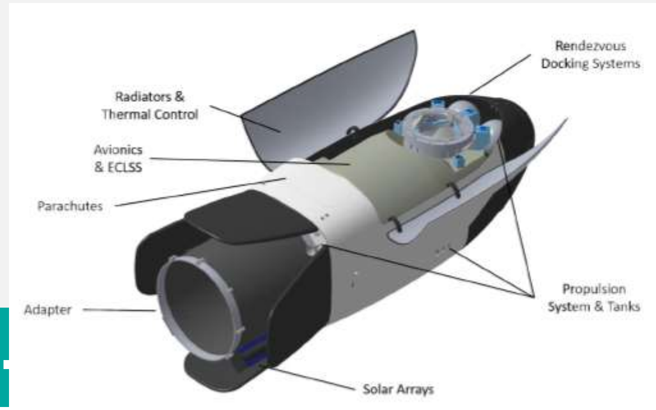
ESA Innovative Propulsion – Cross Cutting Initiative (27/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 6 - Innovative Aerodynamic Surfaces







ESA Innovative Propulsion – Cross Cutting Initiative (28/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 7 - Long-term In-space Cryogenic Propulsion and ISRU Propellants
  - The higher performance of cryogenic propellants and the ubiquity of their precursor availability in the solar system means that they are perfectly suited for in situ resource utilization (ISRU) and in-orbit re-fueling
  - Many lunar and Martian missions in particular hope to exploit these propellant options

ESA Innovative Propulsion – Cross Cutting Initiative (29/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 7 - Long-term In-space Cryogenic Propulsion and ISRU Propellants
  - These mission concepts include:
    - Martian and Lunar transit stages
    - Propulsive Landers
    - Space Tugs
    - Re-fueling stations
  - Such systems must withstand thermal environments for transfers to Mars / Moon and back, including long duration transfers up to 6 months and dwell time of ~12-24 months

ESA Innovative Propulsion – Cross Cutting Initiative (30/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 7 - Long-term In-space Cryogenic Propulsion and ISRU Propellants
  - Current cryogenic approaches are limited to the much shorter-lived applications for launch vehicles
  - The requirements for the in-space applications for these propellants will require a significant overhaul of both our understanding of cryogenic propellant management and the product catalogue that has been evolved to exploit them
  - The scale of these engines will be similar to, or smaller than existing upper stage engines (~ 100 kN)

EPFL

ESA Innovative Propulsion – Cross Cutting Initiative (31/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 7 - Long-term In-space Cryogenic Propulsion and ISRU Propellants
  - However, they will have additional challenging requirements: large number or restarts/reusability, deep ability to throttle, and clustering of engines for higher thrusts (in applications such as landers and large transfer stages)
  - To realize a long-term cryogenic propulsion system several key technologies and operational concepts need to be addressed including: low / zero boil off technologies, cryo-fluid handling and management, thermal management of temperature distribution within the tanks and zero / low consumption chill down in preparation for engine operation

ESA Innovative Propulsion – Cross Cutting Initiative (32/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 8 - Space Tethers
  - Space tethers are long, strong, charged cables which can be used for propulsive maneuvers in space thanks to their interaction with charged particles present in the high layers of the atmosphere and in the solar wind
  - Their working principle allows for propellant-less orbital transfers or de-orbiting satellites at the end of their life

ESA Innovative Propulsion – Cross Cutting Initiative (33/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - A variety of different concepts for space transportation systems with Beamed Energy Propulsion (BEP) engines were proposed in past studies by several different authors
  - They can be roughly grouped in the following categories:
    - Plasma: The incoming beamed energy is focused by a mirror system. In the focal point on-board propellant or ambient air is converted into plasma
    - The ejected plasma propels the vehicle by momentum exchange
    - Laser ablative propulsion, where the target spacecraft or space debris is ablated to create an impulse, also falls in this category

ESA Innovative Propulsion – Cross Cutting Initiative (34/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Thermal: A heat exchanger in the vehicle is heated by beamed energy
    - The heat is transferred to on-board propellant, which is ejected in a classical convergent-divergent nozzle
    - A special form of thermal beamed energy propulsion is the solar thermal propulsion stage, where the beam source is the sun
    - Sail: The beamed energy is reflected by a sail
    - The resulting radiation pressure exacts a force on the vehicle
    - The Solar Sail is a specific concept of this category, using the pressure of the solar light for propellant less propulsion

ESA Innovative Propulsion – Cross Cutting Initiative (35/54)?

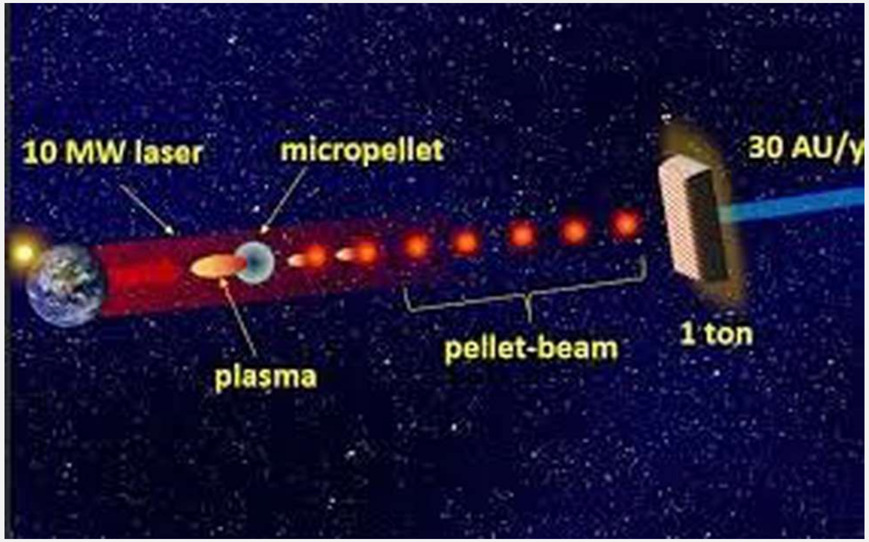
Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Climber: The climber type is a vehicle for a space elevator type transportation system
    - The climber will convert beamed energy into mechanical energy used for climbing the tether to the orbital destination station
  - While the Sail is a feasible approach for in-space applications only, the Climber is a radically different concept and difficult to compare with other propulsion systems
  - And now the pellet beam…out of NASA Innovative Advanced Concepts (NIAC)

ESA Innovative Propulsion – Cross Cutting Initiative (36/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Pellet beam:



ESA Innovative Propulsion – Cross Cutting Initiative (37/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Pellet beam: The pellet-beam concept requires two spacecraft – one that sets off for interstellar space, and one that goes into orbit around Earth
    - The spacecraft orbiting Earth would shoot a beam of tiny microscopic particles at the interstellar spacecraft
    - Those particles would be heated up by lasers, causing part of them to melt into plasma that accelerates the pellets further, a process known as laser ablation

ESA Innovative Propulsion – Cross Cutting Initiative (38/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 9 - Beamed Energy Propulsion
  - They can be roughly grouped in the following categories:
    - Those pellets could reach 120 km / s and either hit the sail of the interstellar spacecraft or repel a magnet within it, helping to propel the spacecraft to huge speeds that would let it whizz out of our heliosphere – the bubble of the solar wind around our Solar System
    - The NIAC proposal examines a new propulsion architecture for fast transit of heavy (1 ton and more) payloads across the Solar System and to the interstellar medium

ESA Innovative Propulsion – Cross Cutting Initiative (39/54)?

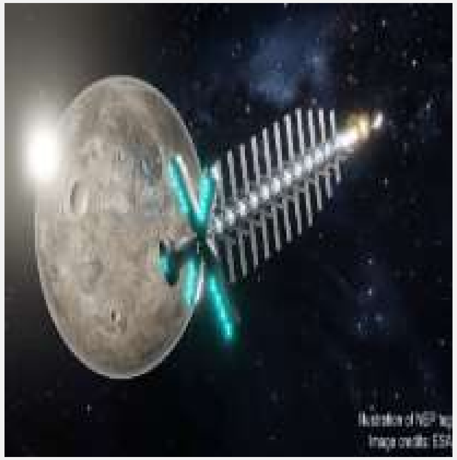
Objective: To describe ideas of cross cutting initiative

- Topic # 10 - Nuclear Electric Propulsion
  - Space nuclear electric propulsion (NEP) is a technology that utilizes nuclear reactions to generate electricity and propel spacecraft using electric propulsion (EP) thrusters
  - The idea of using nuclear energy for space propulsion dates back to the 1950s, with the development of nuclear thermal rockets or nuclear power reactors by the US and the Soviet Union
  - Since then, various countries and organizations have conducted research and development in NEP as it could revolutionize space exploration by enabling faster and more efficient travel through space

ESA Innovative Propulsion – Cross Cutting Initiative (40/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 10 - Nuclear Electric Propulsion
  - Potential applications of NEP include Earth-Moon space tugs, manned missions to Mars, deep space exploration, asteroid mining, or even satellite servicing and maintenance



ESA Innovative Propulsion – Cross Cutting Initiative (41/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 11 - Nuclear Thermal Propulsion
  - In the 1960s and 1970s extensive research on nuclear propulsion was performed by the United States of America and the Soviet Union
  - Due to financial constraints and a shift in focus, this research did ultimately not lead to operational systems
  - Meanwhile a lot of progress has been made, not only in reactor technology, but also in material science
  - Future exploration and science missions with large payload mass and at the same time high delta v demand, can often not be fulfilled by either the available high specific impulse electric propulsion or the available high thrust chemical propulsion

ESA Innovative Propulsion – Cross Cutting Initiative (42/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 11 - Nuclear Thermal Propulsion
  - Already in the early stages of space exploration it became clear that nuclear propulsion and power are key enabling technologies for an extended human presence on moon or Mars
  - Recently NASA and DARPA announced the plans for a nuclear thermal propulsion demonstrator (DRACO) to be launched within fiscal year 2027

ESA Innovative Propulsion – Cross Cutting Initiative (43/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 12 - Metallic Propellant for Chemical Propulsion
  - The potential use of metals can be exploited not only as a fuel for space vehicles but also as a motivating and promising technology for future “settlement plans” on the Moon and Mars
  - The prominent features of metal fuel technology are:
    - It offers a completely CO2-free way to produce heat and/or electrical power and to store energy for deferred uses
    - It is a safe commodity for trading large energy stocks across the world, thanks to its intrinsically high energy density value
    - It relies on existing infrastructures, does not require large investments for new power plants, and does limit to the bare minimum its environmental footprint

ESA Innovative Propulsion – Cross Cutting Initiative (44/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 12 - Metallic Propellant for Chemical Propulsion
  - The prominent features of metal fuel technology are:
    - It is based on a large and practically unlimited resource of fuel food stock and on a fully reversible way to recycle the combustion products in an environmentally friendly manner
  - The main goal of this technology is to zero the CO2 emissions in the production and recycling processes, as well as in storing and trading energy reserves and assets

ESA Innovative Propulsion – Cross Cutting Initiative (45/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 12 - Metallic Propellant for Chemical Propulsion
  - The prospective propellants are:
    - Magnesium powder: With the compromise of specific impulse, ignition condition, combustion rate and sufficiency, powdered magnesium is considered as most promising fuel adopted for Mars or Moon Mission based on ISRU
    - This has huge challenges in terms of feeding powder to a chamber for combustion
    - Nonetheless, it could be interesting from an in-situ resource utilization perspective in that, if the ISRU processes can convert, for example, lunar regolith metal oxides to metal (e.g. magnesium) and oxygen, these can be used as propellants or an energy source and would be 100% locally sourced

ESA Innovative Propulsion – Cross Cutting Initiative (46/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 12 - Metallic Propellant for Chemical Propulsion
  - The prospective propellants are:
    - Magnesium powder: Besides, huge abundance of magnesium oxide mineral in Martian regolith has been discovered, which makes the production of magnesium powder on Mars to be possible in the future
    - Aluminum powder: In energetic applications, such as propellants, pyrotechnics and explosives, aluminum is widely used because of its high combustion enthalpy, easy availability, low toxicity and good stability
    - Aluminum, whether powders or flakes, is used to increase the energy and raise the flame temperature in rocket propellants

ESA Innovative Propulsion – Cross Cutting Initiative (47/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 12 - Metallic Propellant for Chemical Propulsion
  - The prospective propellants are:
    - Hydrogen: Physicists Wigner and Hungtinton predicted that hydrogen could turn into an electricity-conducting solid metal at the right temperature and pressure
    - Metastable metallic hydrogen would be a very light-weight, low volume, powerful rocket propellant
    - Indeed, for comparison, liquid (molecular) hydrogen-oxygen used in modern rockets performs with an Isp of ~460 s whereas metallic hydrogen has a theoretical Isp of 1700 s
    - Nonetheless, producing the pressure required to reach that state is extremely complex

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ESA Innovative Propulsion – Cross Cutting Initiative (48/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 12 - Metallic Propellant for Chemical Propulsion
  - The prospective propellants are:
    - Hydrogen: Currently, several laboratories across the world are working with a Diamand Anvil Cell, in which two opposing diamonds with flattened tips squeeze a thin rhenium gasket
    - Although there are some promising results, this technology is not mature for industrial production of metallic hydrogen

ESA Innovative Propulsion – Cross Cutting Initiative (49/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 13 - Advanced High Altitude Platform Systems (aHAPS)
  - High-Altitude Platform Systems or High-Altitude Pseudo-Satellites are flying vehicles able to fly and/or hover at high altitudes above 20 km in the Earth atmosphere
  - They can operate as Very Low Earth Observation (VLEO) flight vehicles and are considered as pseudo- or atmospheric-satellites
  - Their main applications are telecommunications, weather monitoring, and surveillance, similarly to LEO satellites

ESA Innovative Propulsion – Cross Cutting Initiative (50/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 13 - Advanced High Altitude Platform Systems (aHAPS)
  - Another significant application, distinguishing them from conventional LEO satellites, is using them as carrier vehicles for air-launched rockets, making use of the high altitude the flight vehicle can reach
  - These systems can be in the form of airships, balloons, and airplanes
  - This topic will evolve around the Flight Vehicle Engineering of such systems, specifically on the advanced propulsion and enhanced aerothermodynamics, making them more efficient while increasing their versatility and performance

ESA Innovative Propulsion – Cross Cutting Initiative (51/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 13 - Advanced High Altitude Platform Systems (aHAPS)

ESA Innovative Propulsion – Cross Cutting Initiative (52/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 14 - Innovative Propulsion on Non-Terrestrial Bodies
  - Non-Terrestrial bodies come either with or without an atmosphere where propulsive systems and units would relate to landers or observation vehicles (e.g. drones…)
  - In absence of an atmosphere, one would rather need rocket engines to translate a craft both horizontally and vertically
  - In the presence of an atmosphere, one can exploit it to generate lift or to hover by means of aerodynes and aerostats
  - Within the class of aerodynes, one can distinguish between rotorcraft or fixed-wing planes

ESA Innovative Propulsion – Cross Cutting Initiative (53/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 14 - Innovative Propulsion on Non-Terrestrial Bodies
  - In both cases, lift is generated by fluid-dynamic forces which carry the weight whereas the propulsion system generates the thrust to compensate for the drag and provide the acceleration
  - For aerostats, e.g. balloons, dirigibles…, lift is generated by buoyancy, while lateral translation is generated by wind (drag) or a propulsion unit
  - This propulsive unit can either make use of the atmosphere by means of e.g. an electrical driven fan, an oxidizer breathing engine, a fuel breathing engine... or fall back to a rocket engine not relying on the atmosphere

ESA Innovative Propulsion – Cross Cutting Initiative (54/54)?

Objective: To describe ideas of cross cutting initiative

- Topic # 14 - Innovative Propulsion on Non-Terrestrial Bodies
  - Finally, among these different propulsion innovations, one should assess what power sources feed the engine, namely electrical (photovoltaic or nuclear), chemical (mono- or bi-propellant), 'fluid'-breathing (using the species in the atmosphere), where the chemical propellant might be coming from an ISRU plant

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The End

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