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EPFL Space Center eSpace

Space Propulsion ENG-510

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Lecture # 5 Introduction & General Course Information

Brief update on space propulsion course

eSpace
EPFL Space Center

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

Feedback

Feedback:

- Thank you
- I will for sure try to consider the feedback
- Difficult aspect is number of ECTS points compared to effort

Type V Pressure Vessels

Type V Propellant Tanks:

- 31.03.2025 BRE – AMS – GVA
- 01.04.2025 GVA – AMS – BRE
- 02.04.2025 BRE – AMS – SEA
- 03.04.2025 SEA – HOU
- 04.04.2025 HOU – ATL
- 05.04.2025 ATL – MUC
- 06.04.2025 MUC – BRE
- 07.04.2025 BRE – AMS – GVA
- 08.04.2025 GVA – AMS – BRE

Type V Pressure Vessels

Type V Propellant Tanks:

- Intuitive Machines confirmed that Type V tanks were used on their lunar landers running on pressure-fed LOx / LCH4 cryogenic propellants
- Composite fiber was protected on the inner side against the propellants with a dedicated sheet
- Metallic toss implemented in the composite fiber on the poles
- Metallic brackets were glued to the equator for tank fixation
- Most probable first Type V tanks in orbit

Type V Pressure Vessels

Video

Exercise

Exercise # 4 Description:

- Due date on 13.4.2025: Verification Plan
  - 1-pager with description on how the main requirements will be verified like parachute deployment, safe-landing (maximal speed during landing), maximal altitude below 200 m, vertical lift-off, booster separation
  - Description of verification by test, by analysis, by review of design / inspection or by demonstration during assembly
  - Main focus shall be put on safety, redundancy and parachute deployment
  - It shall be described, how the system / the complete loaded rocket can be checked prior to launch
- Evaluation on 15.4.2025 (usual time slots)

Exercise

Exercise # 5 Description:

- Due date on 27.4.2025: 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 29.4.2025 (usual time slots)

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Lecture # 5 Chemical Propulsion Systems

Brief overview on all space propulsion systems

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Functions
  - Fill & Drain
  - Isolation
  - Regulation
  - Flow control
  - Throttling
  - …

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - Pyro Valves (N/O – normally open – or N/C – normally closed)
  - SMA Valves (Shape Memory Alloy)
  - Check Valves
  - Monostable Valves (Solenoid valves) – Flow Control Valves
  - Bistable Valves (Latch valves)
  - Pneumatic Valves
  - Electric Valves

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - Ball Valves
  - Fill & Drain Valves
  - Burst Disk + Relief Valve

Which Liquid Bi-propellant Propulsion Systems exist?

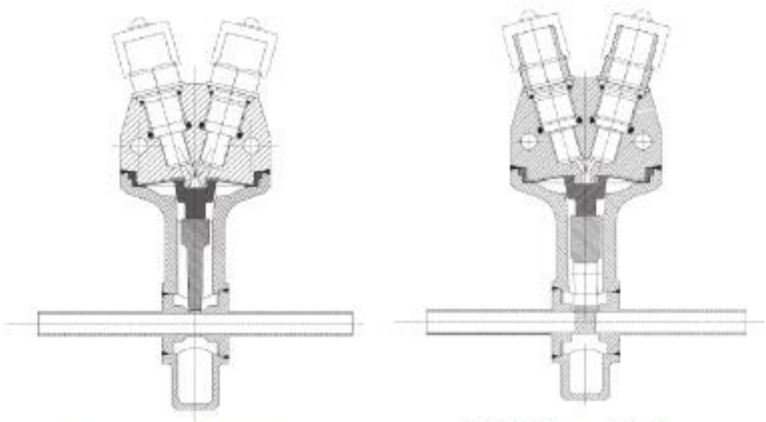
Propulsion Equipment:

- Valve Types
  - Pyro Valves (N/O – normally open – or N/C – normally closed): Redundancy
    - PVs are a one shot deal
    - Explosive charges are fired to open the valve (normally closed type) or to close the valve (normally open type
    - PVs are used to permanently change the flow paths within the propulsion system
    - Better leakage rate than latch or solenoid valves
    - Cost effective

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - Pyro Valves (N/O – normally open – or N/C – normally closed): Redundancy



NO before activation NC before activation

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - SMA Valves (Shape Memory Alloy): Low shock but duration for temperature increase

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Which Liquid Bi-propellant Propulsion Systems exist?

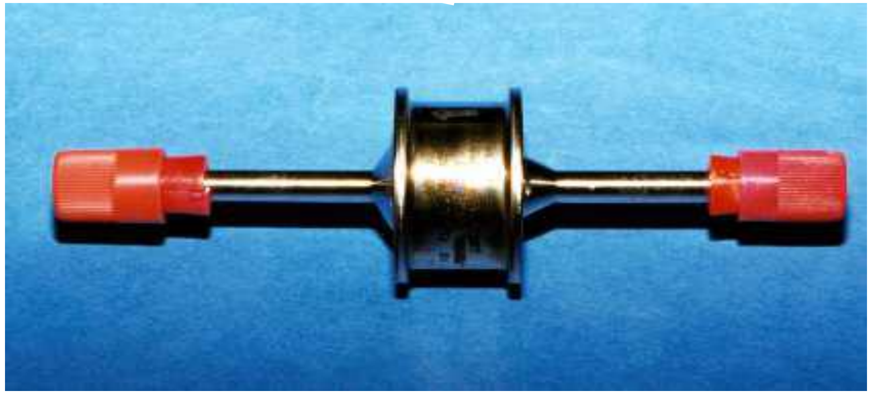
Propulsion Equipment:

- Valve Types
  - Check Valves: Never tight + oscillations
    - Non return valves prevent the mixing of oxidiser and fuel vapour in the pipes
    - No electronic parts
    - Valves allow the flow of gas in one direction only
    - Valves can exert a high pressure drop in the system (especially when series redundant)
    - Good reliability

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - Check Valves: Never tight + oscillations



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

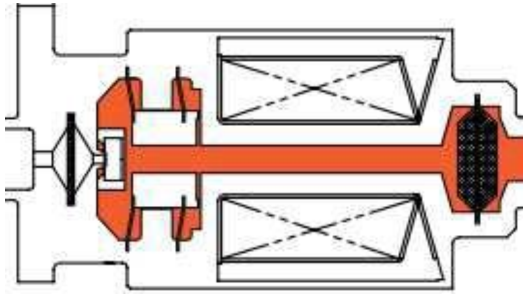
- Valve Types:
  - Monostable Valves (Solenoid valves): Pressure assisted or not + force balance (also in dynamic case) + heating
    - Solenoid valve is a monostable valve
    - “Normally closed” version will only remain open whilst powered, where after they return to closed position
    - “Normally open” versions are also available
    - As with the latch valve, they are used to control propellant flow around the system

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types:
  - Monostable Valves (Solenoid valves):

In-line SV



Which Liquid Bi-propellant Propulsion Systems exist?

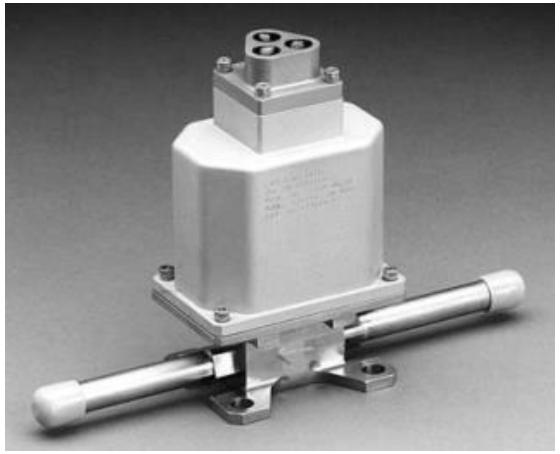
Propulsion Equipment:

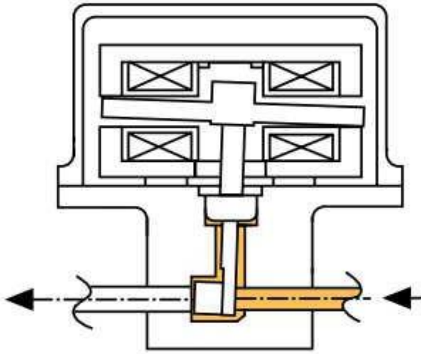
- Valve Types
  - Bistable Valves (Latch valves): Force balance (also in dynamic case) + power need
    - Latch valve is a bistable valve
    - The position open/closed is controlled by a short electrical pulse on demand
    - Most examples contain an internal position indicator to determine valve position
    - The function of the valve is to control propellant (sometimes gas) flow around the propulsion system

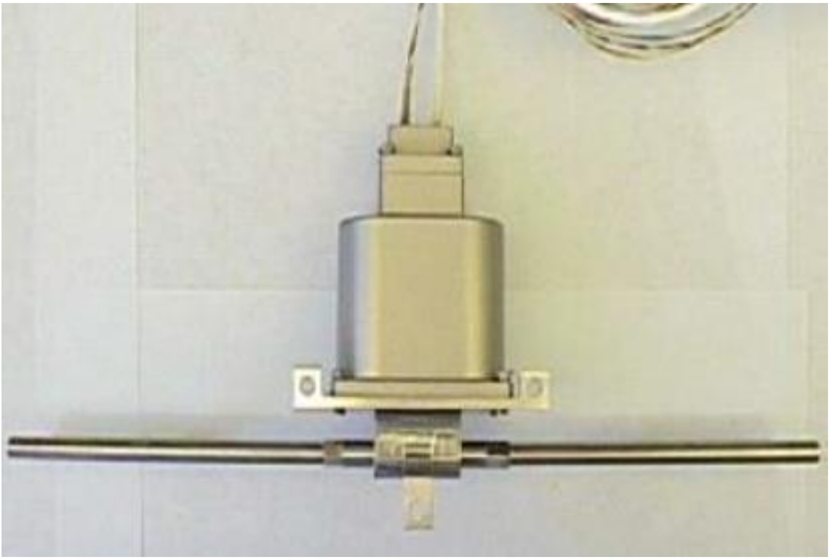
Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - Bistable Valves (Latch valves): Force balance (also in dynamic case) + power need







Which Liquid Bi-propellant Propulsion Systems exist?

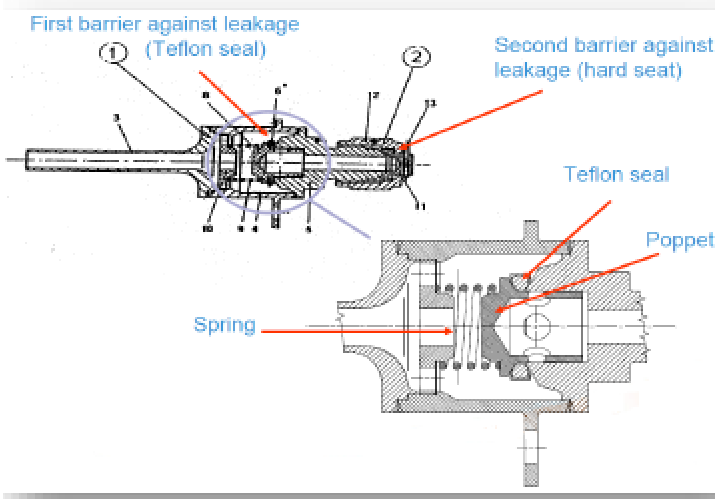
Propulsion Equipment:

- Valve Types
  - Test Ports, Fill and Drain Valves or Fill and Vent Valves (FDV, FVV or TP)
    - The name determines the function, but all are fundamentally the same valve
    - They are used on ground to enable fluids to be put into the system, or to perform tests on ground
    - The valves are operated using a counterpart called a ground half coupling
    - Often called Mechanical Valves, Service Valves or Flight Half Couplings

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - Test Ports, Fill and Drain Valves or Fill and Vent Valves (FDV, FVV or TP)



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - Burst Disk & Relief Valves:
    - Pressure relief valve will be set to a pre-determined “cracking pressure”
    - If the pressure gets too high within the system the relief valve vents gas to prevent over pressurization (particularly tanks)
    - Burst discs work in the same way, but once opened, they cannot be closed
    - They are not particularly desirable as the reliability of the system can be impaired – analytical design solutions are better

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - Burst Disk & Relief Valves:

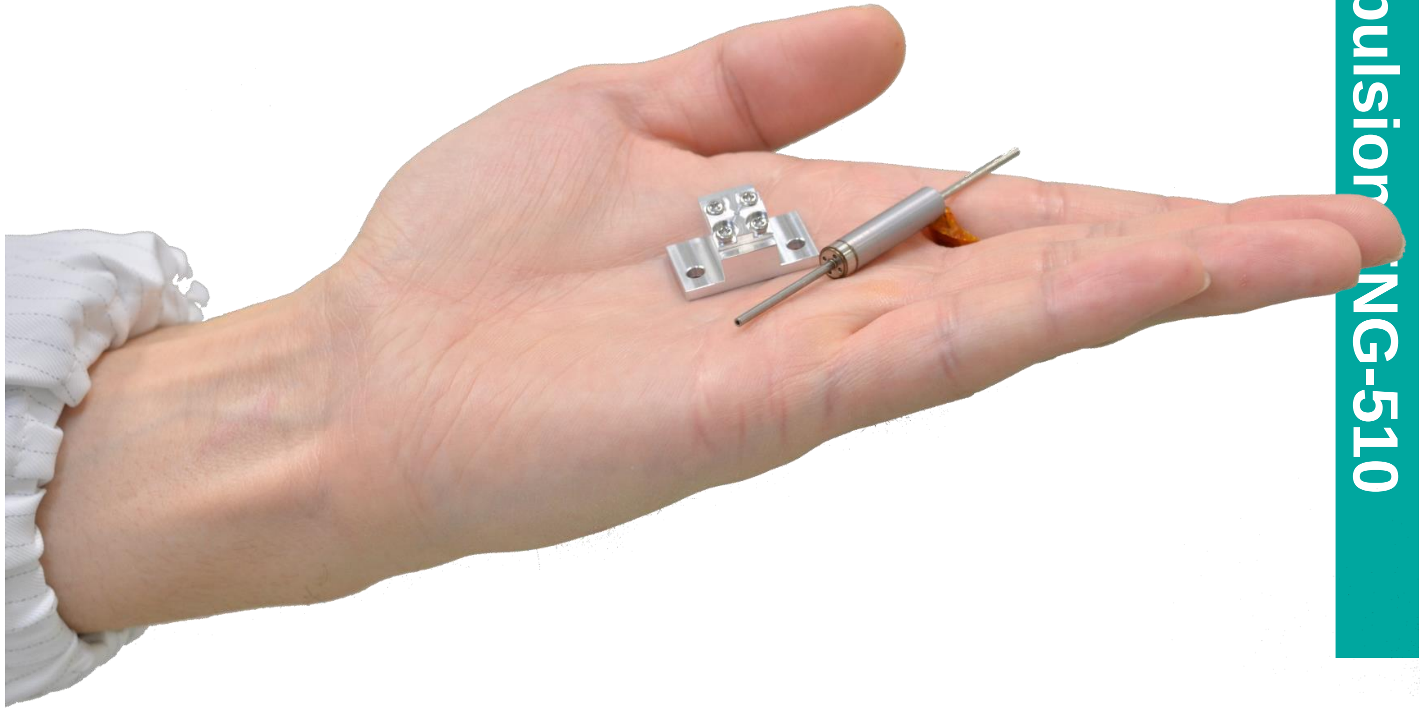
Hydrodyne Burst Disc

Valcor V3500-77

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Valve Types
  - And everything can be a little bit smaller…



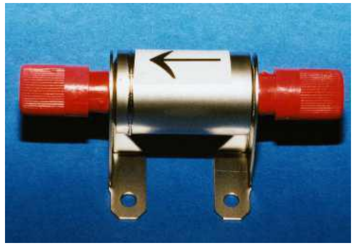
Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

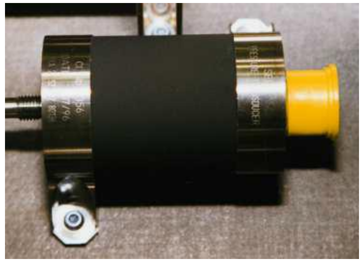
- Other propulsion equipment
  - Transducer (Pressure, Temperature, Flow rate, Position indication, Acceleration)
  - Filter (Liquid and Gaseous)
  - Heater
  - Heat exchanger
  - Electrolyzer
  - Sabatier Reactor
  - Compressor
  - …

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:



He - Filter



Pressure Transducer

Propellant Filter

Pressure Transducer High Accuracy

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Other propulsion equipment
  - Transducer (Pressure, Temperature, Flow rate, Position indication, Acceleration)
    - Pressure transducers convert physical pressure into an equivalent electrical signal
    - PTs are typically powered continuously through life
    - PTs are used to monitor pressure which is used to determine
    - Correct function of the system (Propellant gauging calculations, Thruster performance)
    - The PTs come in various low and high pressure ranges and are calibrated during supplier testing

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Other propulsion equipment
  - Transducer (Pressure, Temperature, Flow rate, Position indication, Acceleration)

Which Liquid Bi-propellant Propulsion Systems exist?

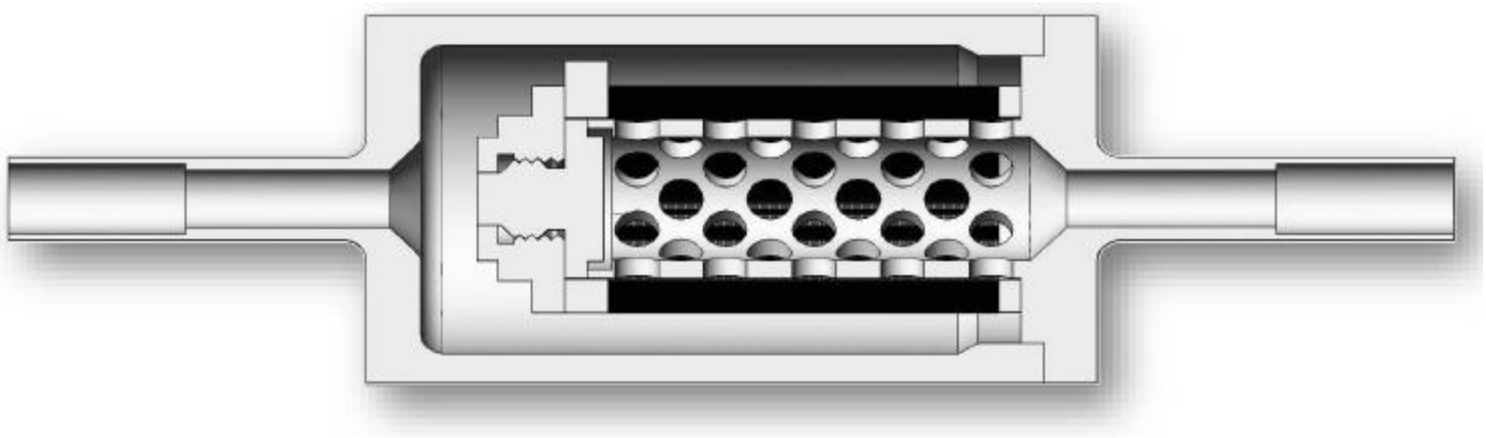
Propulsion Equipment:

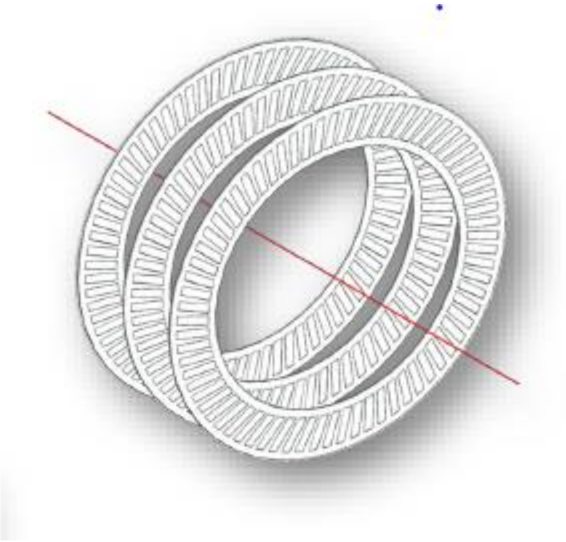
- Other propulsion equipment
  - Filter (Liquid and Gaseous)
    - Filters are used to filter particulate from gas or propellant to protect downstream components
    - The propulsion systems are precision cleaned during assembly, however residual particulate and debris created from pyro valves can damage valves
    - Filters will exert a pressure drop at high flow rates, which must be taken into account

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Other propulsion equipment
  - Filter (Liquid and Gaseous)





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 thruster definitions:
  - Steady State
    - Refers to the configuration where the thruster valves are fully open
    - Continuous thrust is produced (provided conditions remain stable)

Which Liquid Bi-propellant Propulsion Systems exist?

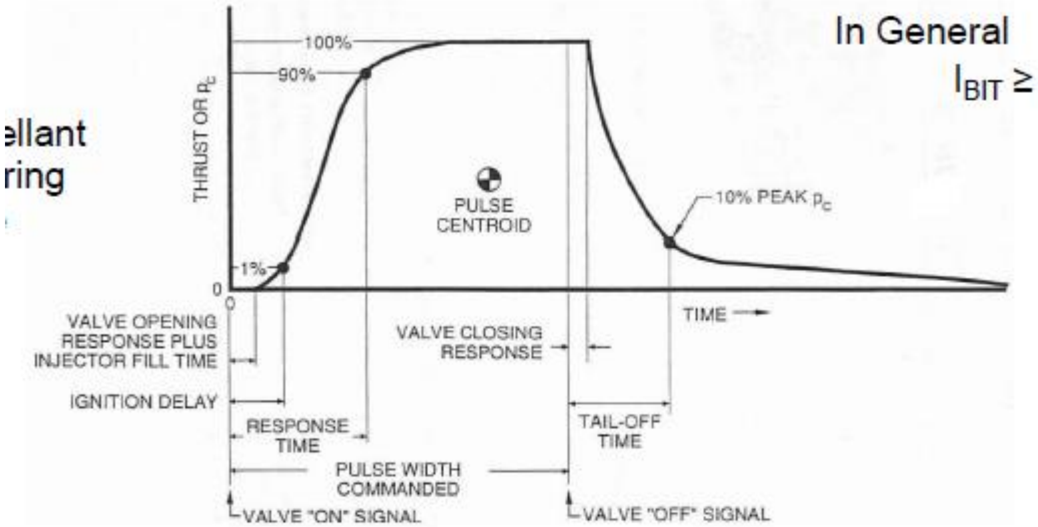
Propulsion Equipment:

- Bi-propellant thruster definitions:
  - Pulse Mode
    - At the same pressure, a net lower thrust can be produced by cycling the valve producing a series of impulsive pulses for more accurate positioning
    - The Impulse bit is the equivalent thrust which can be produced for a given pulse
    - Minimum Impulse bit is the smallest possible amount of thrust which can be produced by a thruster for given operating conditions

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thruster definitions:
  - Pulse Mode
    - Duty cycle
  - Transient Phases
    - Thrust rise time
    - Thrust decay time



$$\text{Duty Cycle (\%)} = \frac{t_{ON}}{t_{ON} + t_{OFF}}$$

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

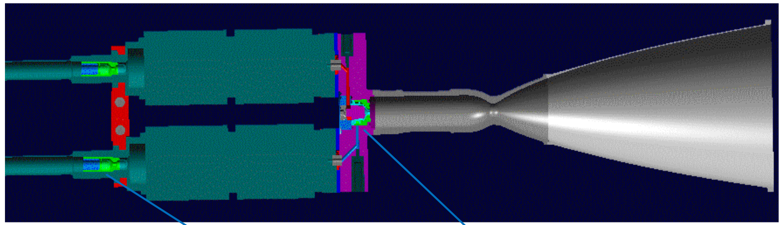
- Bi-propellant thrusters / engines
  - Injection method for propellants (e.g. spin, showerhead, …)
  - Cooling of engine
  - Trimming of engine
  - Ignition of propellants

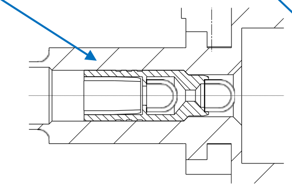
Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

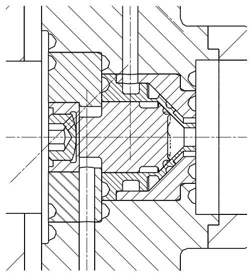
- Bi-propellant thrusters / engines
  - Trimming / calibration of engine
    - Orifice (passive)
    - Throttling valve / injector (active)

22N Zweistoff-Triebwerk

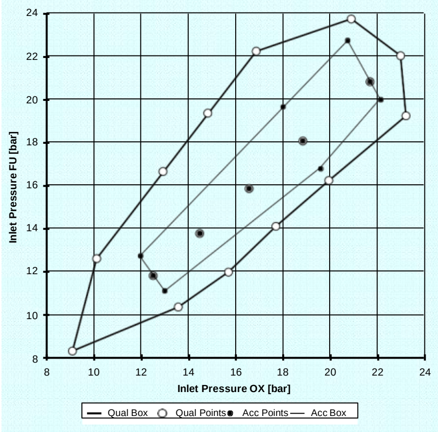


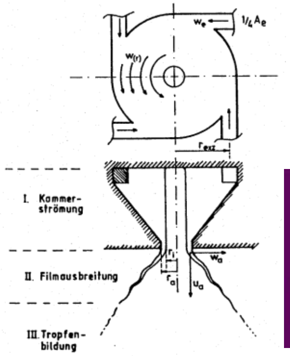


Variable Trimmblende



Doppeldrall-Einspritzsystem





Funktionsmechanismen bei Dralleinspritzdüsen

Which Liquid Bi-propellant Propulsion Systems exist?

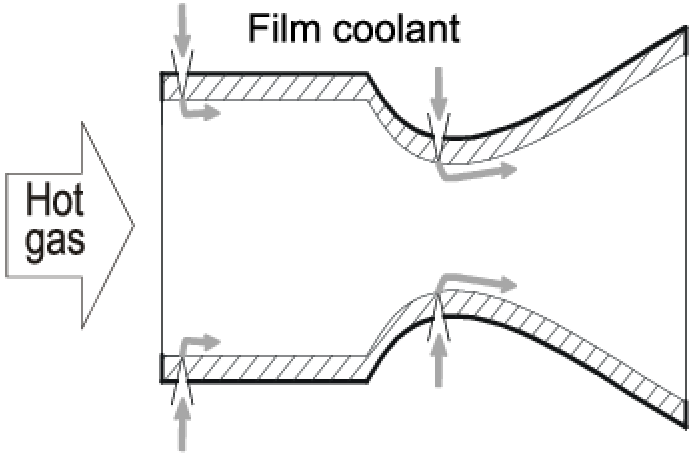
Propulsion Equipment:

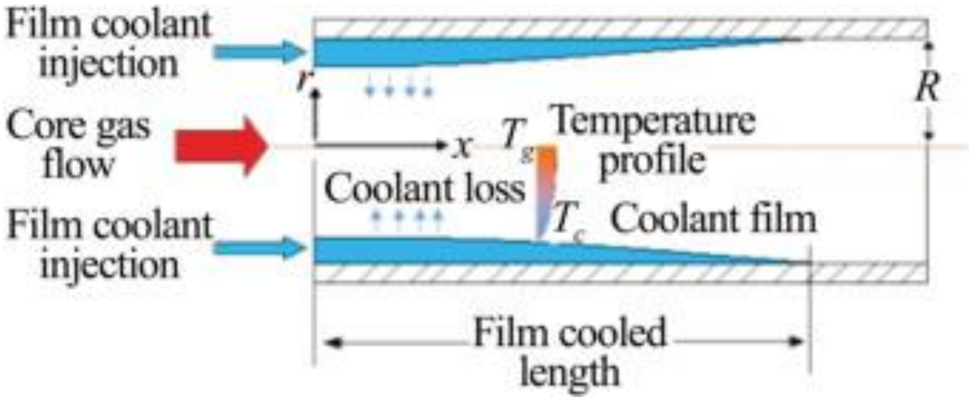
- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Radiative cooling
    - Capacitive cooling (Phase change material)
    - Film cooling
    - Vortex cooling
    - Regenerative cooling
    - Ablative cooling
    - Transpiration cooling

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

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

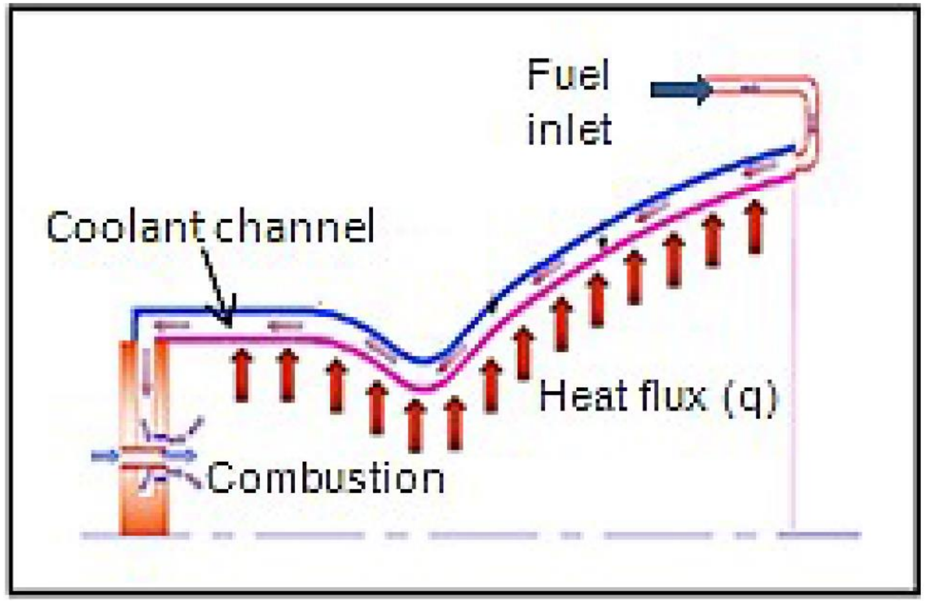




Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

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

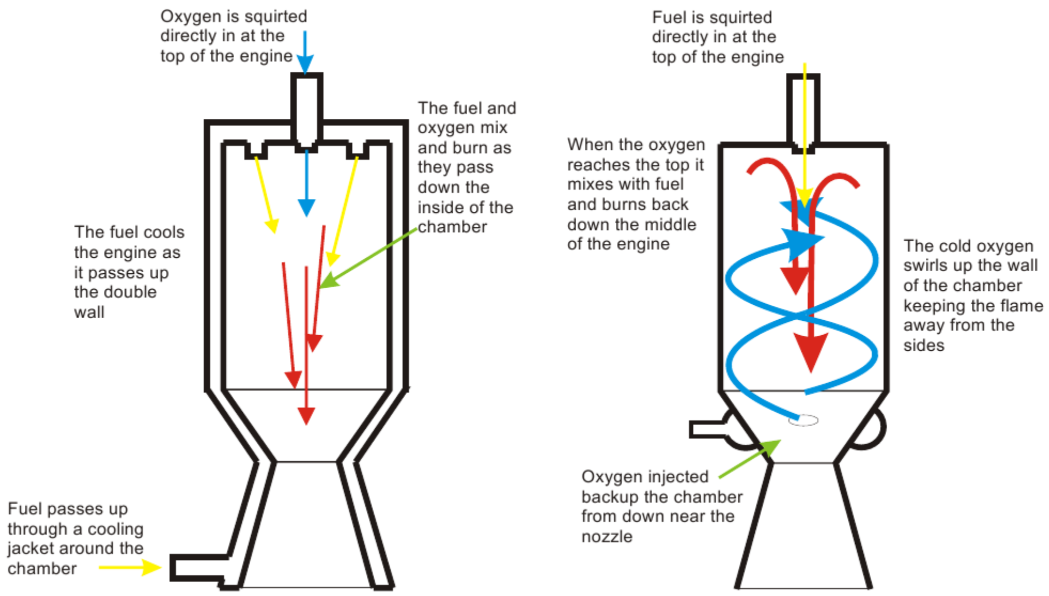


Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

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

Which Liquid Bi-propellant Propulsion Systems exist?



Liquid cooled rocket engine | **Vortex rocket engine**

Which Liquid Bi-propellant Propulsion Systems exist?

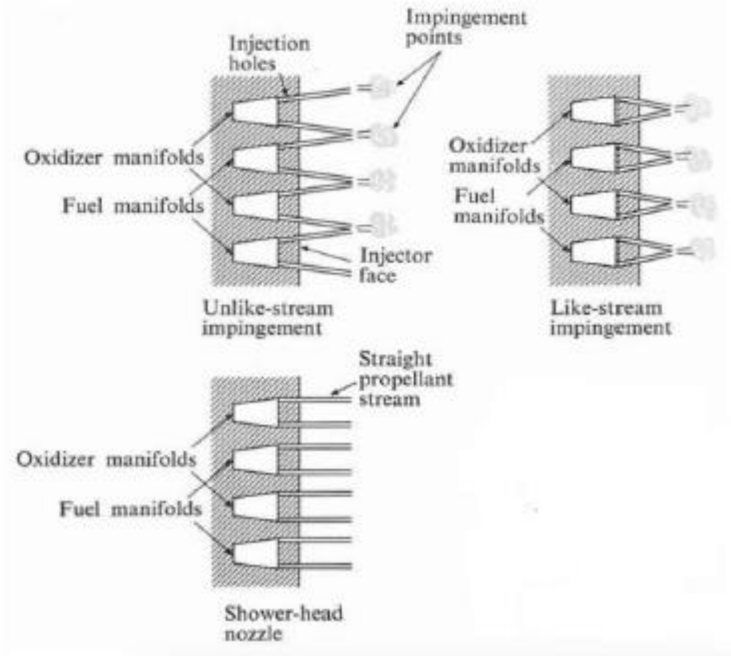
Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Injection method for propellants (e.g. spin, showerhead, …)
    - 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 (e.g. spin, showerhea



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion Equipment:

- Bi-propellant thrusters / engines
  - Ignition of propellants
    - Hypergolic ignition
    - Catalytic decomposition
    - Thermal decomposition
    - …

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
    - Thermal wire
    - …
    - Torch ignitor (Different propellant or same propellants with smaller amount)

Which Liquid Bi-propellant Propulsion Systems exist?

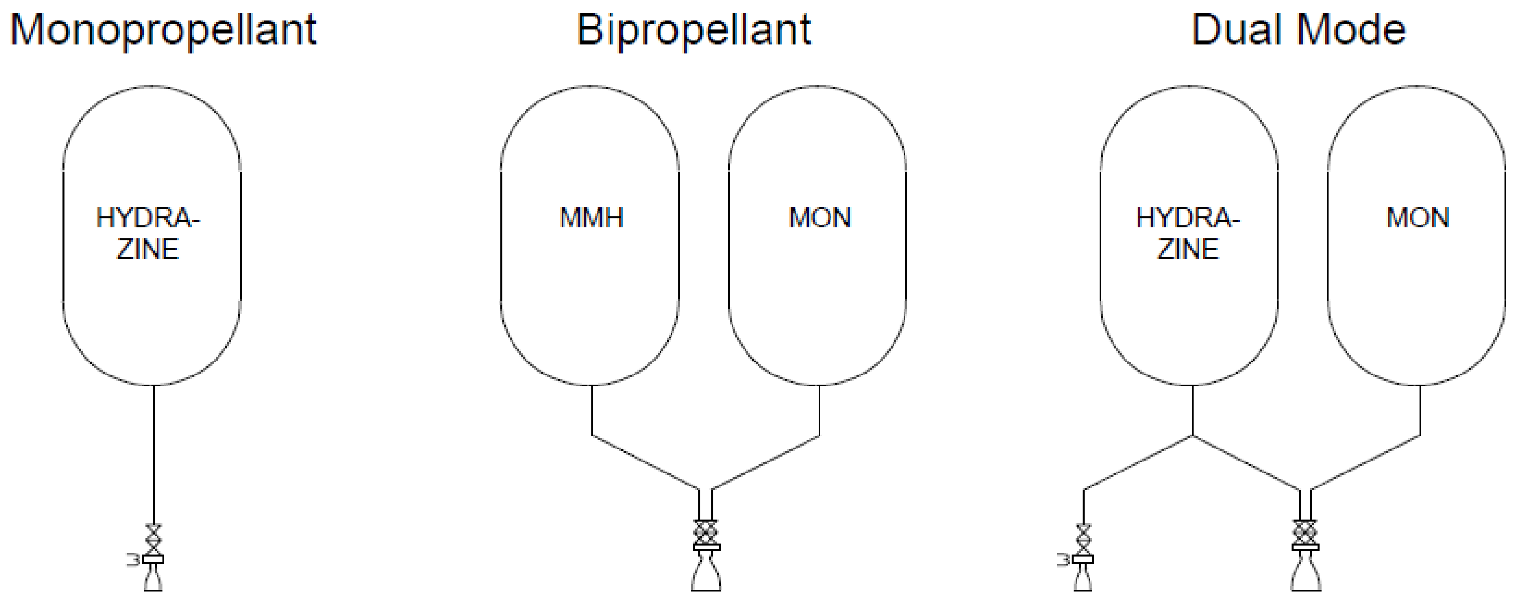
Propulsion System Combination:

- Dual Mode Propulsion
  - Dual Mode systems combine elements of monopropellant and bipropellant systems
  - Dual mode propulsion system can have a high thrust bipropellant engine and small precise monopropellant engines
  - Or resistojets or arcjets may be used instead of catalytic hydrazine thrusters

Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion System Combination:

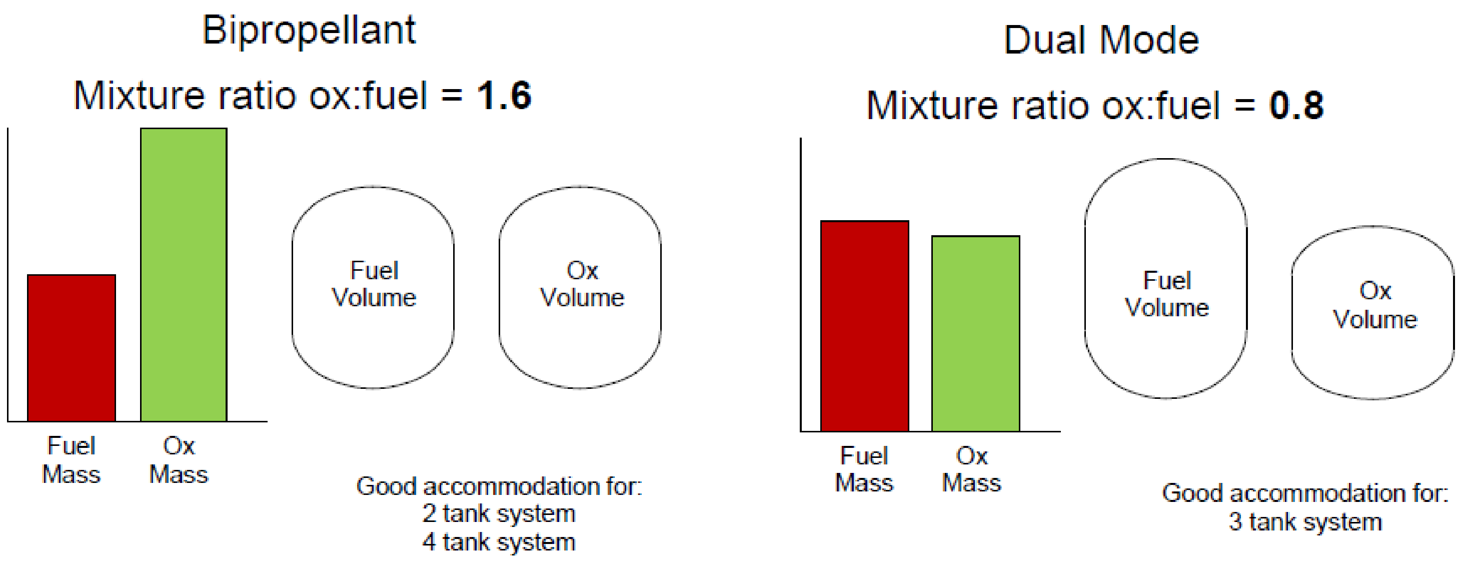
- Dual Mode Propulsion



Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion System Combination:

- Dual Mode Propulsion



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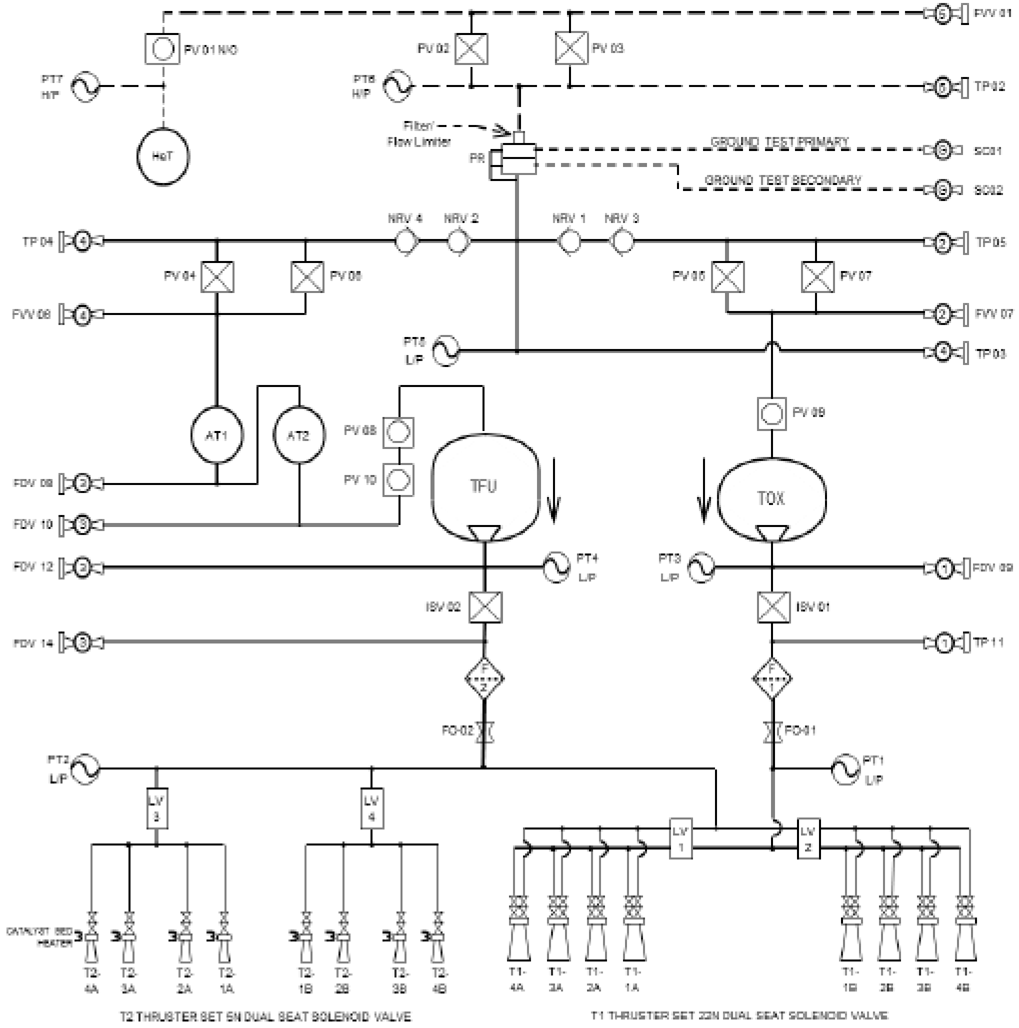
Which Liquid Bi-propellant Propulsion Systems exist?

Propulsion System Combination

- Dual Mode Propulsion
  - Example: Bepi Colombo

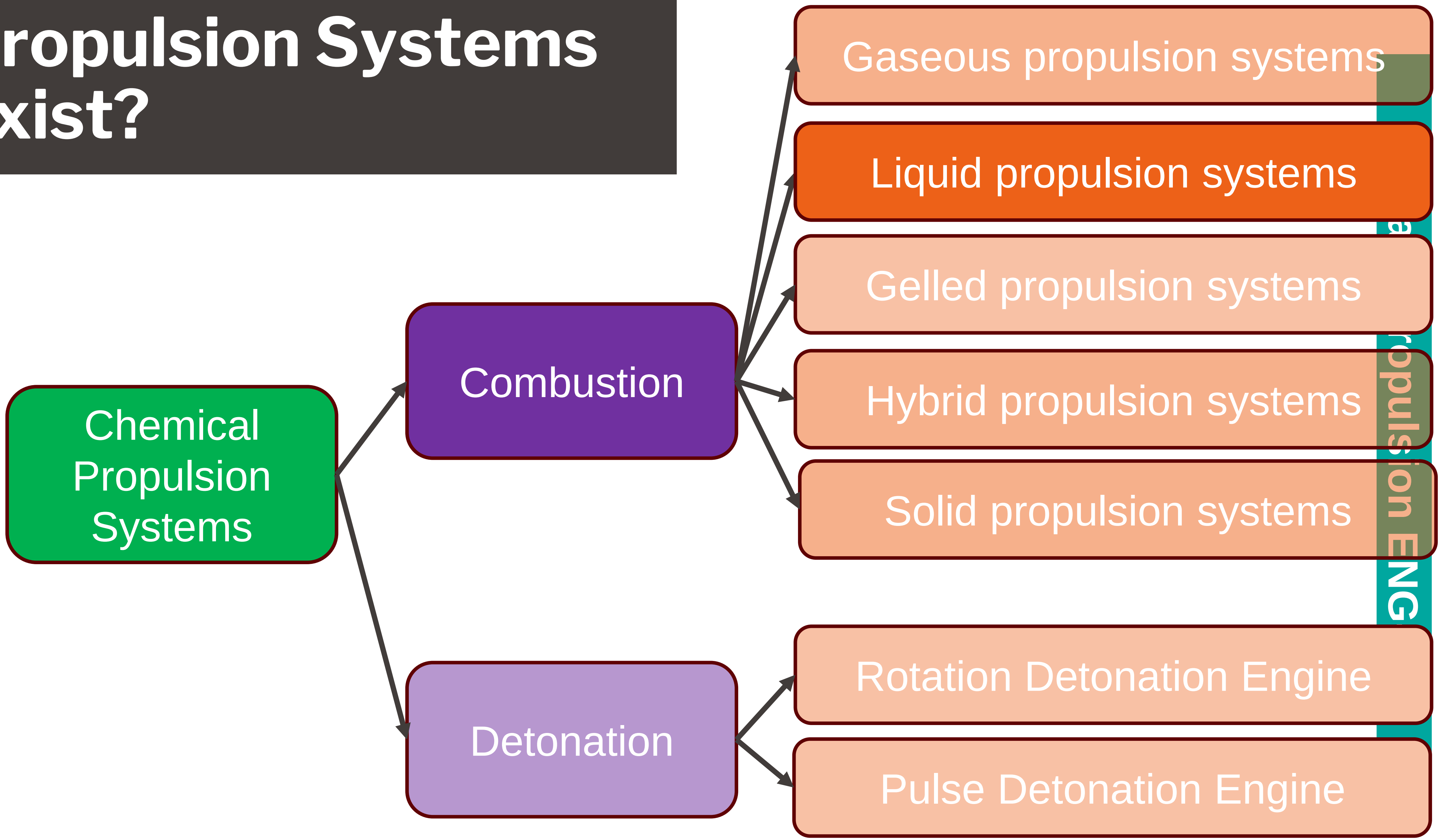


Which Liquid Bi-propellant Propulsion Systems exist?

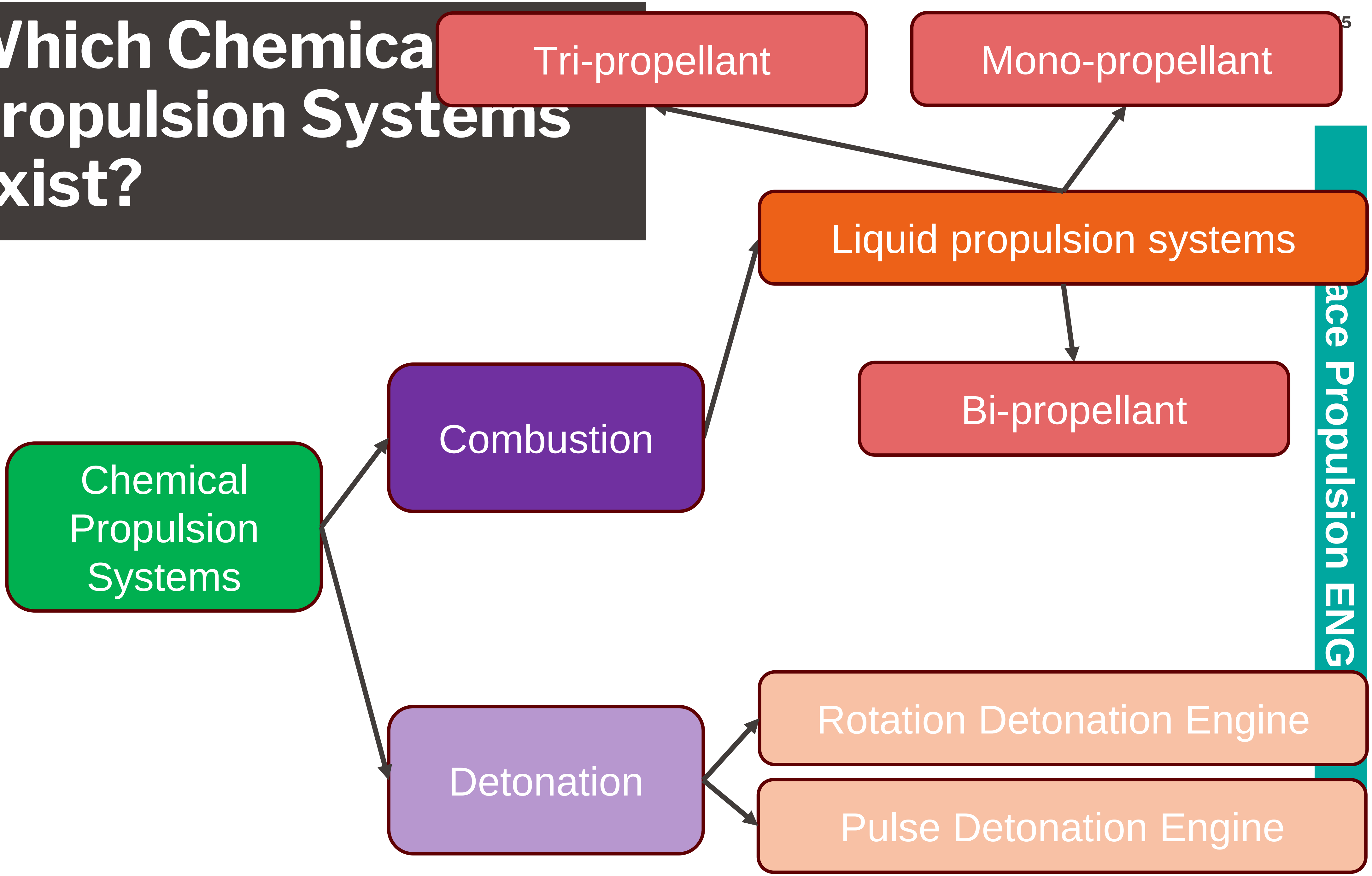
Propulsion System Combination:

- Mixed Mode Propulsion
  - Mixed Mode propulsion refers to the use of different propellant types with one thruster:
    - Cold gas, mono-prop or bi-prop operation of a thruster
    - Small flow (igniter flow) or full flow

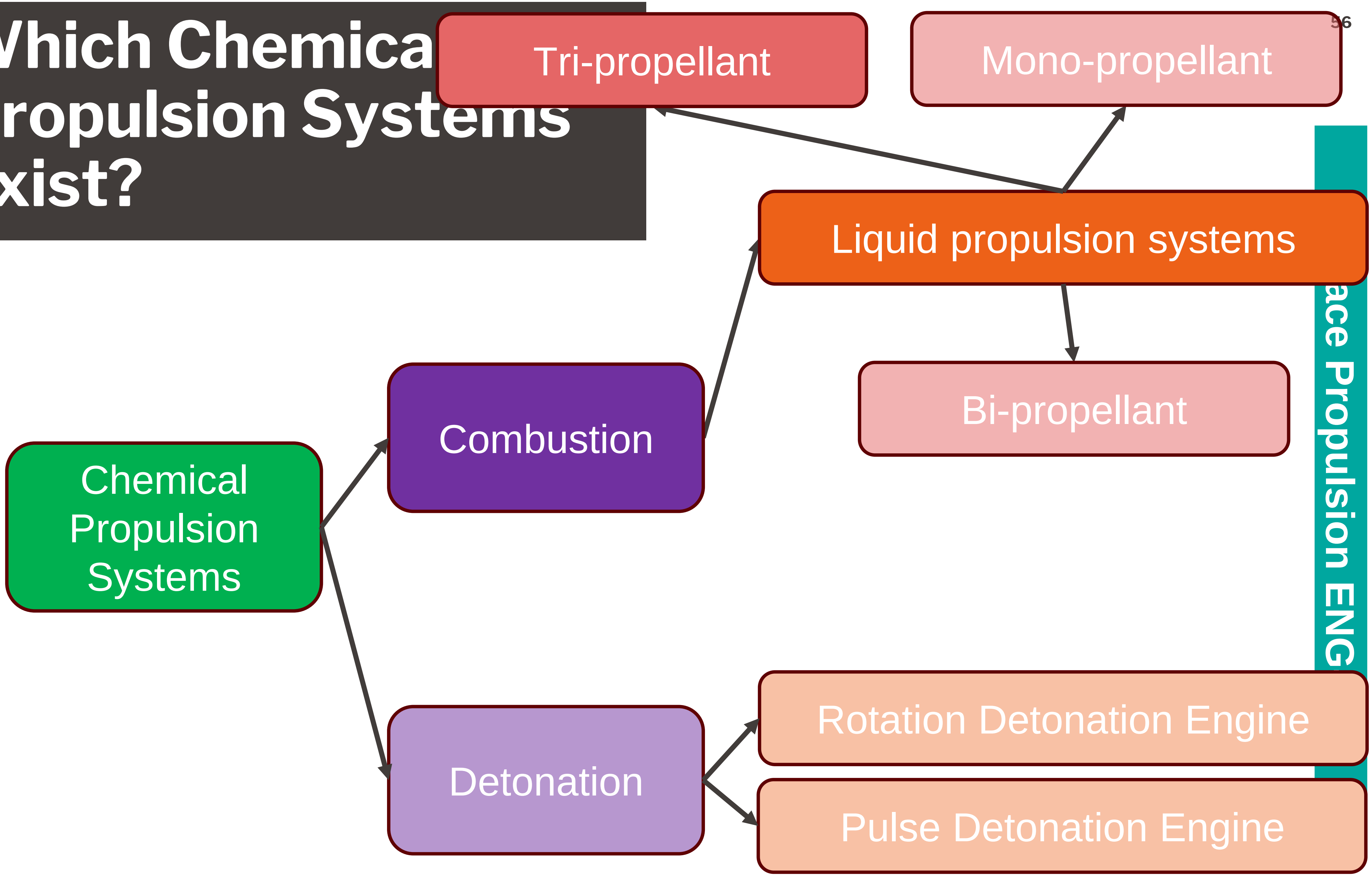
Which Chemical Propulsion Systems exist?



Which Chemica Propulsion Systems exist?



Which Chemica Propulsion Systems exist?



Which Liquid Tri-propellant Propulsion Systems exist?

Chemical Propulsion Systems:

- Liquid propulsion systems
  - Monopropellant, bi-propellant or **tri-propellant**
  - Storable or cryogenic propellants
  - Toxic or non-toxic (hazardous or green) propellants
  - Hypergolic or non-hypergolic propellants
  - Pressure-fed (self-pressurization, blow-down or regulated) or pump-fed propulsion

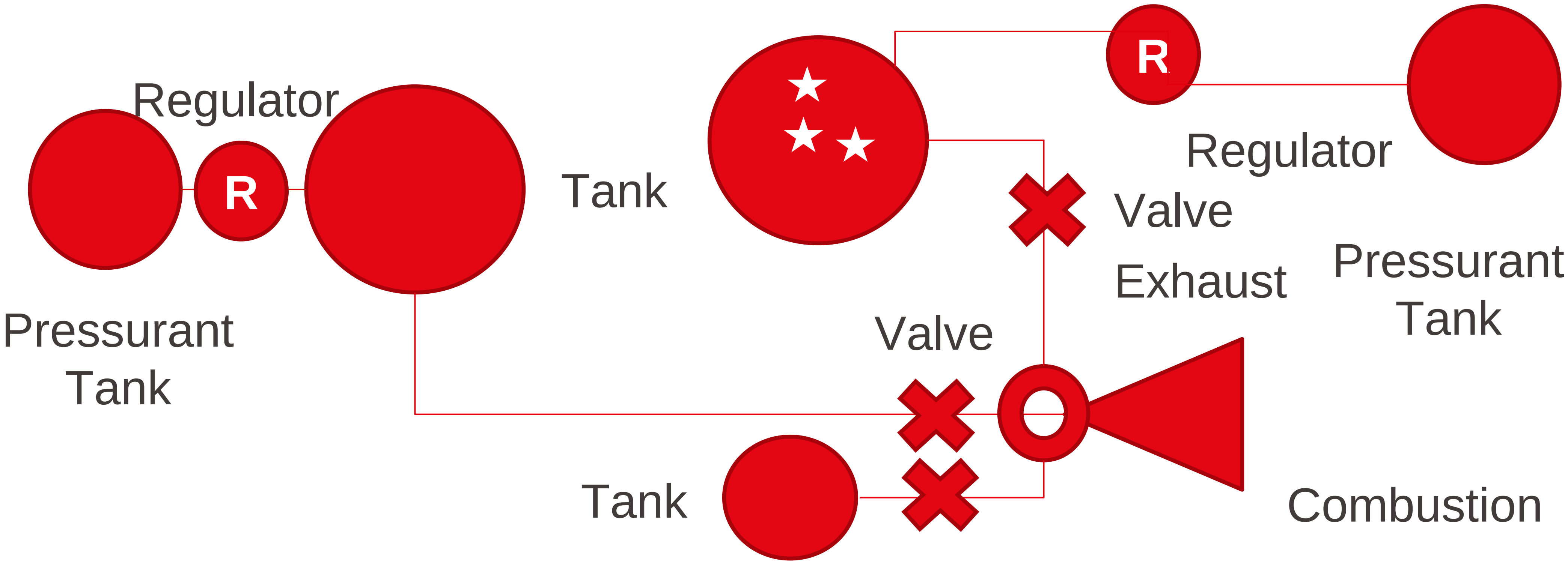
Propellant Phase in Tanks

		Solid	Liquid	Gas
Chemical Reaction	Combustion	Two liquid propellants with metallic additives or three liquid propellants		
	Decomp			
	No			

Tri-propellant Thruster

Which Liquid Tri-propellant Propulsion Systems exist?

Architecture for Liquid Tri-propellant Combustion Propulsion Systems:



Which Liquid Tri-propellant Propulsion Systems exist?

Liquid tri-propellant propulsion systems:

- A tri-propellant rocket is a rocket that uses three propellants, as opposed to the more common bi-propellant rocket or monopropellant rocket designs, which use two or one propellants, respectively
- Tri-propellant systems can be designed to have high specific impulse and have been investigated for single stage to orbit designs
- While tri-propellant engines have been tested, no tri-propellant rocket has been built or flown

Which Liquid Tri-propellant Propulsion Systems exist?

Liquid tri-propellant propulsion systems:

- There are two different kinds of tri-propellant rockets
- One is a rocket engine which mixes three separate streams of propellants, burning all three propellants simultaneously respectively some solid additives are pre-mixed into the liquid fuel and such two separate streams of propellant are injected simultaneously
- The other kind of tri-propellant rocket is one that uses one oxidizer but two fuels, burning the two fuels in sequence during the flight

Which Liquid Tri-propellant Propulsion Systems exist?

Liquid tri-propellant propulsion systems:

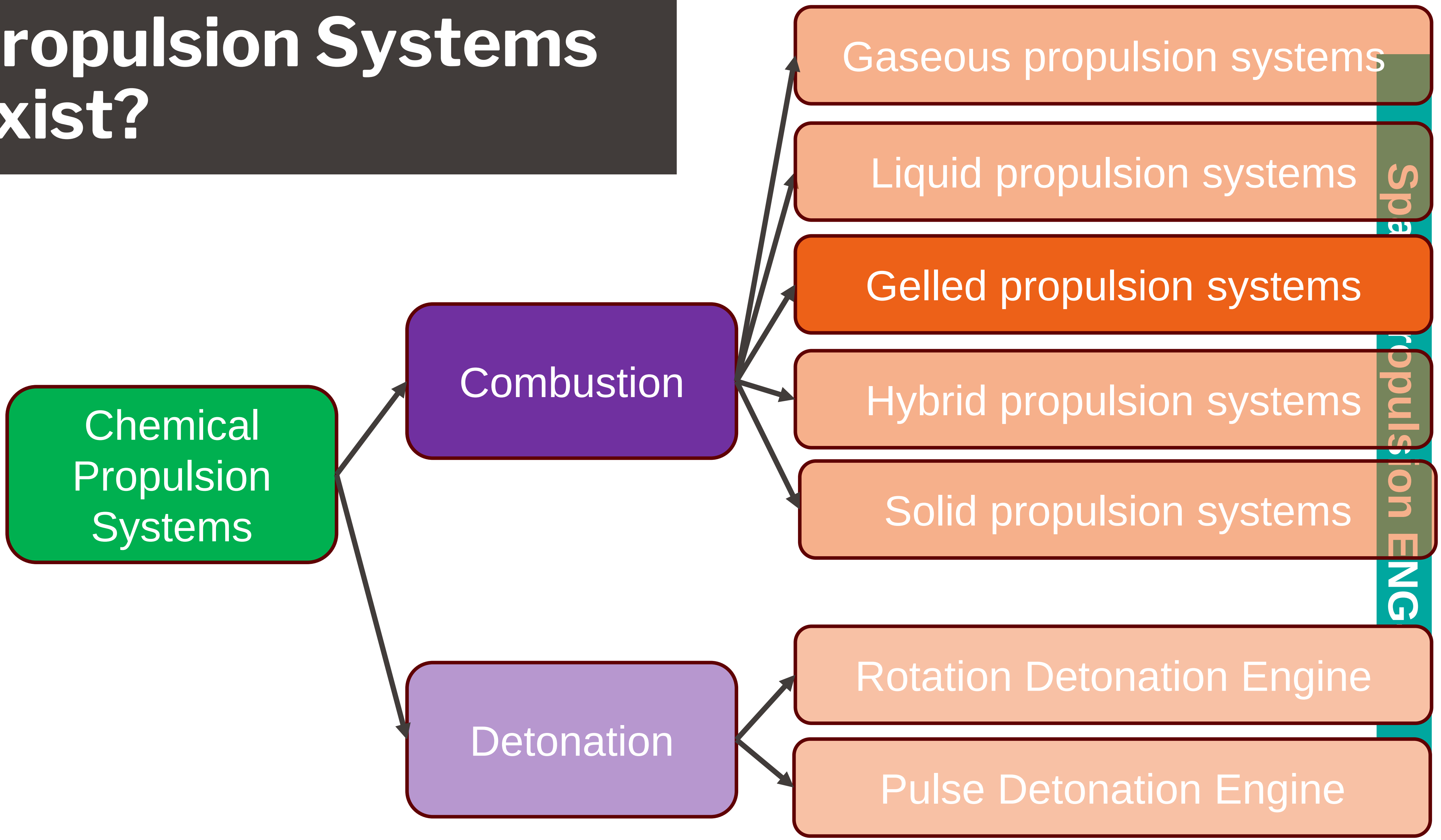
- Simultaneous tri-propellant systems often involve the use of a high energy density metal additive (Beryllium or Lithium) with existing bi-propellant systems
- In these motors, the burning of the fuel with the oxidizer provides an activation energy needed for a more energetic reaction between the oxidizer and the metal (a kind of staged combustion)
- While theoretical modeling of these systems suggests an advantage over bipropellant motors, several factors limit their practical implementation, including the difficulty of injecting solid metal into the thrust chamber; heat, mass, and momentum transport limitations across phases; and the difficulty of achieving and sustaining combustion of the metal

Which Liquid Tri-propellant Propulsion Systems exist?

Liquid tri-propellant propulsion systems:

- In the 1960s, an engine was fired using a mixture of liquid lithium, gaseous hydrogen, and liquid fluorine to produce a specific impulse of 542 s
- In sequential tri-propellant rockets, the fuel is changed during flight, so the motor can combine the high thrust of a dense fuel like kerosene early in flight with the high specific impulse of a lighter fuel like liquid hydrogen (LH2) later in flight
- The result is a single engine providing some of the benefits of staging

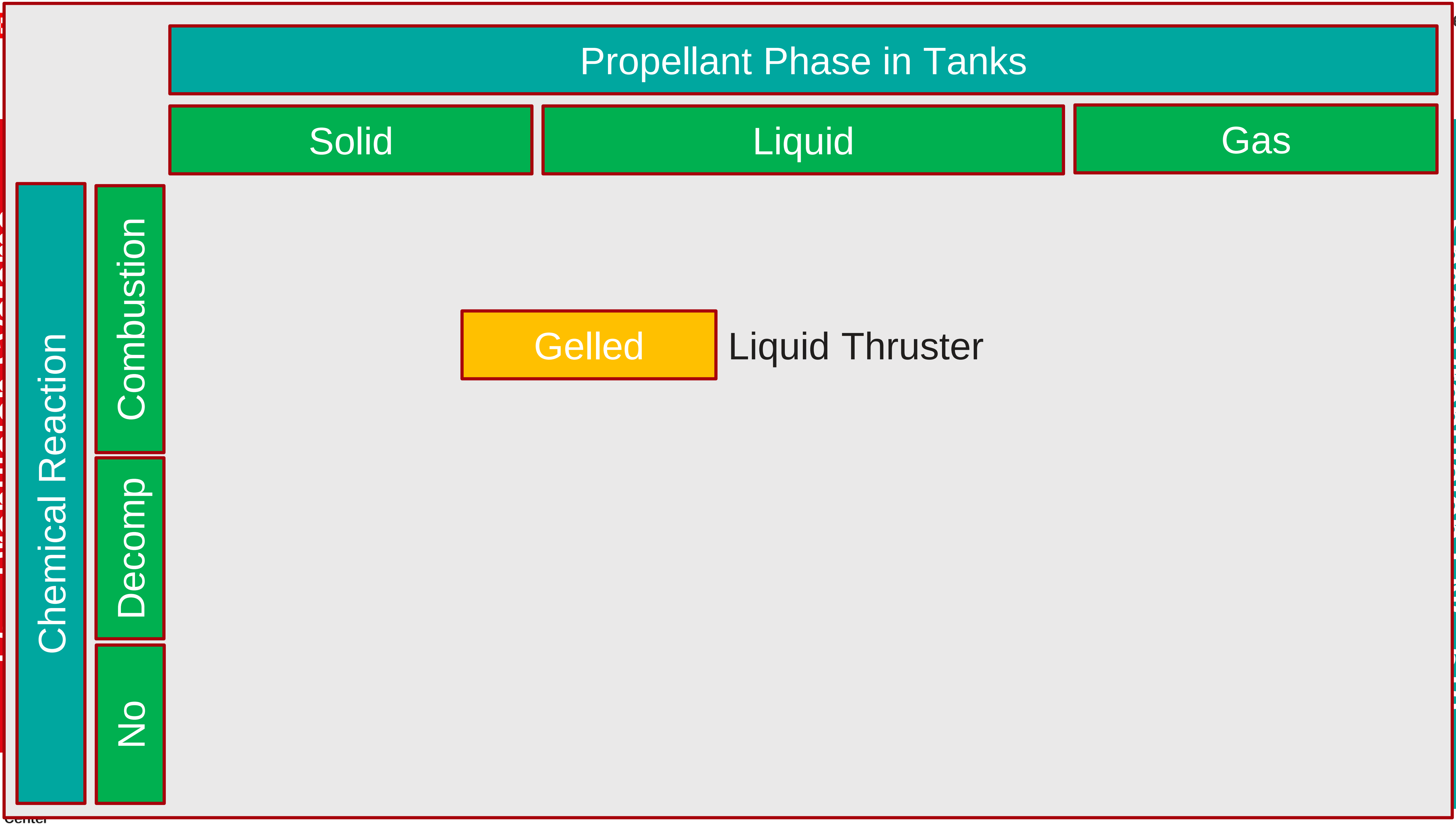
Which Chemical Propulsion Systems exist?



Which Gelled Propulsion Systems exist?

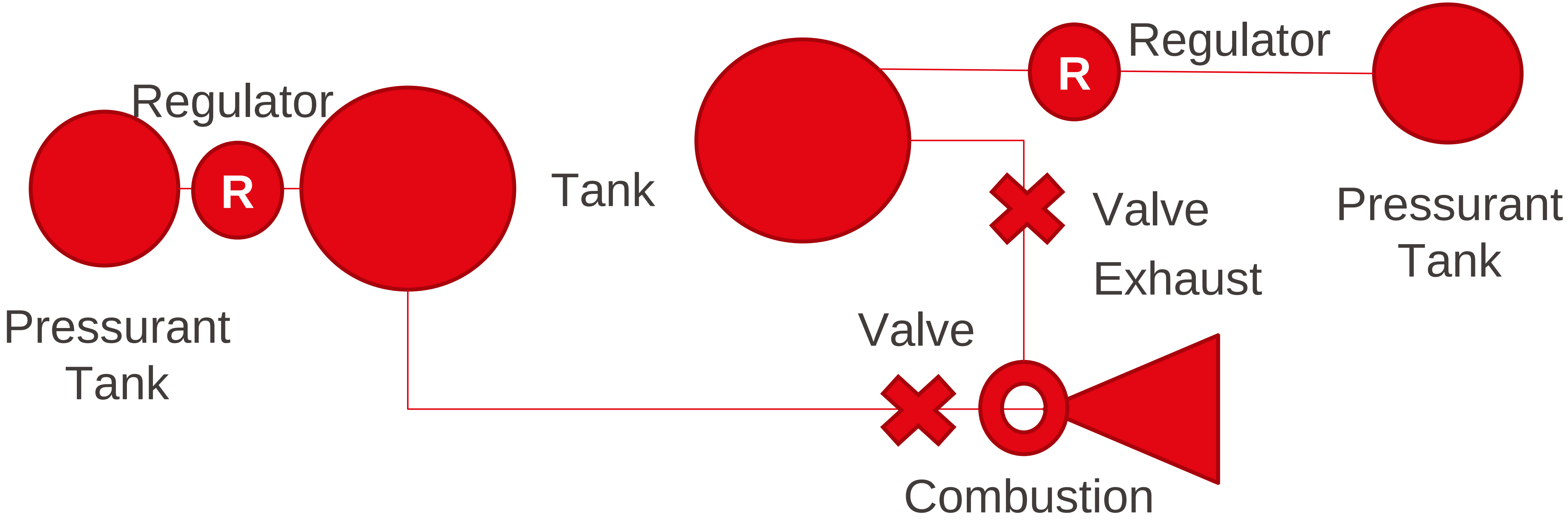
Chemical Propulsion Systems

- 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
Gelled
Liquid Thruster

Which Gelled Propulsion Systems exist?

Architecture for Gelled Bi-propellant Combustion Propulsion Systems:



Which Gelled Propulsion Systems exist?

Gelled Propulsion Systems:

- Gelled propellants are produced from liquid fuels and gelling agents
- Once in a tank, i.e. in idle state, they change from solid into liquid state when shear stress is applied
- This particular feature provides a combination of major advantages to gelled propellants for use in liquid and solid propellants
- Developing such highly performing and advantageous propellants requires still comprehensive research

Which Gelled Propulsion Systems exist?

Gelled Propulsion Systems:

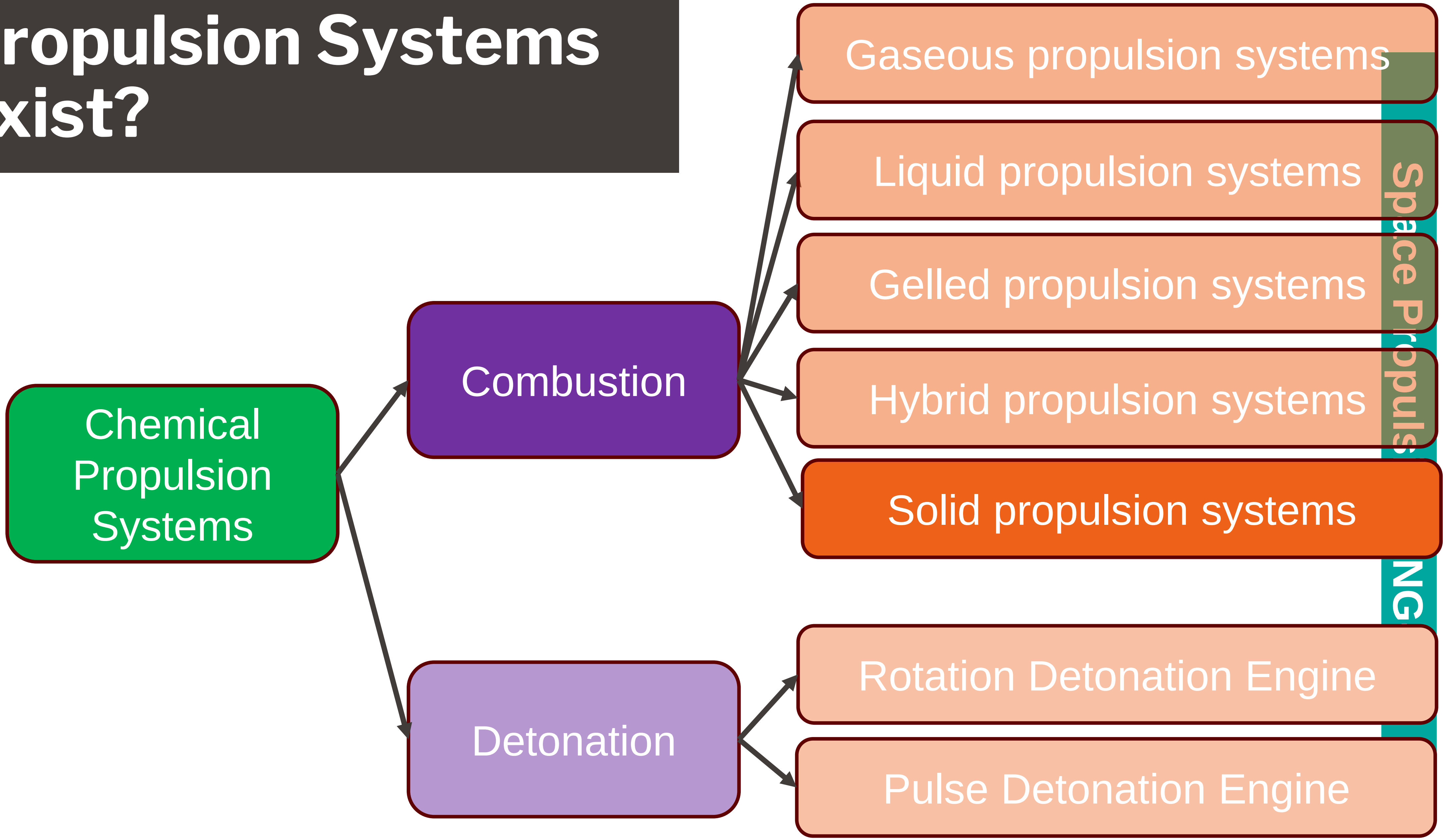
- Physical-chemical laboratory is needed to analyze rheological and physical features of gelled propellants, like viscosity and surface tension
- The special rheological and physical features of gelled propellants may differ significantly from conventional liquid fuels in terms of fuel conditioning (vaporization and injection) in the combustion chamber
- While certain gelled propellants show rather similar vaporization behavior compared to traditional liquid fuels, others may react with entirely different vaporization images

Which Gelled Propulsion Systems exist?

Gelled Propulsion Systems:

- Therefore, detailed vaporization tests in separate experimental structures are needed
- At DLR Lampoldshausen, the application of gelled propellants is tested in modular model combustion chambers
- Gathered data are used to identify appropriate combustion chamber processes and to evaluate the performance characteristics of such propulsions

Which Chemical Propulsion Systems exist?



Which Solid 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	Double base or composite Bi-prop Thruster		
	Decomp			
	No			

Which Solid Propulsion Systems exist?

Architecture for Solid Propulsion Systems:

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Performance comparison
  - A solid fuel-oxidizer mixture (propellant) is packed into the rocket, with a cylindrical hole in the middle
  - An igniter combusts the surface of the propellant
  - The cylindrical hole in the propellant acts as a combustion chamber
  - The hot exhaust is choked at the throat, which, among other things, dictates the amount of thrust produced
  - Exhaust exits the rocket

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Casing
  - Casing may be constructed from a range of materials
    - Steel was used for the Space Shuttle boosters
    - Filament-wound graphite epoxy casings are used for high-performance motors
  - Casing must be designed to withstand the pressure and resulting stresses of the rocket motor, possibly at elevated temperature
  - To protect the casing from corrosive hot gases, a sacrificial thermal liner on the inside of the casing is often implemented, which ablates to prolong the life of the motor casing

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Nozzle
  - A convergent-divergent design accelerates the exhaust gas out of the nozzle to produce thrust
  - The nozzle must be constructed from a material that can withstand the heat of the combustion gas flow
  - Often, heat-resistant carbon-based materials are used, such as amorphous graphite or reinforced carbon-carbon
  - Some designs include directional control of the exhaust by gimballing the nozzle

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Performance comparison
  - Key parameter for the solid propulsion system performance is the burn rate (e.g. cm / s) together with the burning area and the solid propellant density

W
Pr
ex

Propellant Type[a]	I_S Range (sec)[b]	Flame Temperature[e] (°F)	Flame Temperature[e] (K)	Density or Spec. Gravity[e] (lbm/in^3)	Density or Spec. Gravity[e] (SG)	Metal Content (mass %)	Burning Rate[c,e] (in./sec)	Pressure Exponent[e] n
DB	220–230	4100	2550	0.058	1.61	0	0.05–1.2	0.30
DB/AP/Al	260–265	6500	3880	0.065	1.80	20–21	0.2–1.0	0.40
DB/AP–HMX/Al	265–270	6700	4000	0.065	1.80	20	0.2–1.2	0.49
PVC/AP/Al	260–265	5600	3380	0.064	1.78	21	0.3–0.9	0.35
PU/AP/Al	260–265	5700	3440	0.064	1.78	16–20	0.2–0.9	0.15
PBAN/AP/Al	260–263	5800	3500	0.064	1.78	16	0.25–1.0	0.33
CTPB/AP/Al	260–265	5700	3440	0.064	1.78	15–17	0.25–2.0	0.40
HTPB/AP/Al	260–265	5700	3440	0.067	1.86	4–17	0.25–3.0	0.40
HTPE[f]/AP/Al	248–269	5909	3538	0.07	1.70		0.4–0.7	0.50
PBAA/AP/Al	260–265	5700	3440	0.064	1.78	14	0.25–1.3	0.35
AN/Polymer	180–190	2300	1550	0.053	1.47	0	0.06–0.5	0.60

[a] Al, aluminum; AN, ammonium nitrate; AP, ammonium perchlorate; CTPB, carboxy-terminated polybutadiene; DB, double-base; HMX, cyclotetramethylene tetranitramine; HTPB, hydroxyl-terminatd polybutadiene; PBAA, polybutadiene-acrylic acid polymer; PBAN, polybutadiene–acrylic acid–acrylonitrile terpolymer; PU, polyurethane; PVC, polyvinyl chloride.
[b] At 1000 psia expanding to 14.7 psia, ideal or theoretical value at reference conditions.
[c] At 1000 psia.
[d] See hazard classification section.
[e] I_s flame temperature, density, burn rate, and pressure exponent will vary slightly with specific composition.
[f] Data from Ref. 13–8 and CPIAC, and ATK Launch systems.

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Advantages
  - Simple
  - High thrust
  - Thrust can be adapted
- Disadvantages
  - Not stoppable
  - Toxic

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Propellant Types
  - Double-base propellants
  - Composite propellants
  - *Black powder (gun-powder) propellant*
  - *Zinc–sulfur (ZS) propellants*
  - *"Candy" propellants (sugar fuel)*
  - *High-energy composite (HEC) propellants*
  - *Composite modified double base propellants*
  - *Minimum-signature (smokeless) propellants*
  - *Electric solid propellants*

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Propellant Types
  - Double-base propellants
    - DB propellants are composed of two monopropellant fuel components where one typically acts as a high-energy (yet unstable) monopropellant and the other acts as a lower-energy stabilizing and gelling monopropellant
    - In typical circumstances, Nitroglycerin is dissolved in a gel and solidified with additives
    - DB propellants are implemented in applications where a medium-high Isp of roughly 235 s is required
    - Addition of metal fuels (such as Aluminium) can increase performance to around 250 s

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Propellant Types
  - Composite propellants
    - A powdered oxidizer and powdered metal fuel are intimately mixed and immobilized with a rubbery binder (that also acts as a fuel)
    - Composite propellants are often either ammonium nitrate-based (ANCP) or ammonium perchlorate-based (APCP)
    - Ammonium nitrate composite propellant often uses magnesium and / or aluminium as fuel and delivers medium performance (Isp of about 210 s)
    - Ammonium perchlorate composite propellant often uses aluminium fuel and delivers high performance: vacuum (Isp up to 296 s)

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Propellant Types
  - Composite propellants
    - Aluminium is used as fuel because it has a reasonable specific energy density, a high volumetric energy density, and is difficult to ignite accidentally
    - Composite propellants are cast, and retain their shape after the rubber binder, such as Hydroxyl-terminated polybutadiene (HTPB), cross-links (solidifies) with the aid of a curative additive
    - Because of its high performance, moderate ease of manufacturing, and moderate cost, APCP finds widespread use in space rockets and military rockets

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- More exotic propellant types
  - Black powder (gun-powder) propellant
    - Black powder (gunpowder) is composed of charcoal (fuel), potassium nitrate (oxidizer), and sulfur (fuel and catalyst)
    - It is one of the oldest pyrotechnic compositions with application to rocketry
    - In modern times, black powder finds use in low-power model rockets
    - The Isp of black powder is low, around 80 s

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- More exotic propellant types
  - Zinc–sulfur (ZS) propellants
    - Composed of powdered zinc metal and powdered sulfur (oxidizer), ZS or "micrograin" is another pressed propellant that does not find any practical application outside specialized amateur rocketry circles due to its poor performance (as most ZS burns outside the combustion chamber) and fast linear burn rates on the order of 2 m/s
    - ZS is most often employed as a novelty propellant as the rocket accelerates extremely quickly leaving a spectacular large orange fireball behind it

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- More exotic propellant types
  - "Candy" propellants (sugar fuel)
    - In general, rocket candy propellants are an oxidizer (typically potassium nitrate) and a sugar fuel (typically dextrose, sorbitol or sucrose) that are cast into shape by gently melting the propellant constituents together and pouring or packing the amorphous colloid into a mold
    - Candy propellants generate a low-medium specific impulse of roughly 130 s

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- More exotic propellant types
  - High-energy composite (HEC) propellants
    - Typical HEC propellants start with a standard composite propellant mixture (such as APCP) and add a high-energy explosive to the mix
    - This extra component usually is in the form of small crystals of RDX or HMX, both of which have higher energy than ammonium perchlorate
    - Despite a modest increase in specific impulse, implementation is limited due to the increased hazards of the high-explosive additives

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- More exotic propellant types
  - Composite modified double base propellants
    - Composite modified double base propellants start with a nitrocellulose / nitroglycerin double base propellant as a binder and add solids (typically ammonium perchlorate (AP) and powdered aluminium) normally used in composite propellants
    - The ammonium perchlorate makes up the oxygen deficit introduced by using nitrocellulose, improving the overall specific impulse
    - The aluminium improves specific impulse as well as combustion stability
    - The mixing of composite and double base propellant ingredients has become so common as to blur the functional definition of double base propellants

Which Solid Propulsion Systems exist?

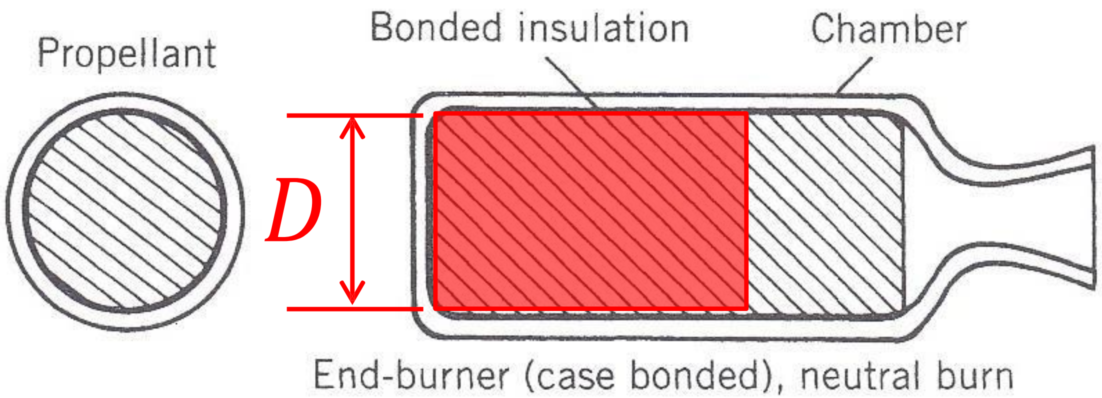
Solid Propulsion Systems:

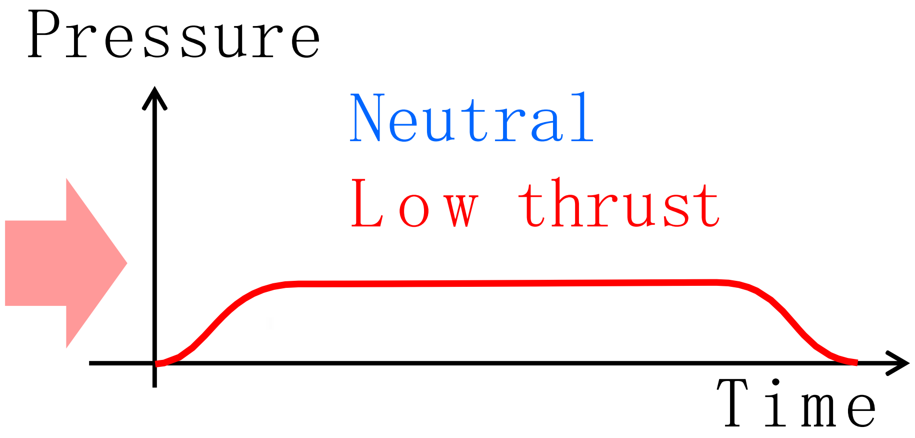
- More exotic propellant types
  - Minimum-signature (smokeless) propellants
    - One of the most active areas of solid propellant research is the development of high-energy, minimum-signature propellant using C6H6N6(NO2)6, which has 14% higher energy per mass and 20% higher energy density than HMX
    - The new propellant has been successfully developed and tested in tactical rocket motors
    - The propellant is non-polluting: acid-free, solid particulates-free, and lead-free
    - It is also smokeless and has only a faint shock diamond pattern that is visible in the otherwise transparent exhaust
    - Production costs remain high

Which Solid Propulsion Systems exist?

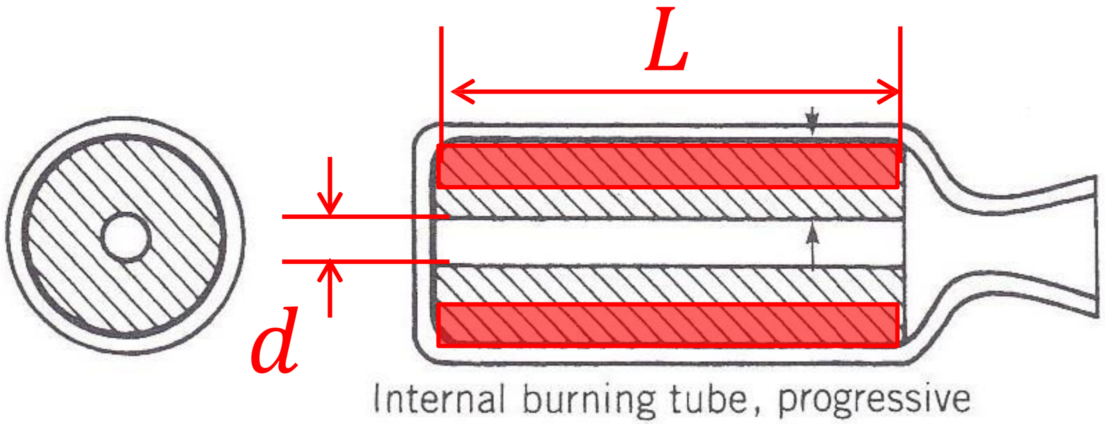
Solid Propulsion Systems:

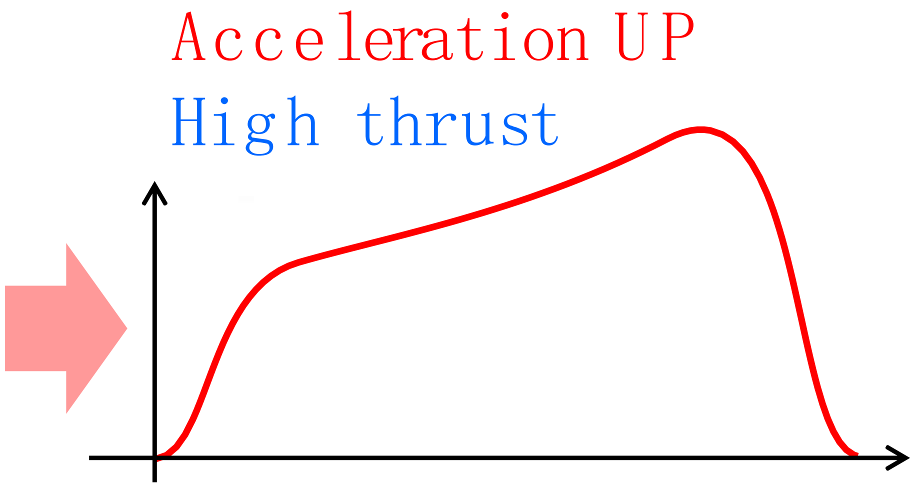
- More exotic propellant types
  - Electric solid propellants
    - Electric solid propellants (ESPs) are a family of high performance plastisol solid propellants that can be ignited and throttled by the application of electric current
    - Unlike conventional rocket motor propellants that are difficult to control and extinguish, ESPs can be ignited reliably at precise intervals and durations
    - It requires no moving part and the propellant is insensitive to flames or electrical sparks





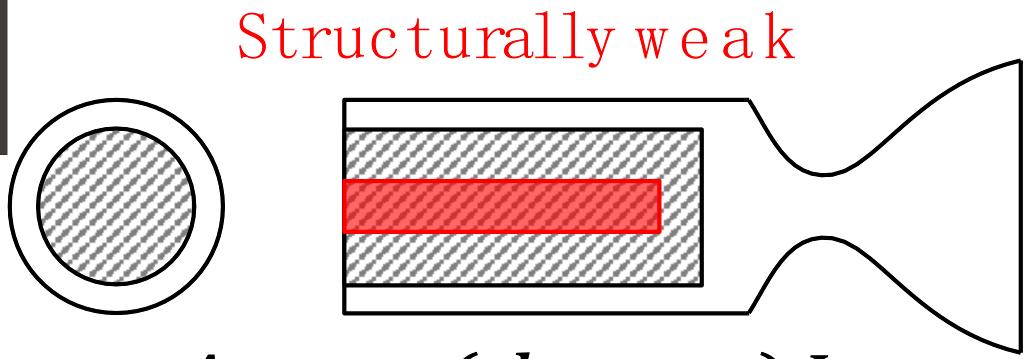
$$A_b = \pi D^2/4$$



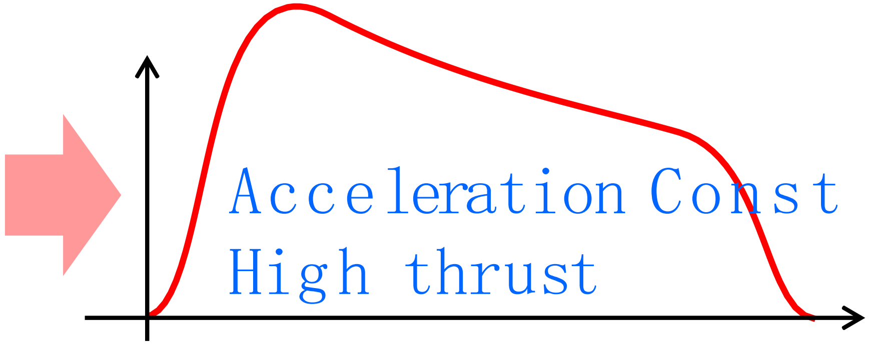


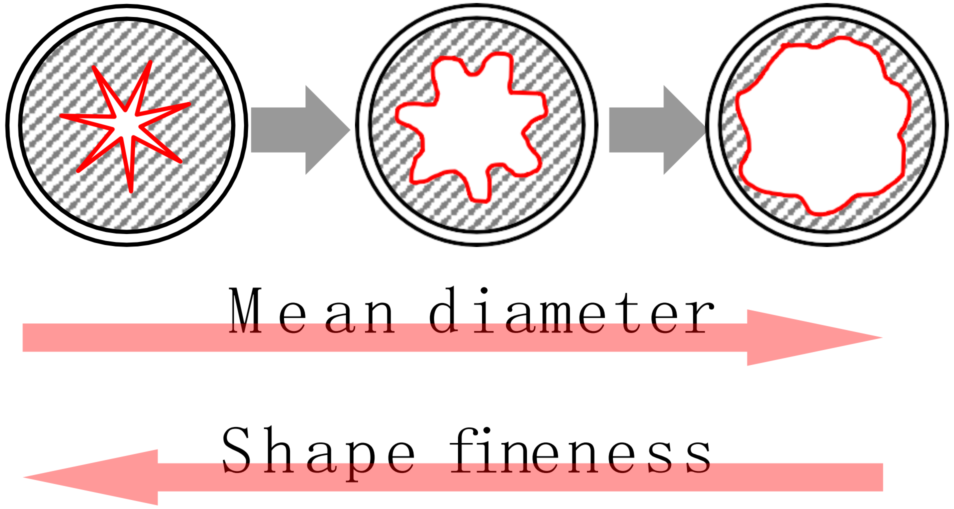
$$A_b = \pi d L = \pi(d_0 + rt)L$$

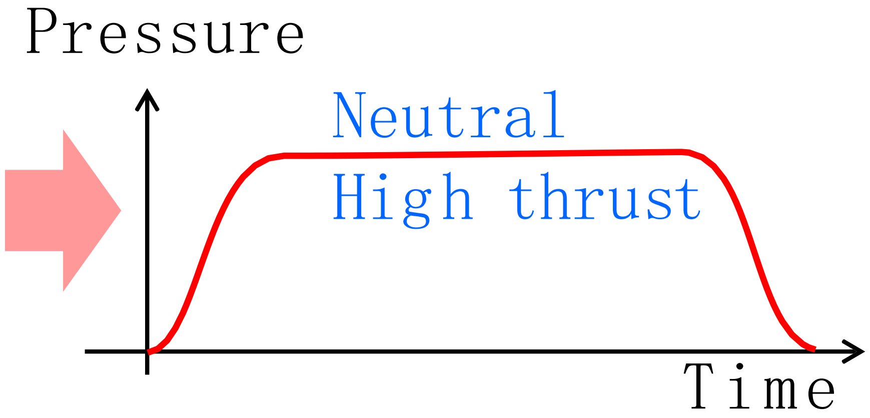
Burning area change & Thrust



$$A_b = \pi(d_0 - rt)L$$



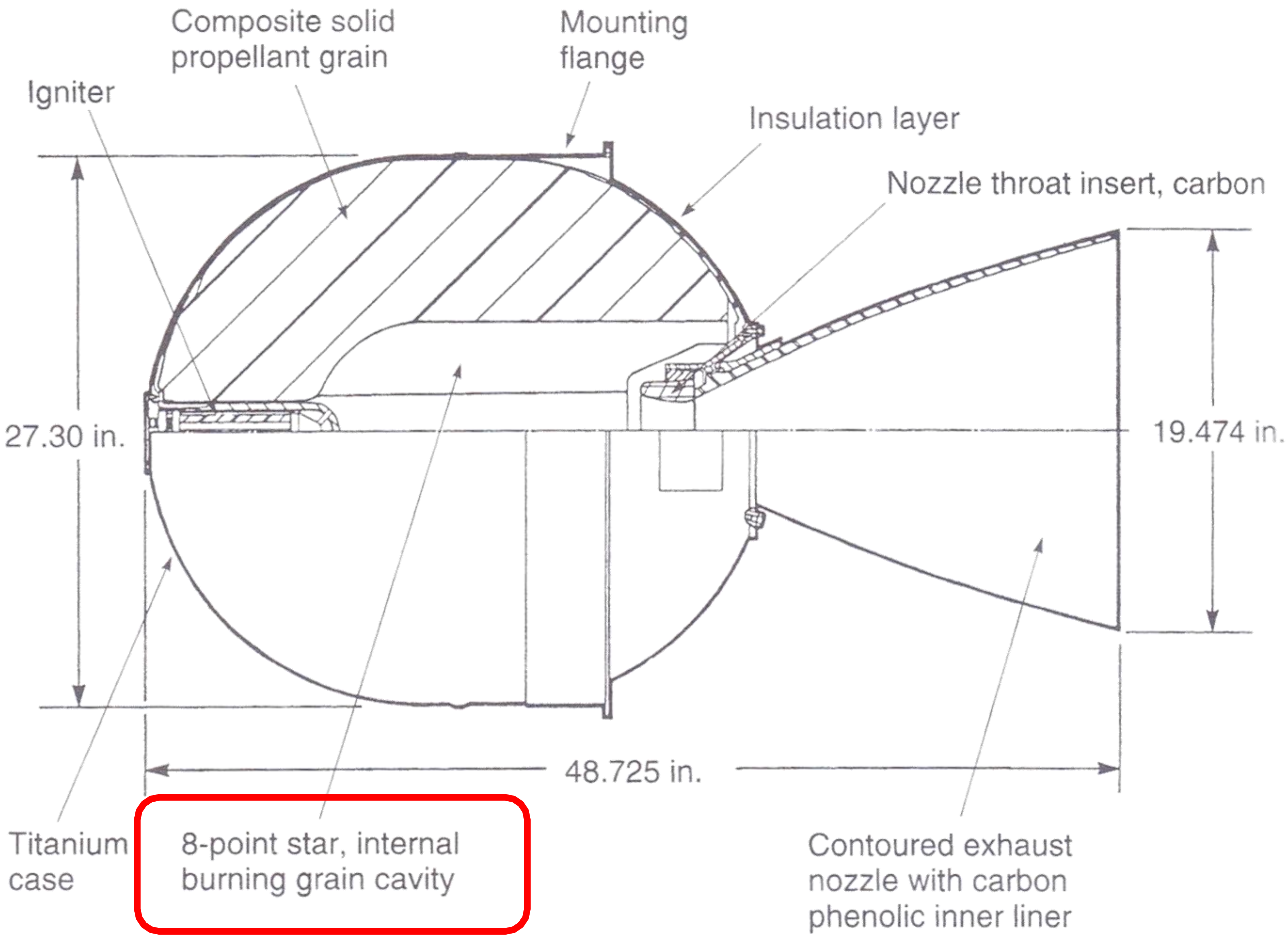




Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Example: Small acceleration rocket for stage separation (de-orbiting)


Composite solid
propellant grain
Mounting
flange
Igniter
Insulation layer
Nozzle throat insert, carbon
27.30 in.
19.474 in.
48.725 in.
Titanium
case
8-point star, internal
burning grain cavity
Contoured exhaust
nozzle with carbon
phenolic inner liner

Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Question: How to distinguish a solid propellant engine?
- Answer from Los Alamos National Laboratory
  - A solid rocket is simple, with only a few major components. It includes a combustion chamber containing an ignition system and propellant, and an exhaust nozzle. LANL recently developed a safer propellant system with separated solid fuel and solid oxidizer
  - For ignition, LANL replaced traditional pyrotechnics with water. Once on orbit and just prior to a burn, an electrolyzer would separate the water into hydrogen and oxygen gases. At the moment of ignition, the hydrogen and oxygen would be rapidly injected into the combustion chamber and lit by a spark. The resulting flame would ignite the solid propellant

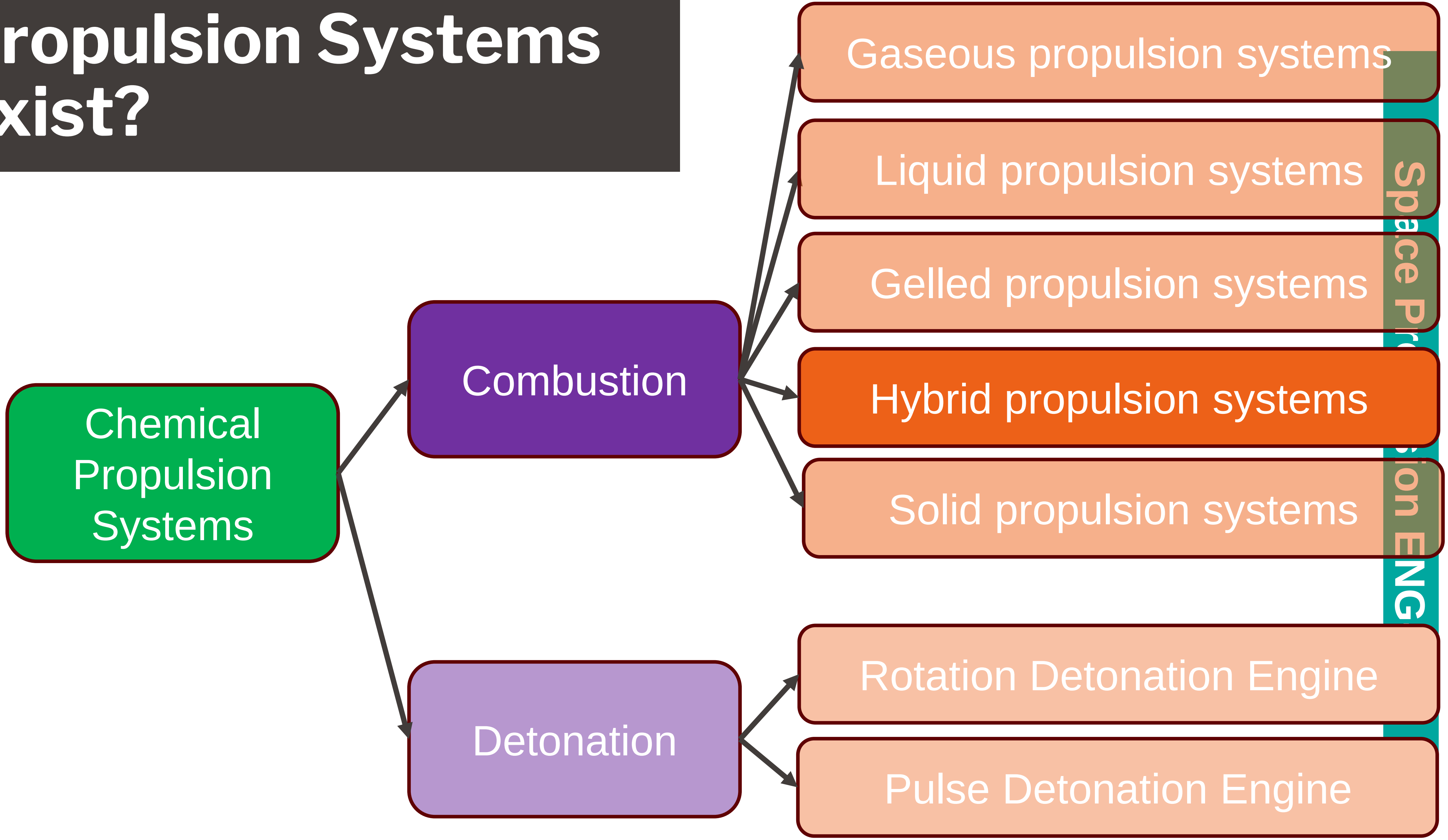
Which Solid Propulsion Systems exist?

Solid Propulsion Systems:

- Question: How to distinguish a solid propellant engine?
- Answer from Los Alamos National Laboratory
  - The next challenge was to figure out how to extinguish the burn. It has long been understood that a rapid decompression of the chamber can reliably cause a solid rocket to extinguish
  - LANL developed an aerospike nozzle with a changeable choke area. Once the burn has achieved a desired velocity change, the choke area would be opened, decompressing the chamber and extinguishing the burn. When another burn of the rocket is needed, the choke area is reset to its original position. Repeat as needed.
  - LANL recently demonstrated multiple independent burns from a single solid rocket in static test stands at Los Alamos

L5 – Propulsion Systems

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

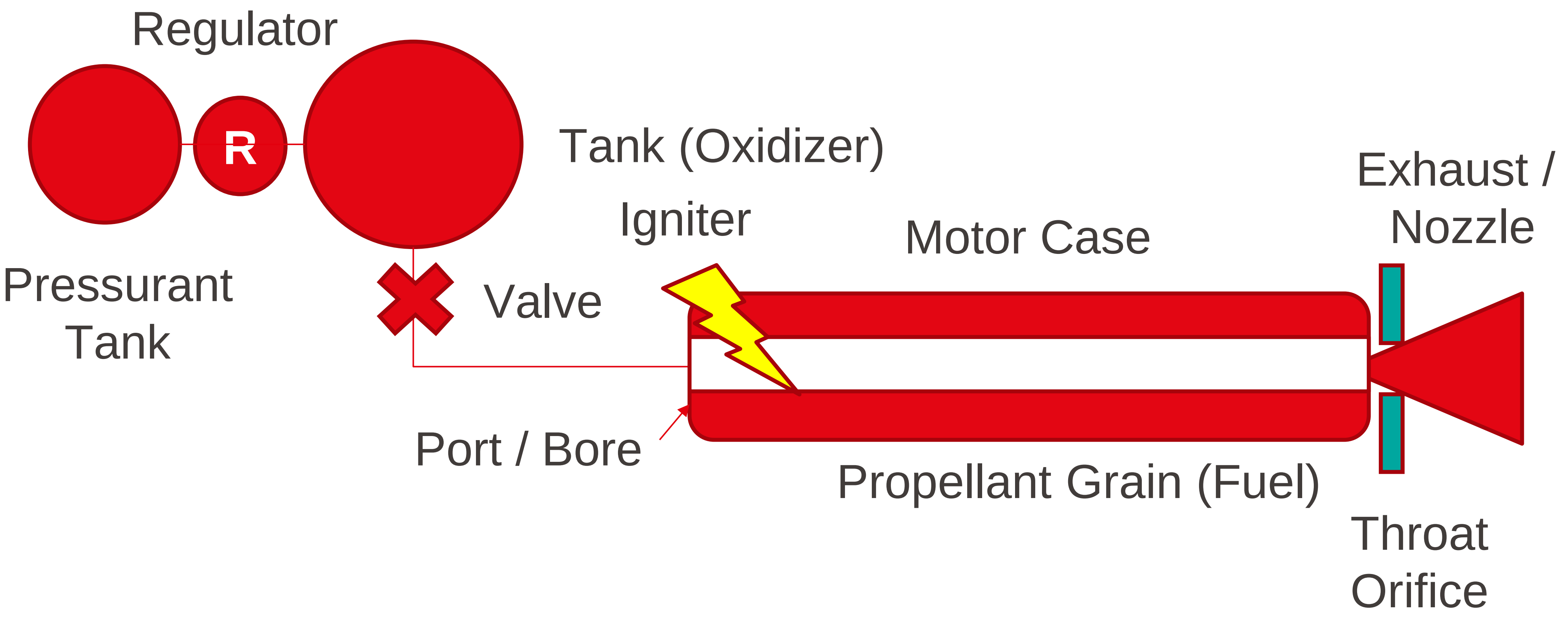
Chemical Reaction		Solid	Liquid	Gas
	Combustion	Solid / Liquid (Hybrid Thruster, Bi-prop)		
	Decomp			
	No			

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?

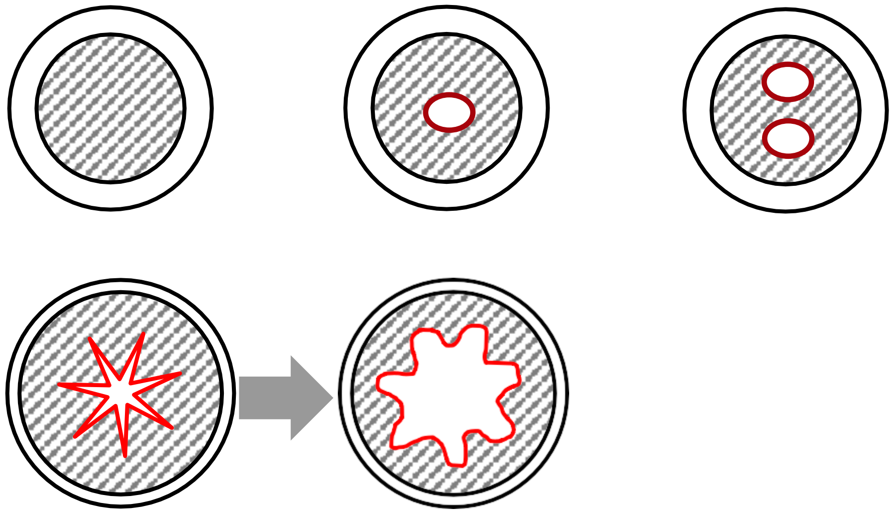
Hybrid Propulsion Systems:

- 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
  - C
    - D

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?

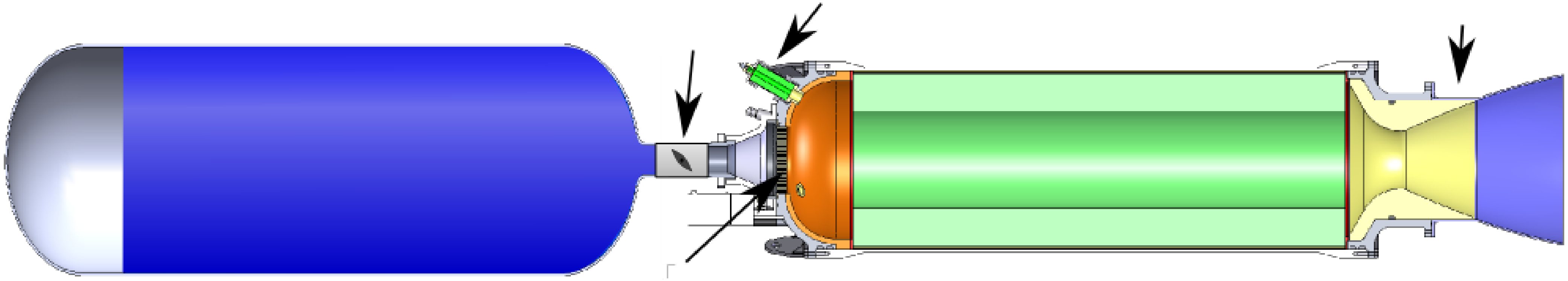
Hybrid Propulsion Systems:

- 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

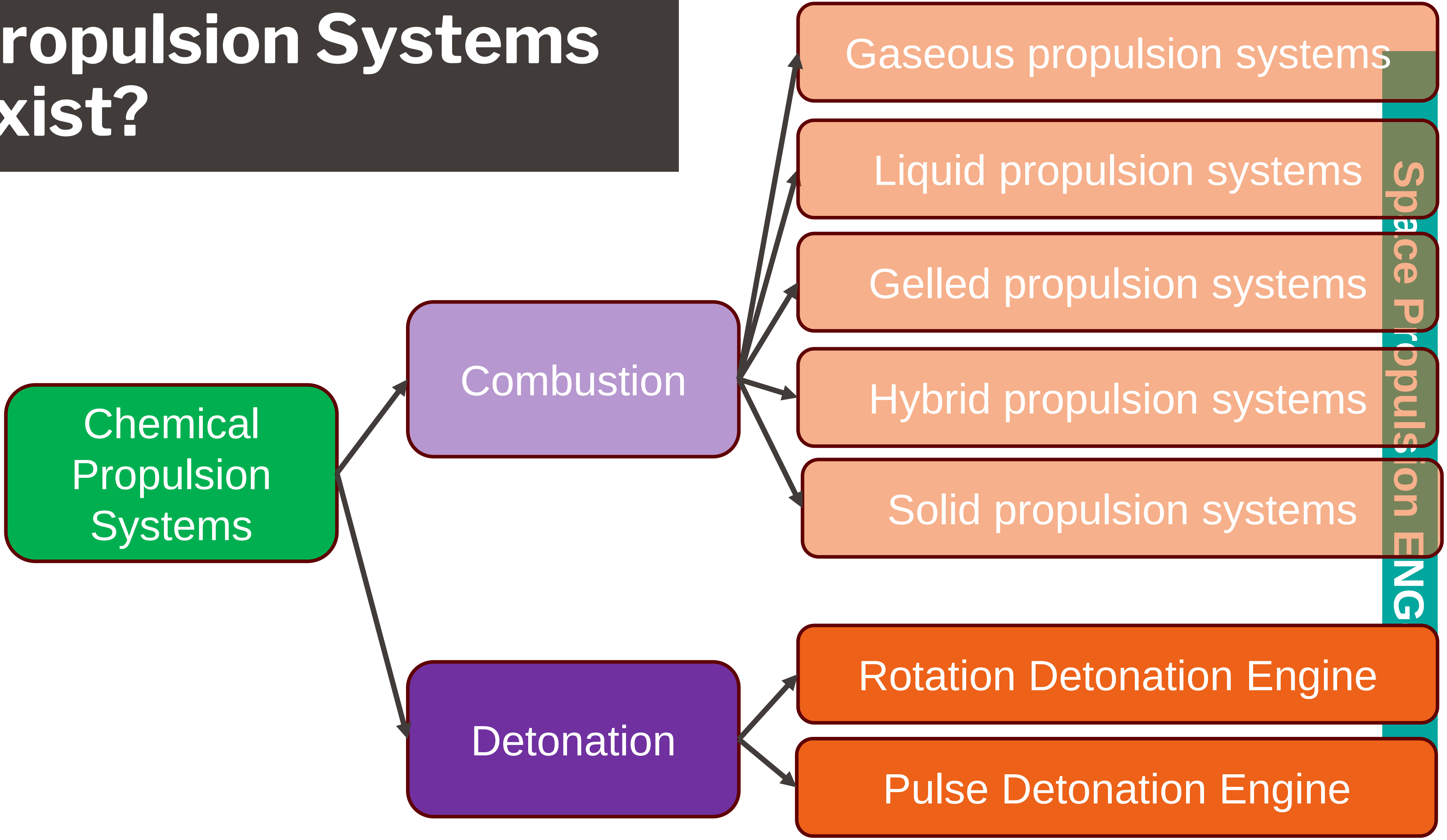
Which Hybrid Propulsion Systems exist?

Hybrid Propulsion Systems:

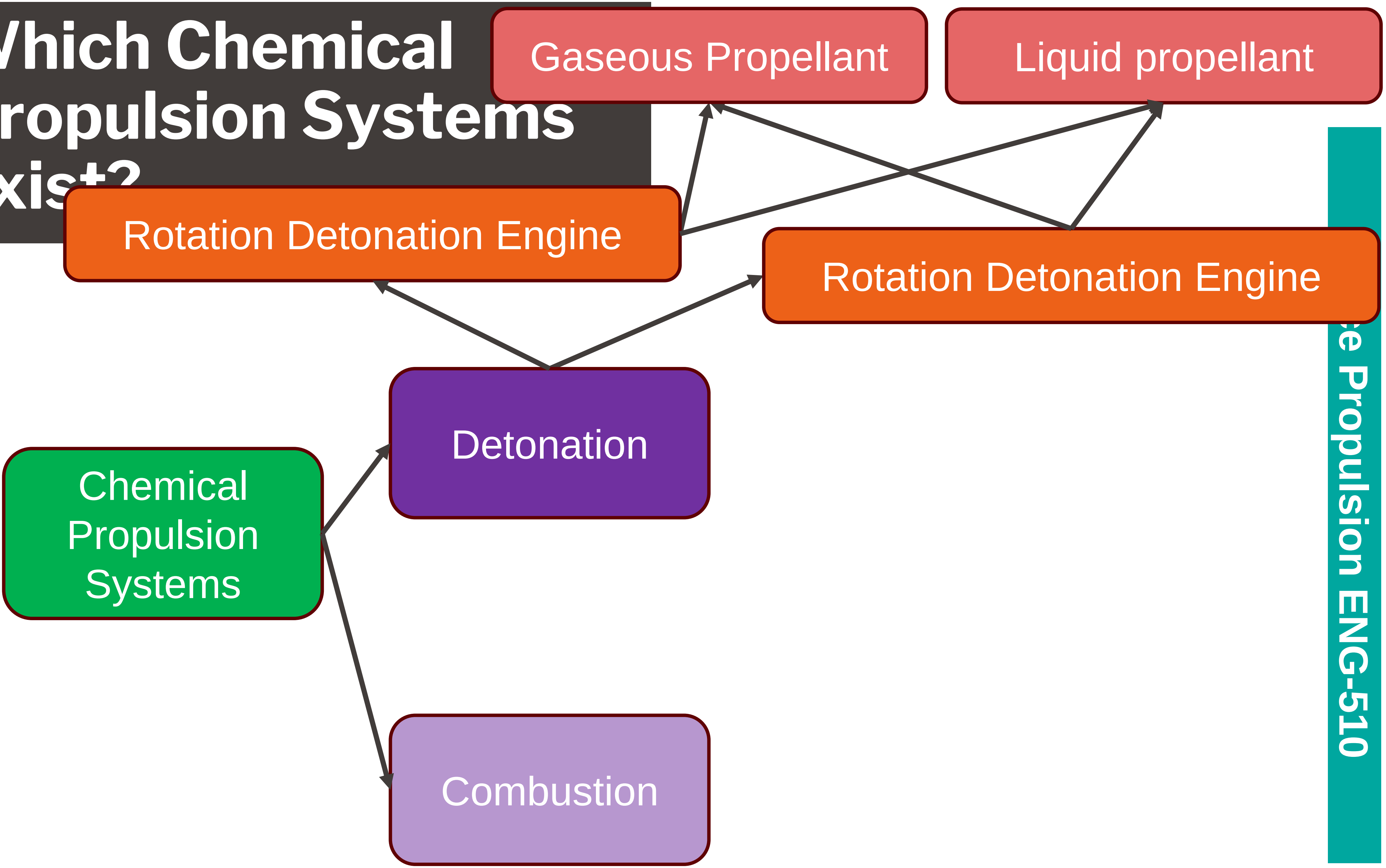
- Example: Autophage rocket from Alpha Impulsion

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?

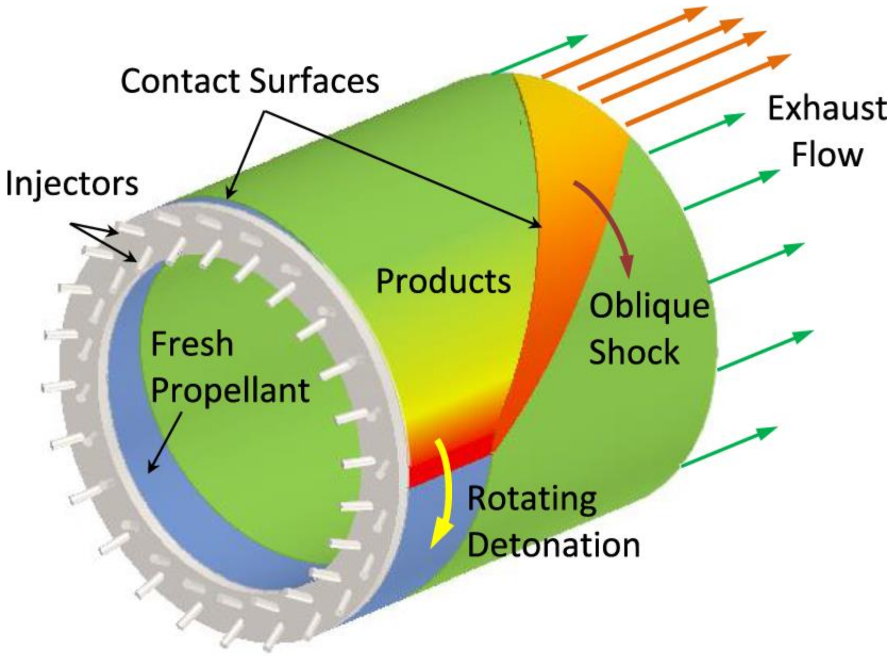
Rotation Detonation Engine

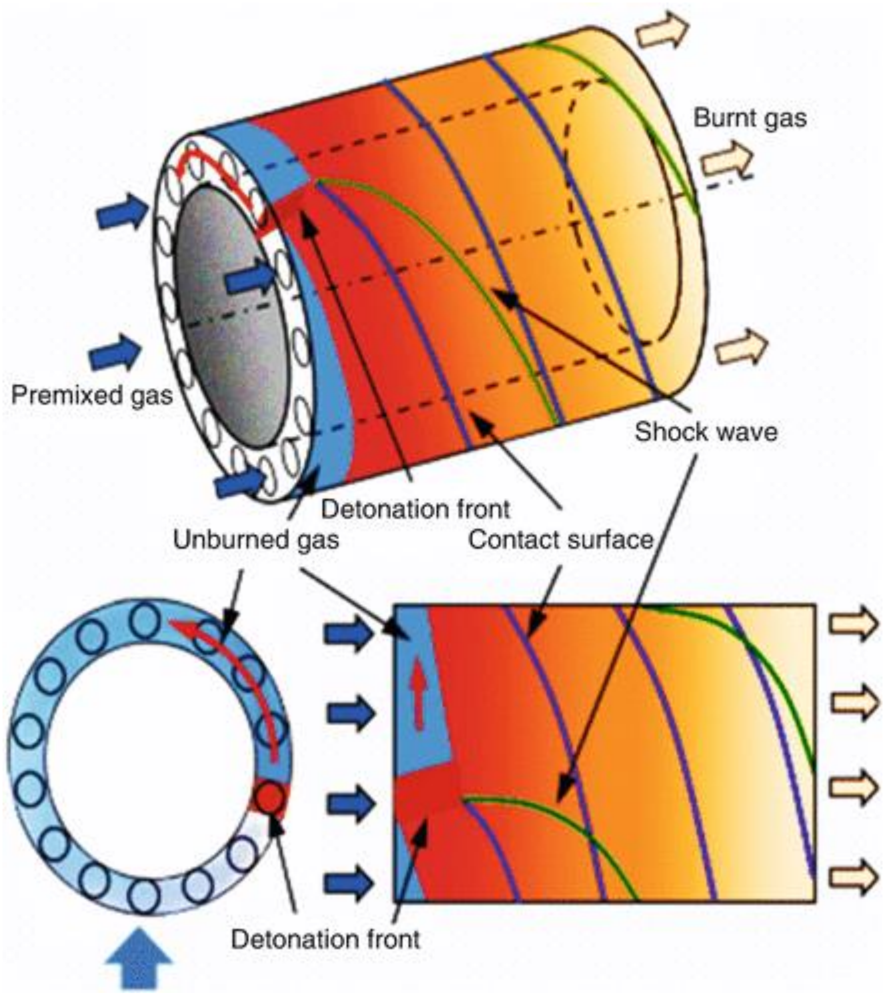
- Principle
  - From a thermodynamic point of view, detonations are more efficient than the more commonly known deflagration (classic combustion)
  - While classic combustion in rocket engines takes place at constant pressure or even with a slight loss of pressure, the pressure increases significantly 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)

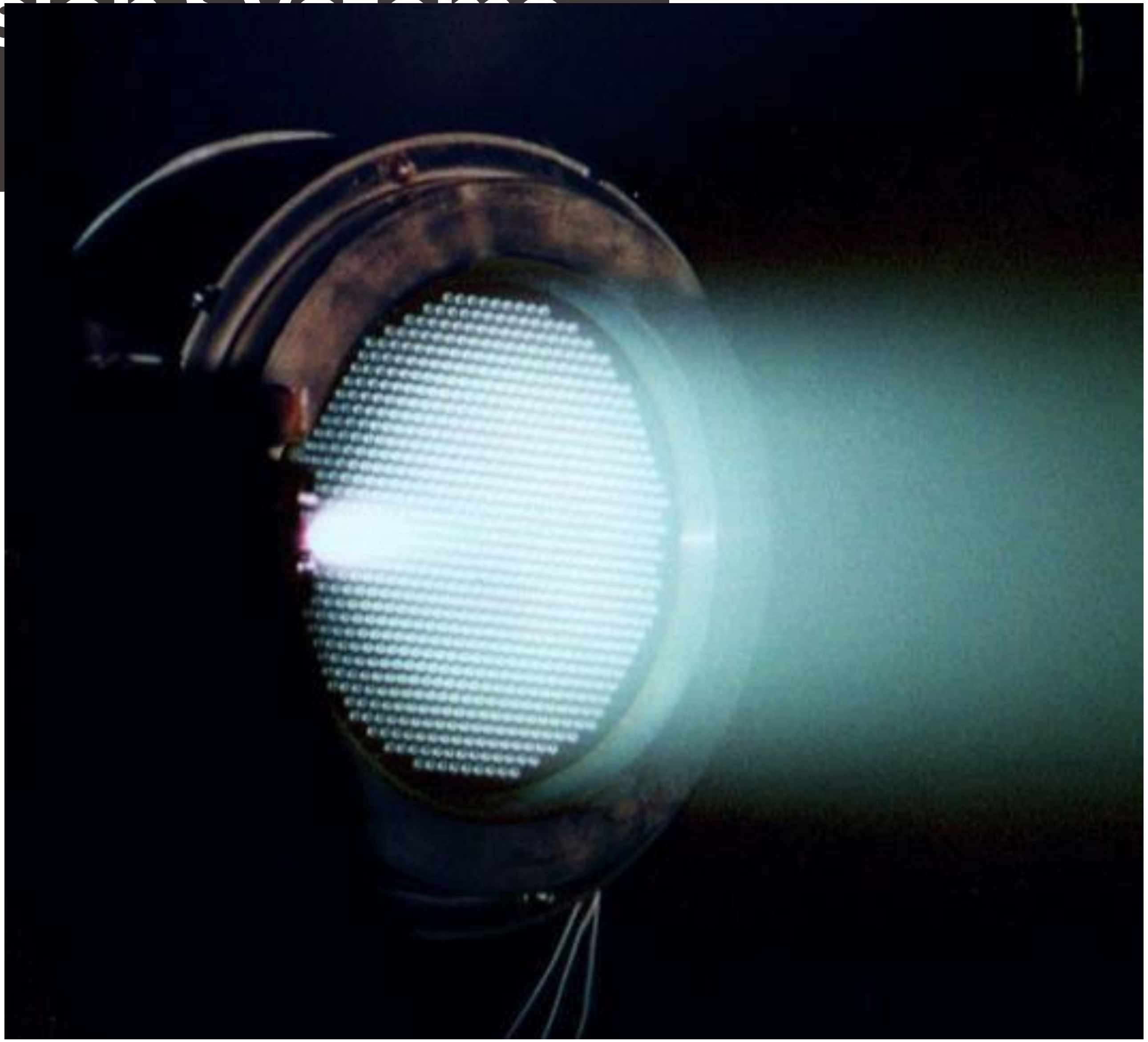
- Principle
  - A pulse detonation engine (PDE) is a type of propulsion system that uses detonation waves to combust the fuel and oxidizer mixture
  - The engine is pulsed because the mixture must be renewed in the combustion chamber between each detonation wave and the next
  - Theoretically, a PDE 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

Lecture # 5 Eletrical Propulsion Systems

Brief overview on all space propulsion systems

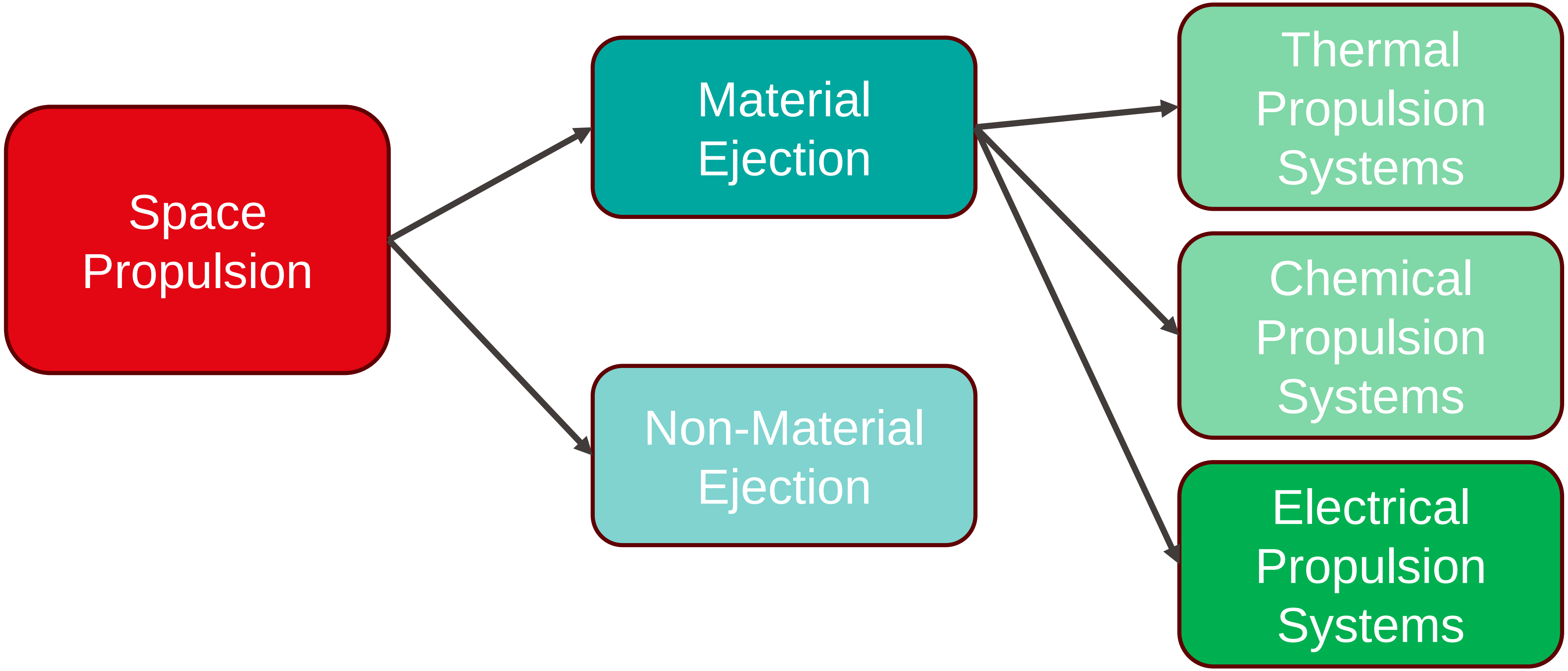
eSpace
EPFL Space Center

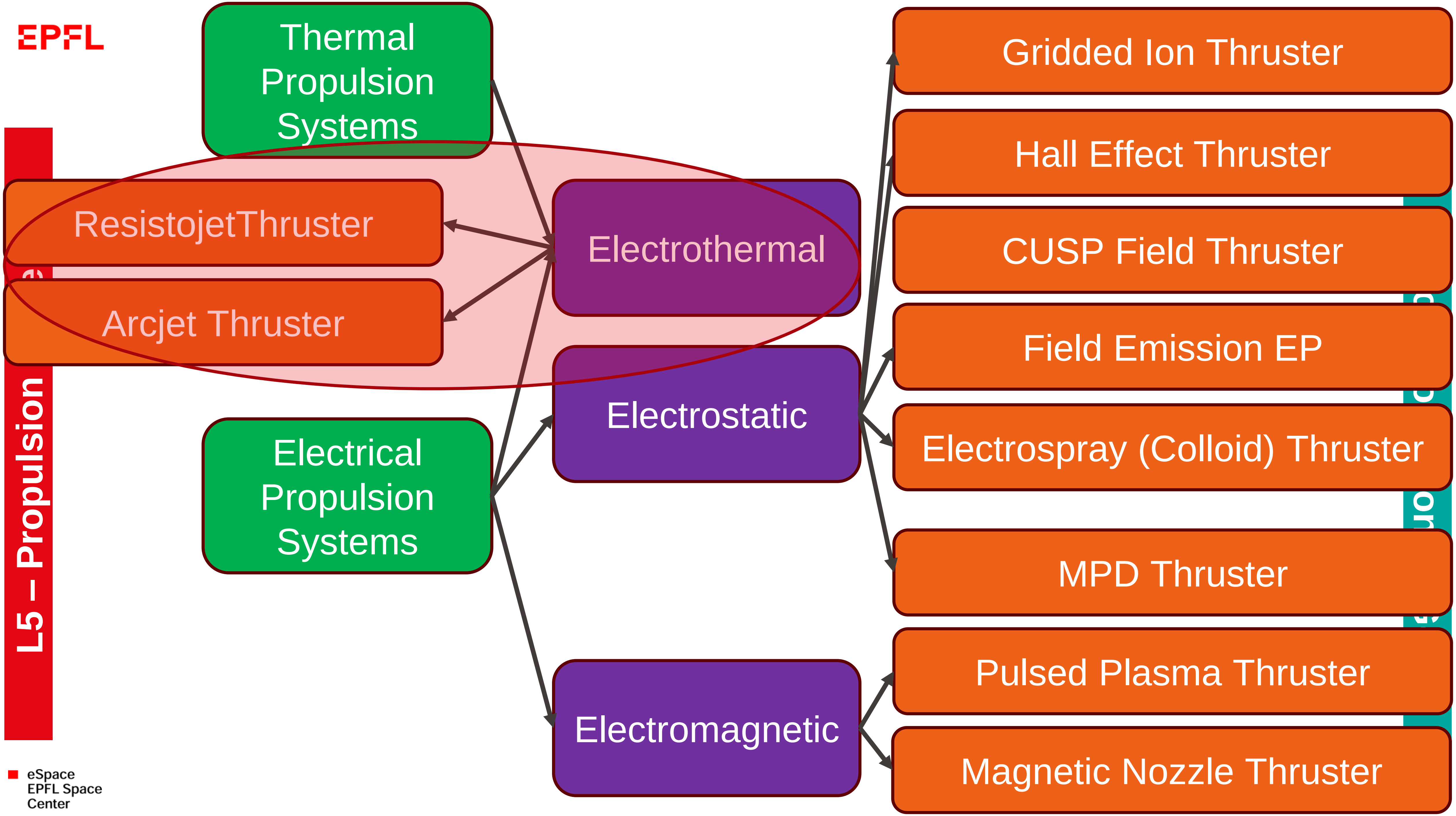
Which Electrical Propulsion Systems exist?

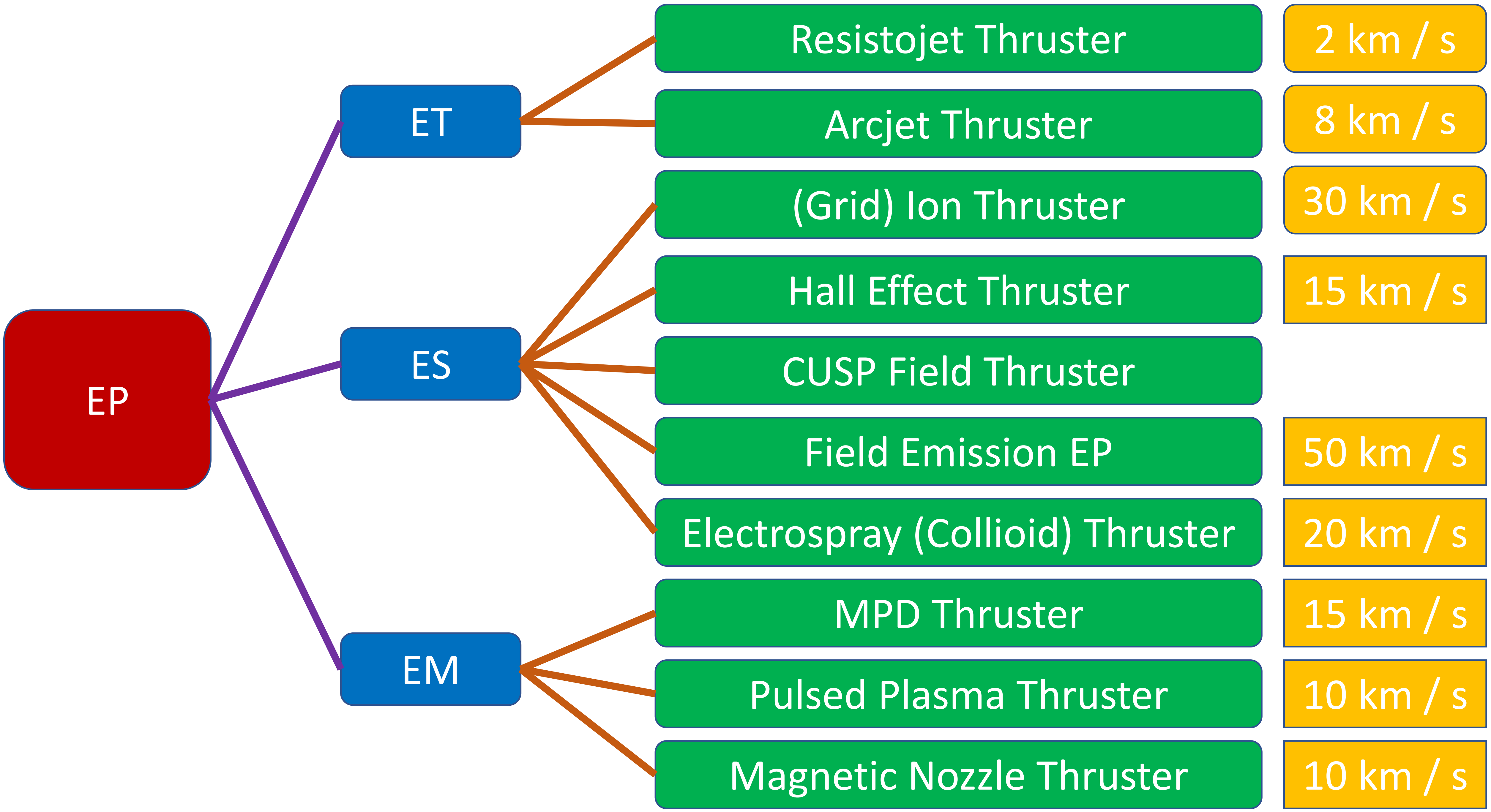


Which Electrical Propulsion Systems exist?

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
L5 – Propulsion


EP
ET
ES
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Resistojet Thruster
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MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster
2 km / s
8 km / s
30 km / s
15 km / s
50 km / s
20 km / s
15 km / s
10 km / s
10 km / s

Which Electrical Propulsion Systems exist?

Electrical Propulsion Systems:

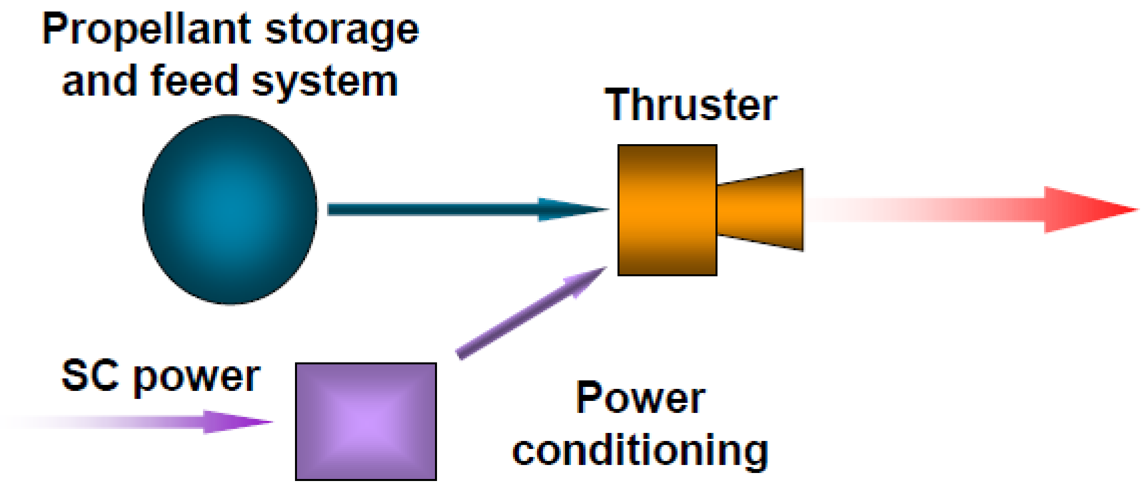
- Performance description
  - Isp
  - Thrust
  - Propellant mass compared to delta v requirement
  - Structural mass
  - **Power need**

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

Which Electrical Propulsion Systems exist?



Electrical Propulsion Systems:

- Basics
  - For all EP, the following elements are required:
    - Propellant storage and feed system
    - 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

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）

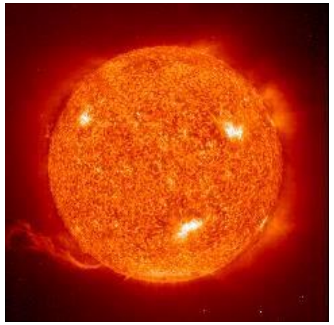
Which Electrical Propulsion Systems exist?

Electrical Propulsion

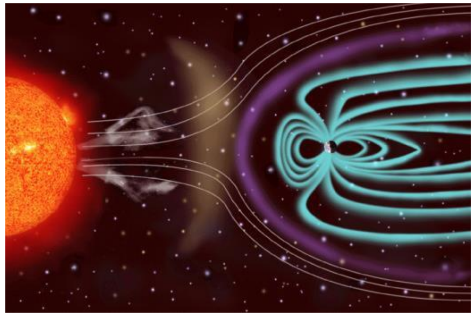
- Basics
  - Plasma is needed..

Fluorescent lamp

Sun

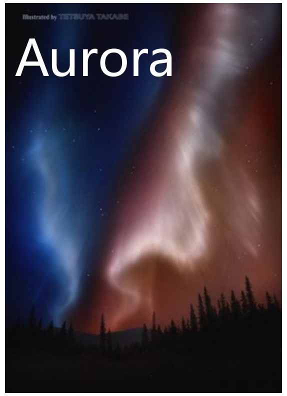


Solar wind



Lightning

Neon lamp



Aurora

Nebula

Which Electrical Propulsion Systems exist?

Electric Propulsion S

- Basics
  - What is Plasma?

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?

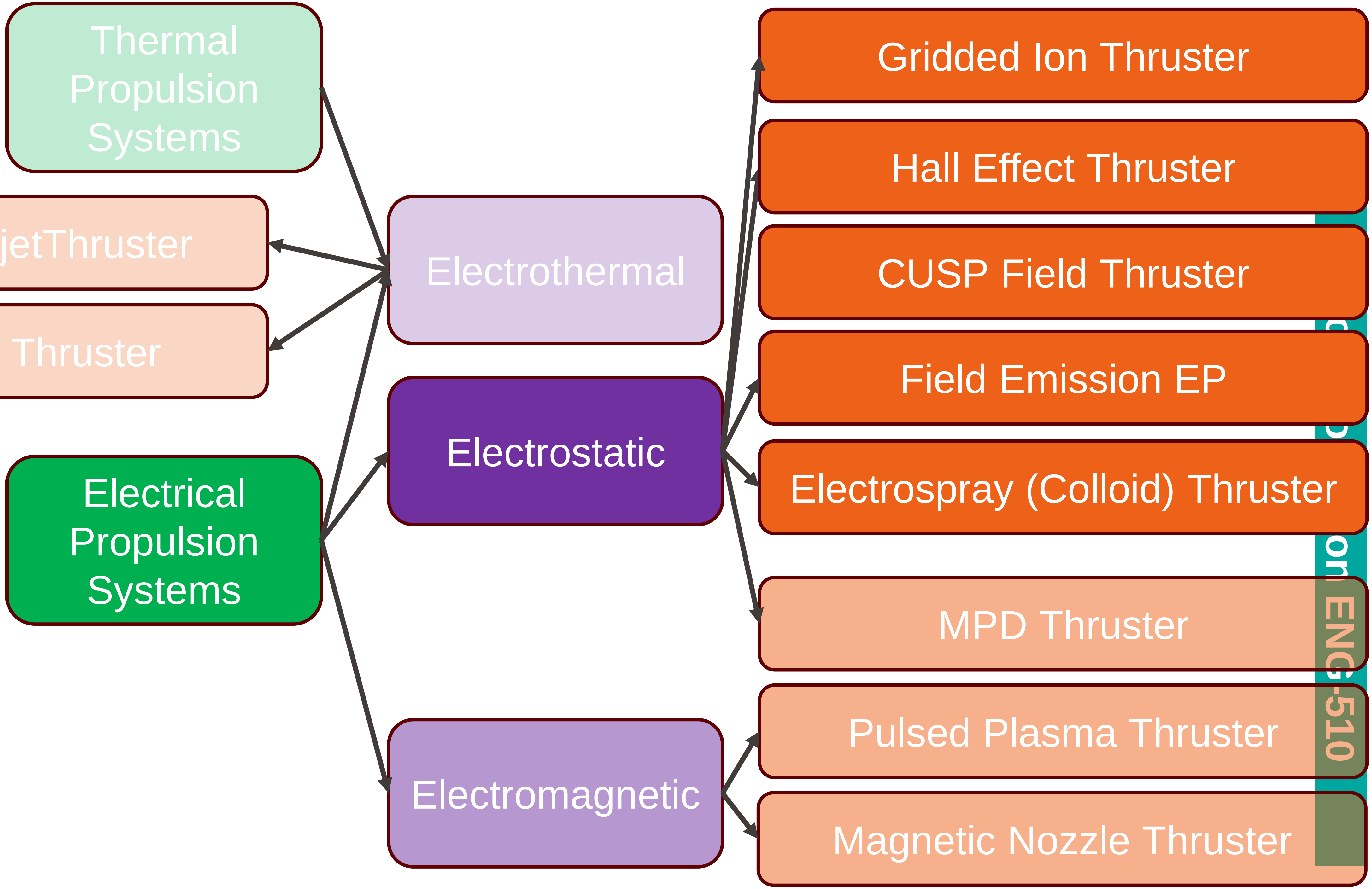
Electrical Propulsion Systems:

- 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

Plasma physics

↓

Gas dynamics × Electromagnetism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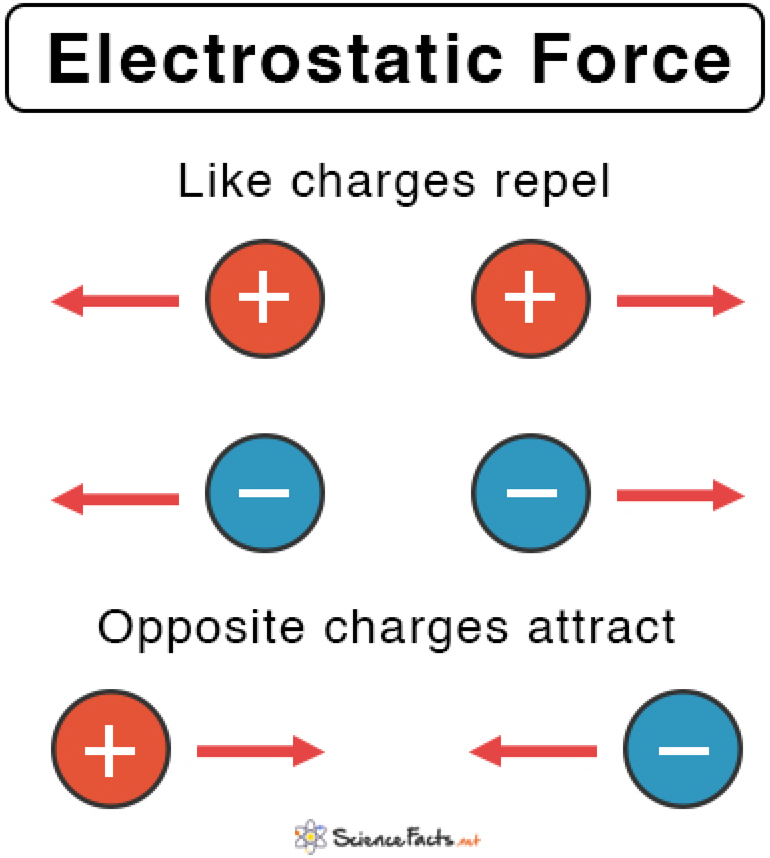
Magnetic Nozzle Thruster

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Electrostatic Force:
  - The electrostatic force is the force of attraction 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?

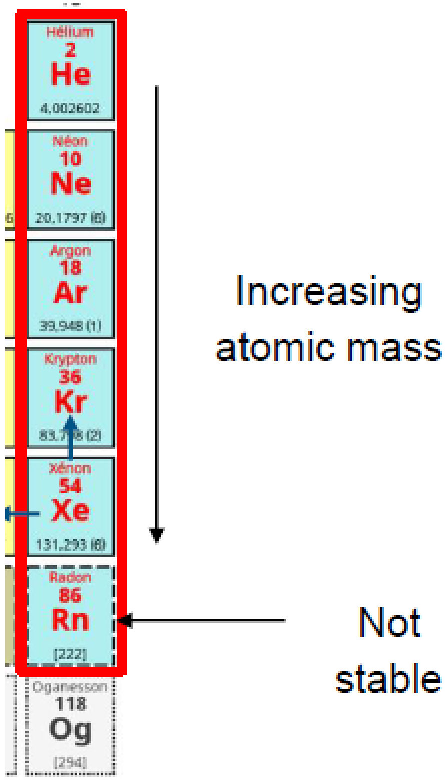
Electrostatic Propulsion Systems:

- 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 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



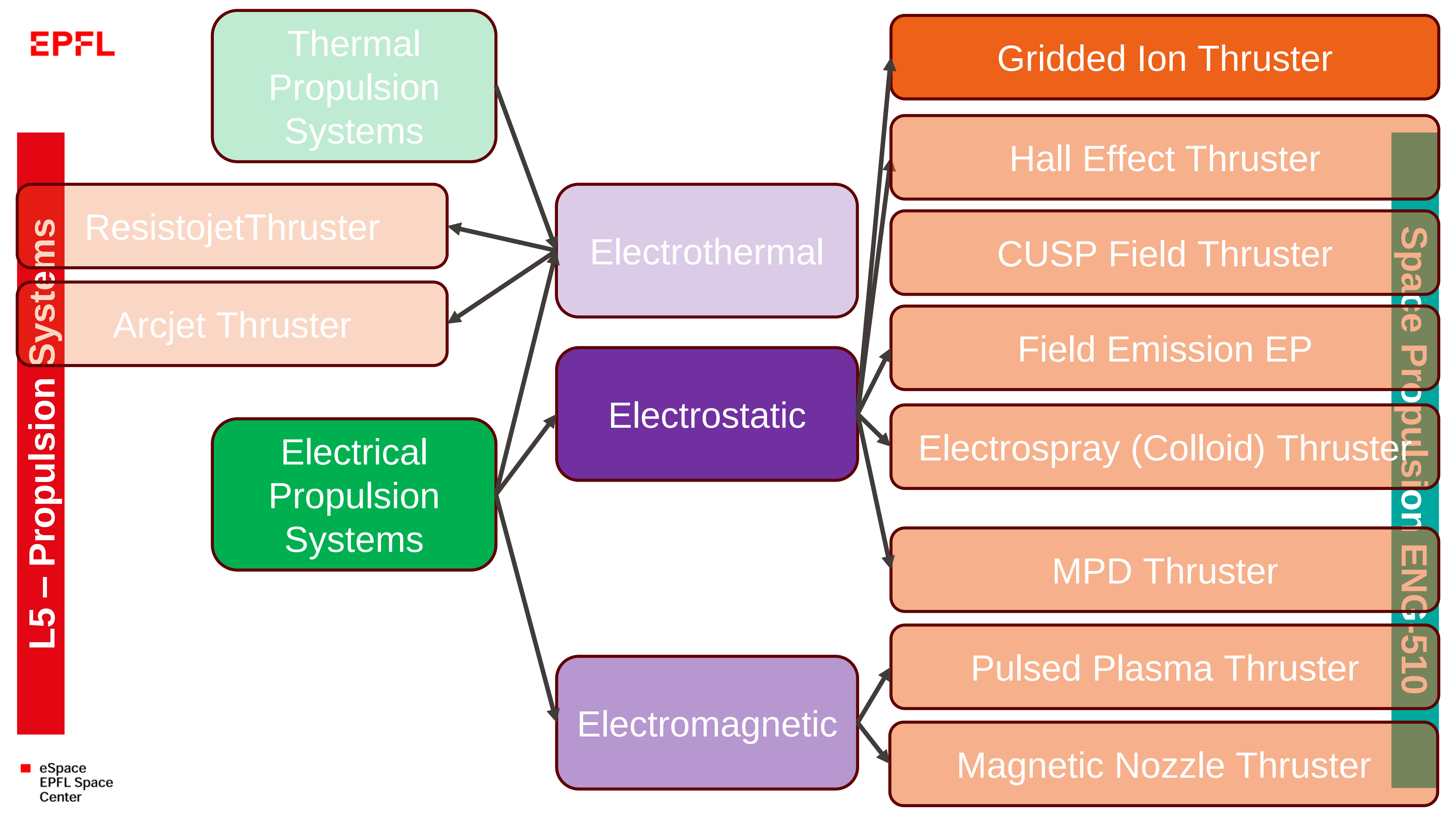
Which Electrical Propulsion Systems exist?

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


EPFL
L5 – Propulsion Systems
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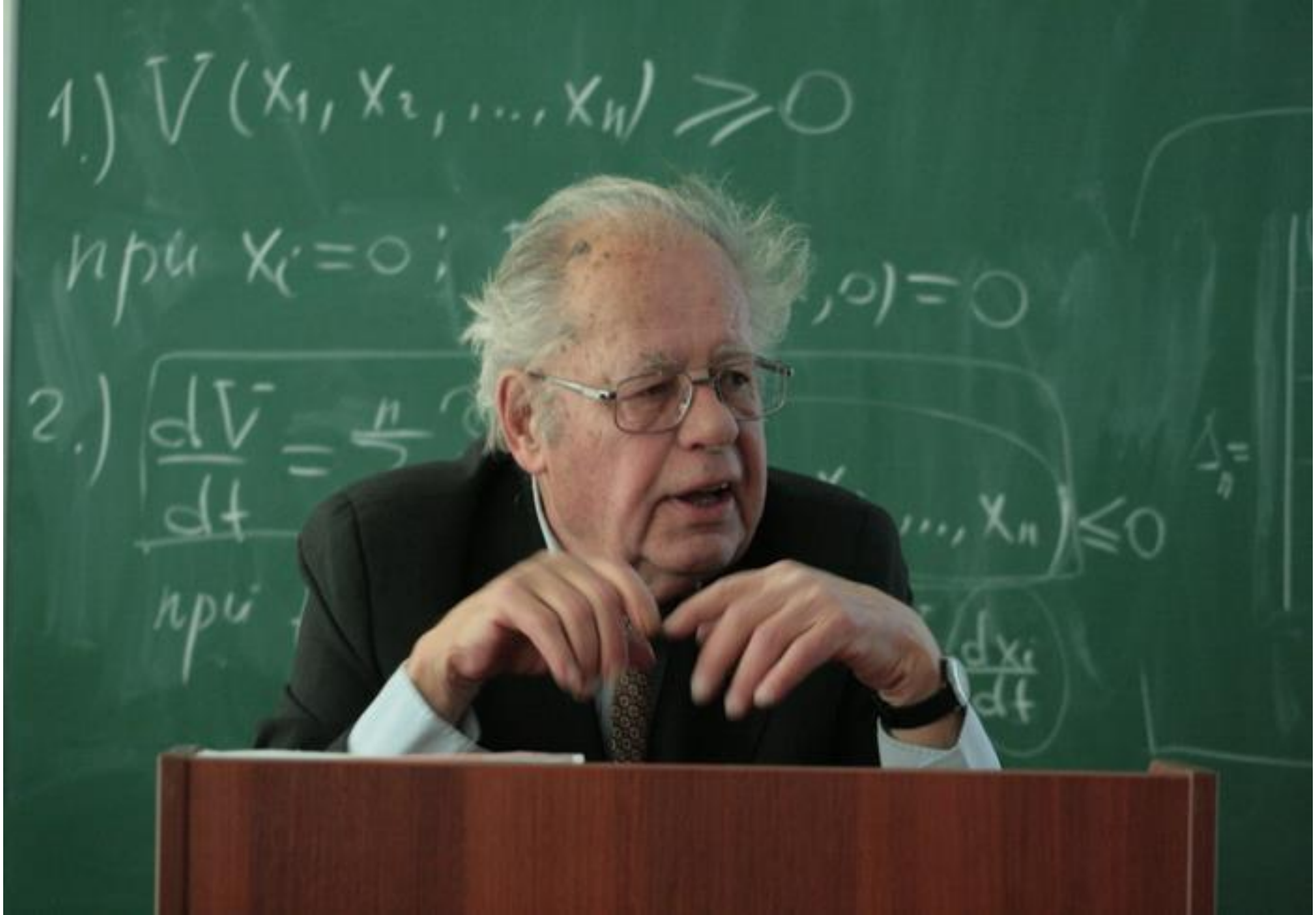
Electrospray (Colloid) Thruster
MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster
Space Propulsion ENG-510
eSpace
EPFL Space
Center

V
F
e

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?

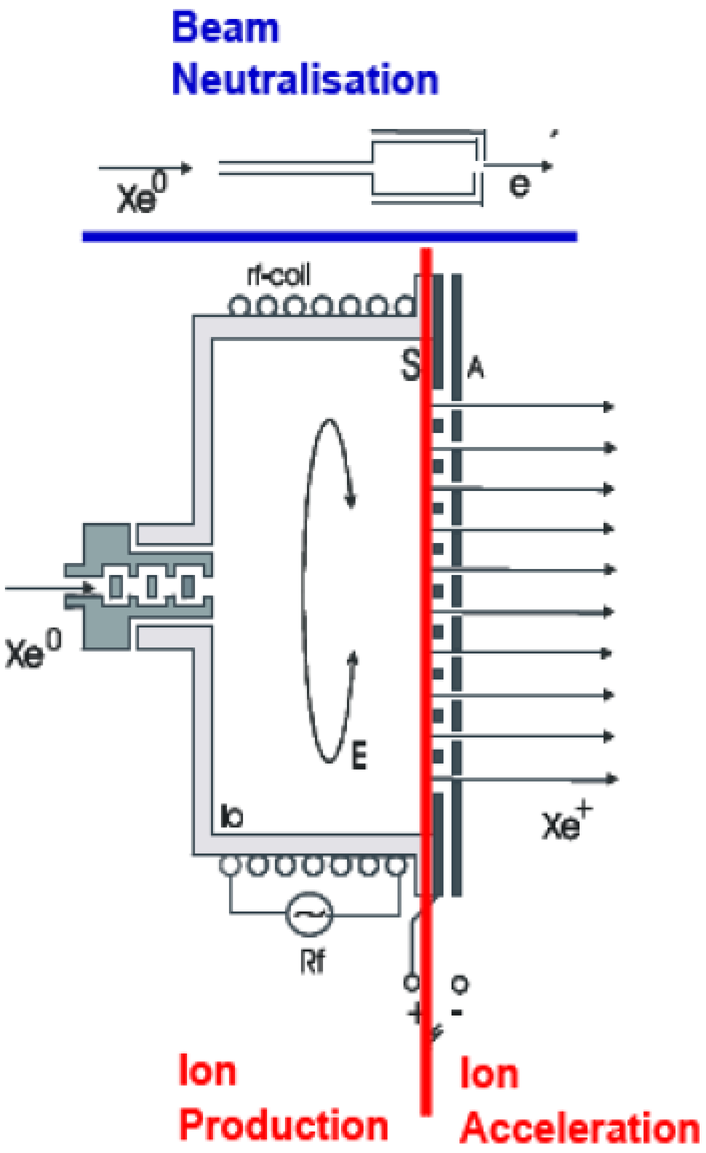
Electrostatic Propulsion Systems:

- Gridded Ion Thruster - Two 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

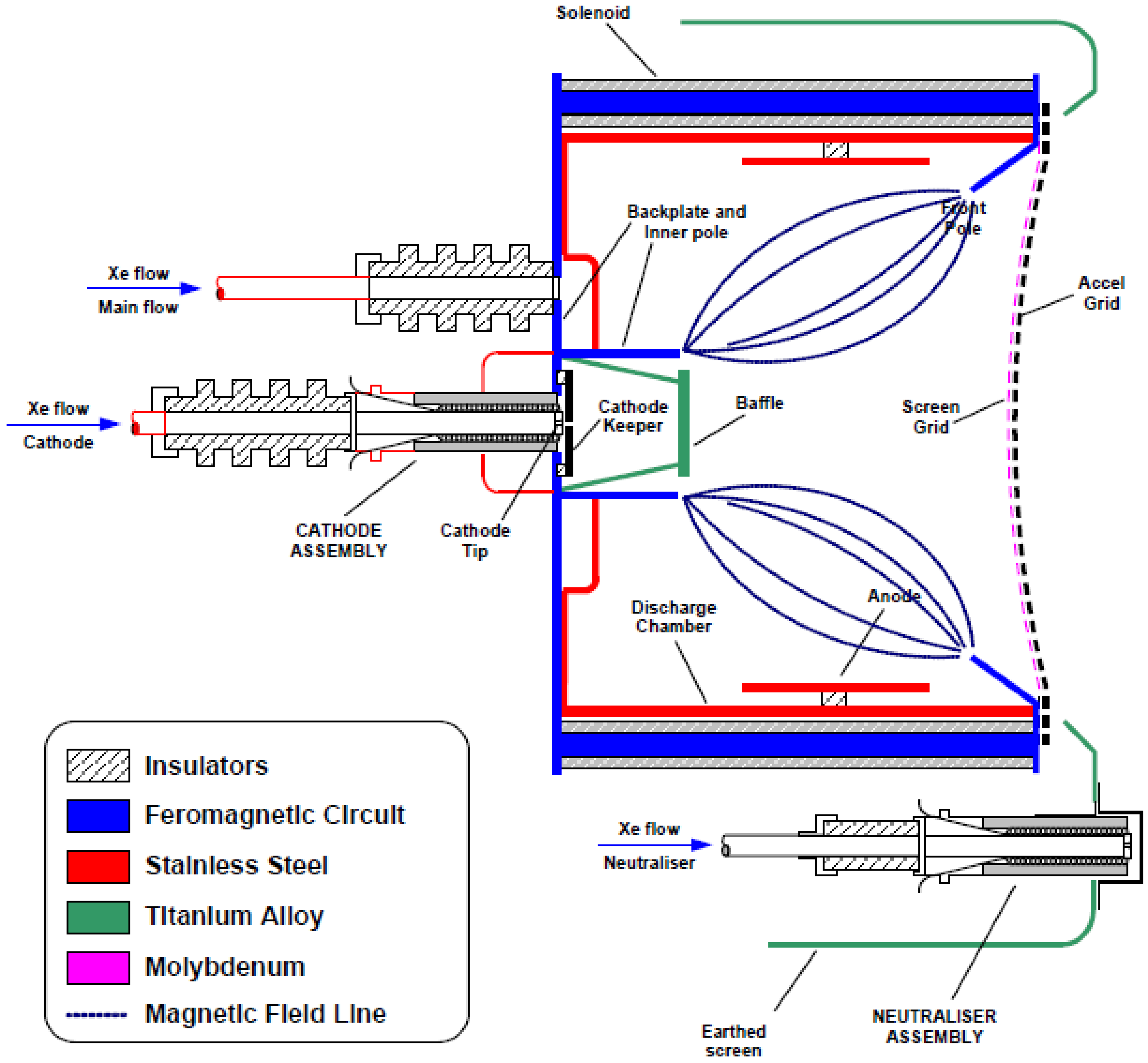
EPFL

Which Electrical Propulsion System exist?

L5 – Propulsion Systems

Electrostatic Propulsion System

- Gridded Ion Thruster:
  - Electron-Bombardment (Kauffma



Space Propulsion ENG-510

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?

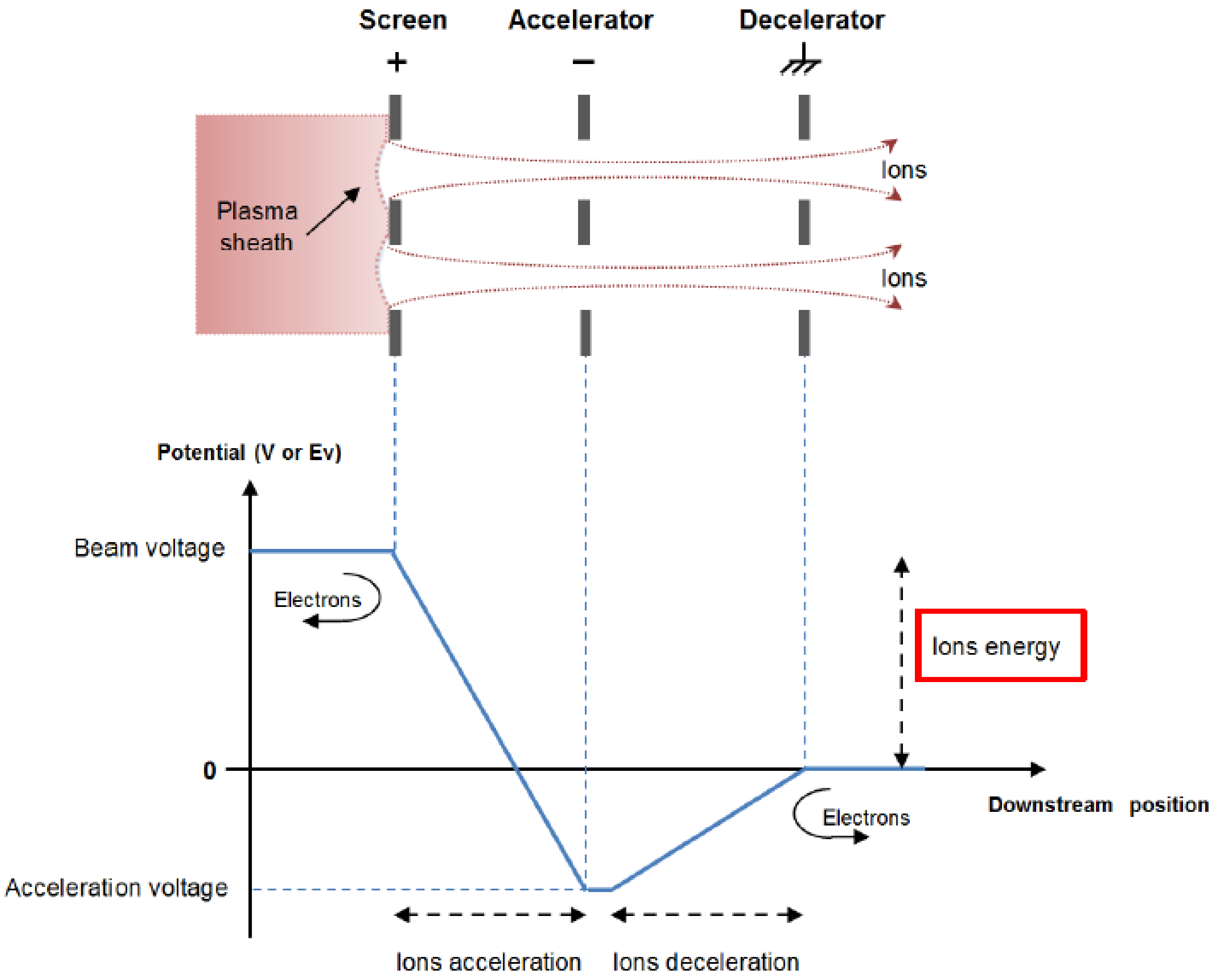
Electrostatic Propulsion Systems:

- 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)

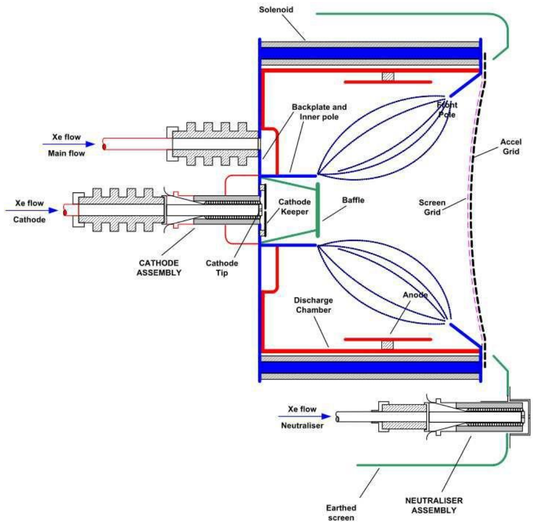
Which Electrical Propuls exist?

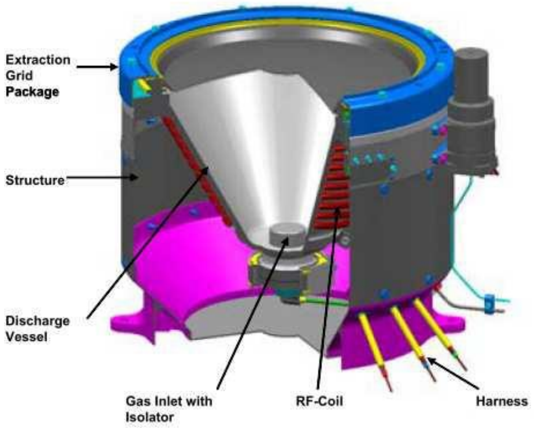
Electrostatic

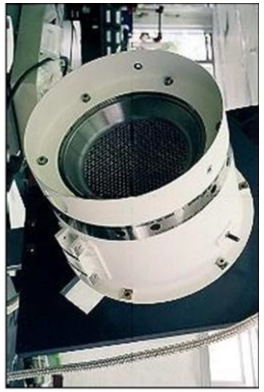
- Gridded Ior
  - Ions Acce



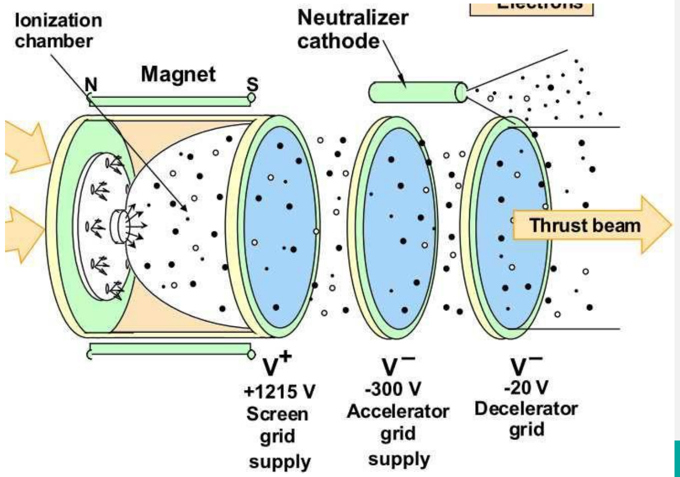
Which Gridded Ion Electric Propulsion Systems exist (9/70)?





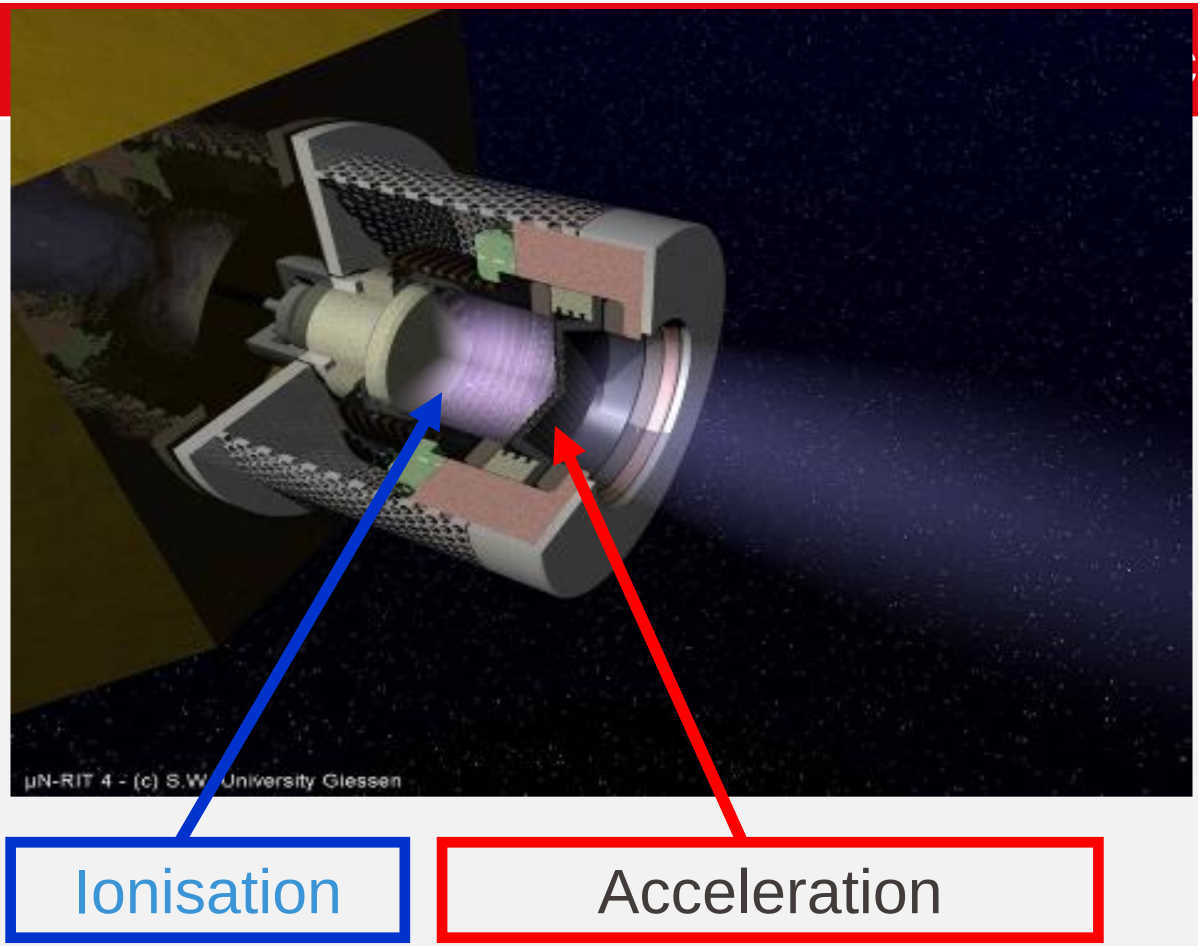


- Invented at Uni Gießen, Prof. Löb, 1964
- Ionization Principle:
  - Electric arc (T6)
  - Inductive coupled excitation (RIT)
- Acceleration Principle:
  - Electric fields between grids
- Propellants:
  - Low ionization energy, noble gases
  - High mass for higher thrust at “lower” Isp (Xe)
- Typical Isp: 3000-5000 s (Xe) @ 50 to 70 %



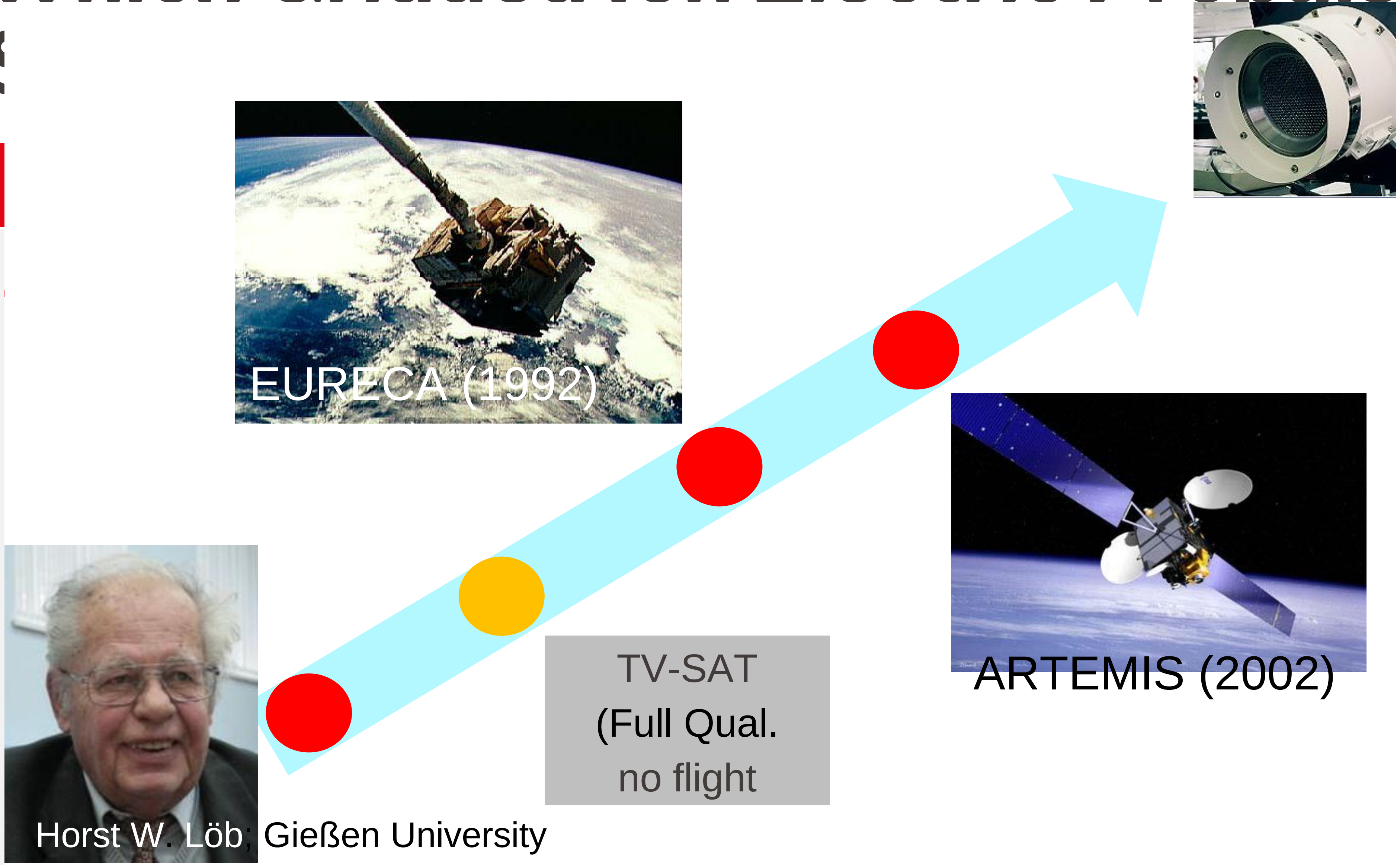
Which Gridded Ion Electric Propulsion Systems exist (10/70)?

s of Gridded Ion EP



- Highest exhaust velocities
- Highest electric efficiency
- Highly scalable
- Perfect thrust control

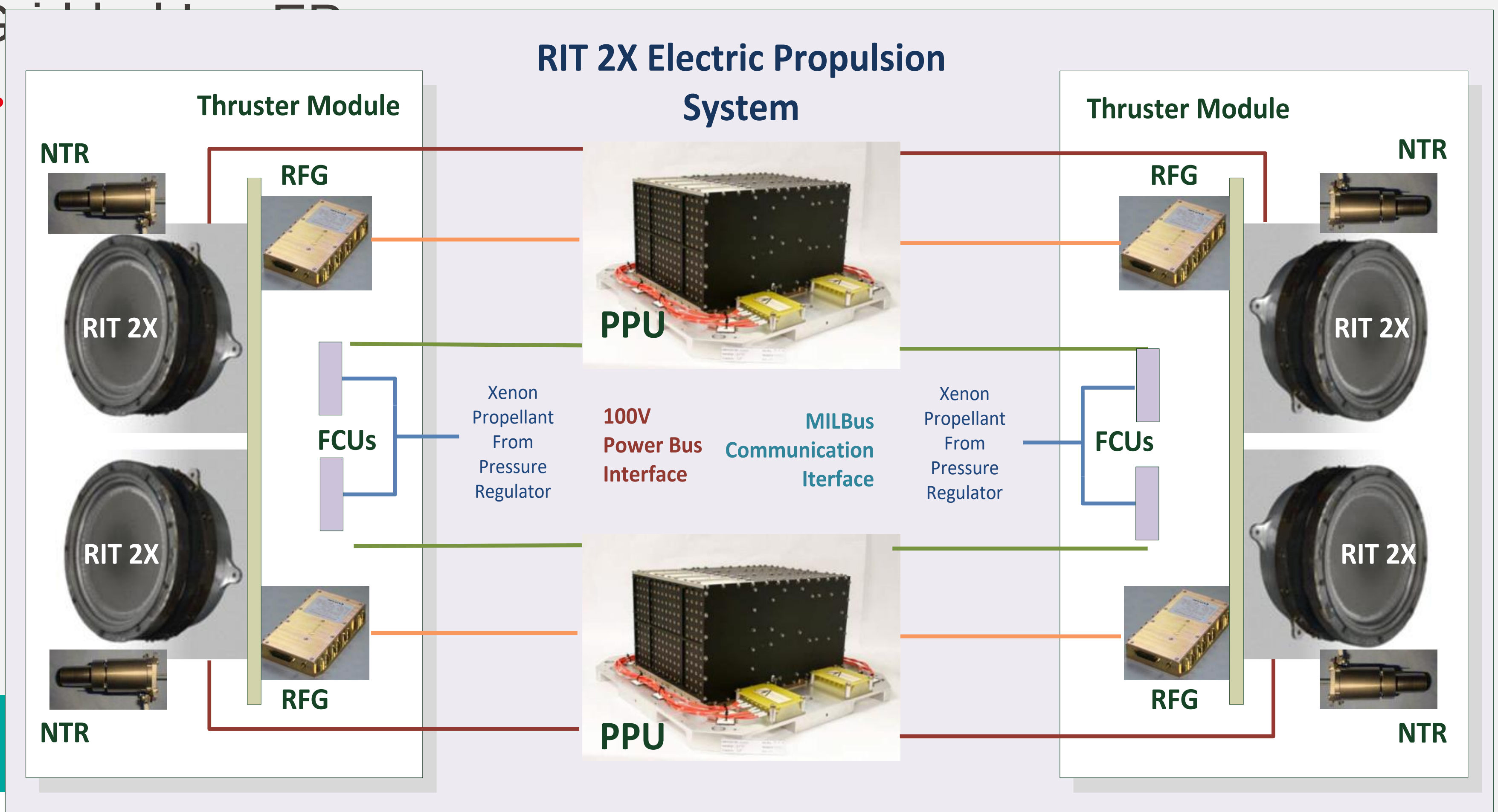
Which Gridded Ion Electric Propulsion



Which Gridded Ion Electric Propulsion Systems exist (13/70)?

Objective: To develop the basics of Gridded Ion EP

- G

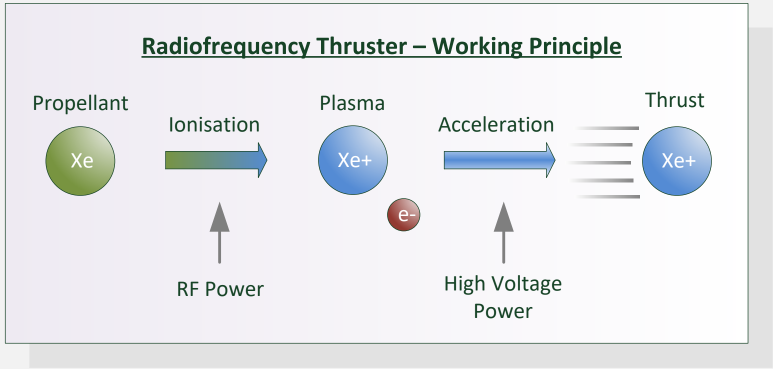


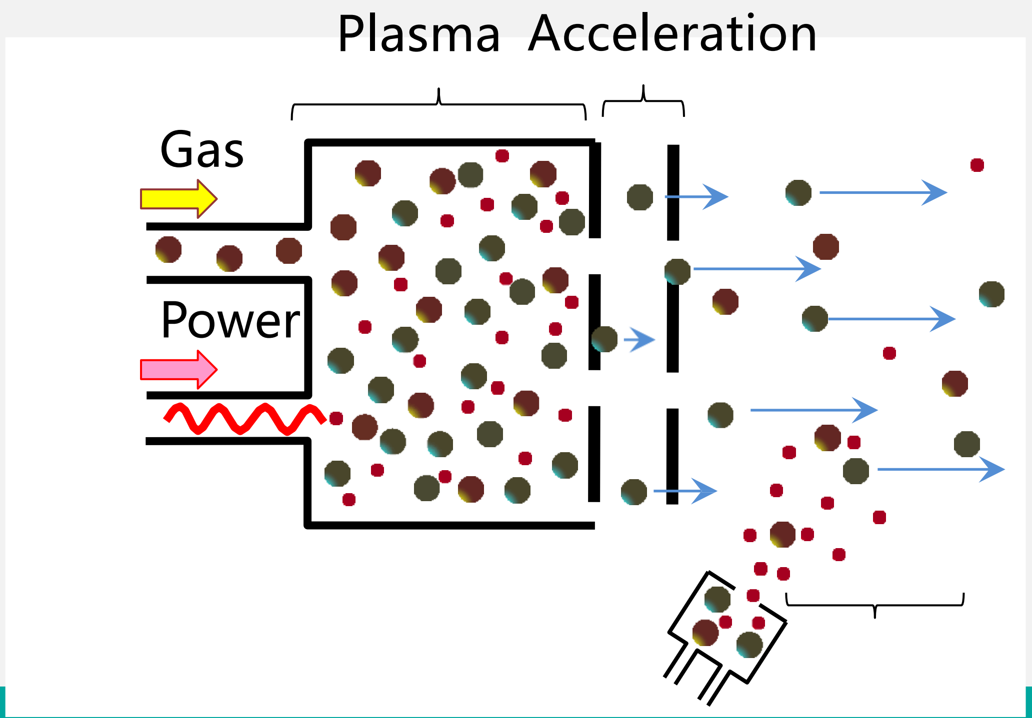
EPFL

Which Gridded Ion Electric Propulsion Systems exist (14/70)?

Objective: To develop the basics of Gridded Ion EP

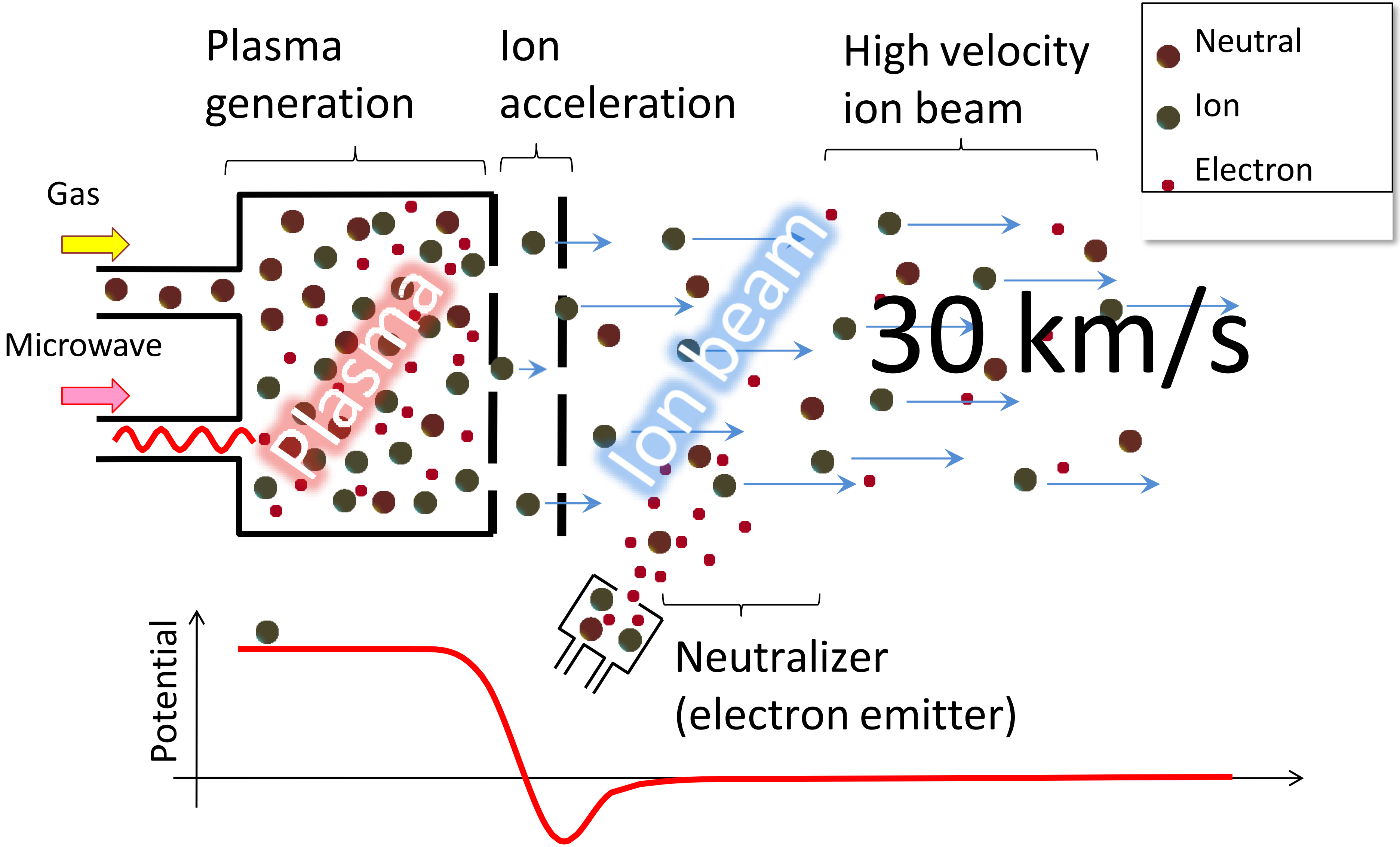
- Gridded Ion EP
  - Working fluid generation:
    - DC-discharge
    - Radio Frequency
    - Microwave

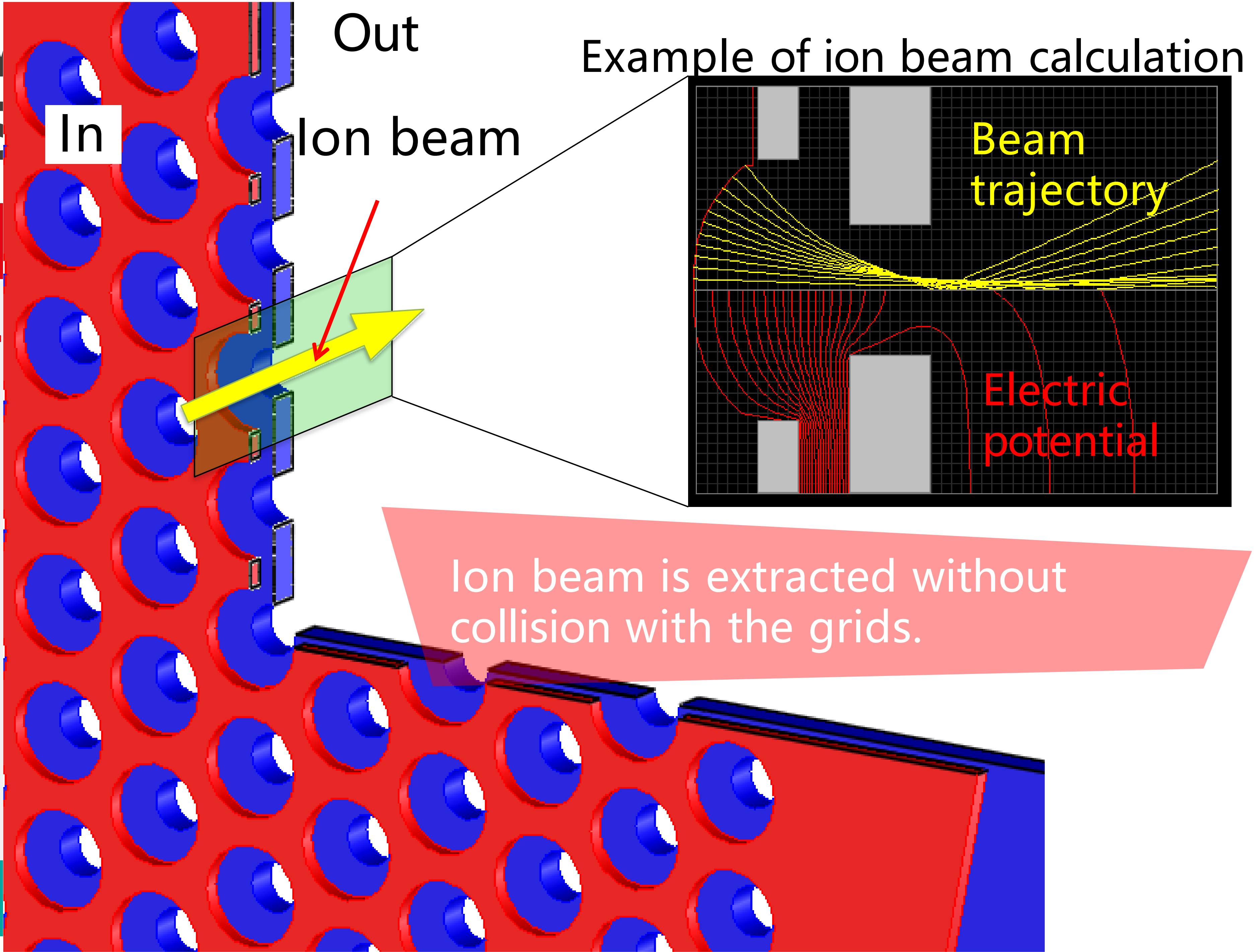




EPFL

Which Gridded Ion Electric Propulsion Systems exist (15/70)?




Out
In
Ion beam
Example of ion beam calculation
Beam trajectory
Electric potential
Ion beam is extracted without collision with the grids.

Which Gridded Ion Electric Propulsion Systems exist (17/70)?

Objective: To develop the basics of Gridded Ion EP

- Gridded Ion EP
  - 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

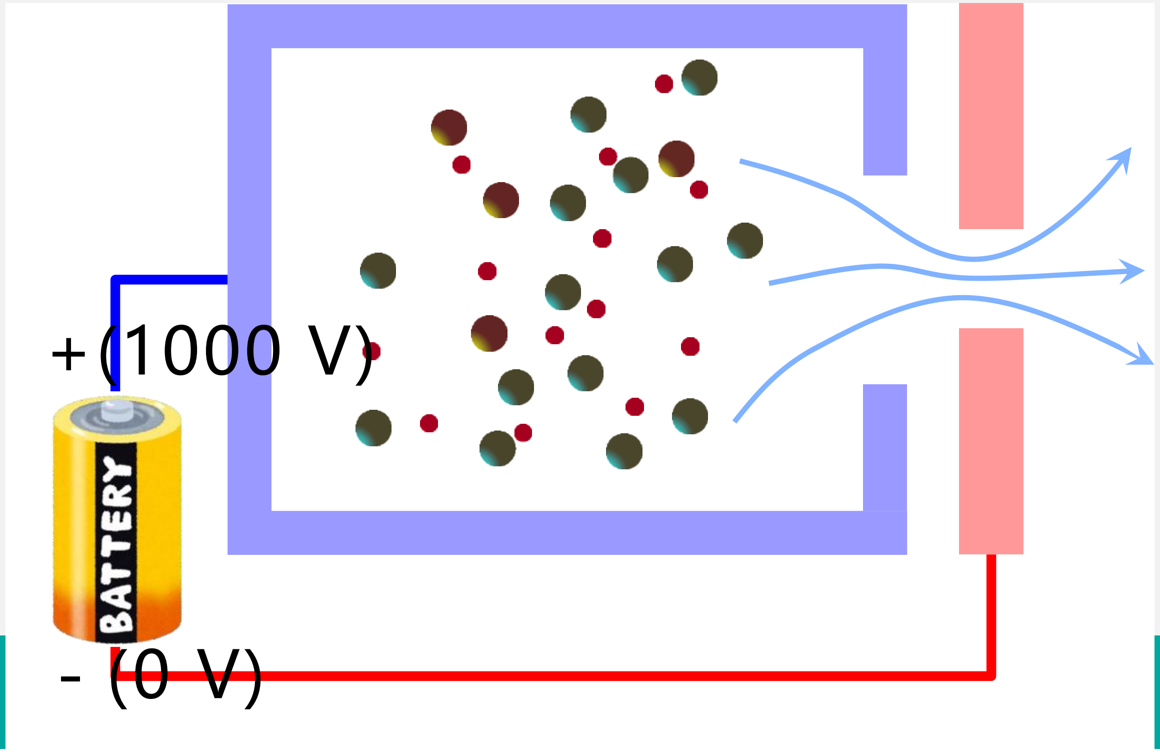
$$P = P_{\text{plasma}} + P_{\text{beam}} + P_{\text{neut}}$$

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

Which Gridded Ion Electric Propulsion Systems exist (18/70)?

Objective: To develop the basics of Gridded Ion EP

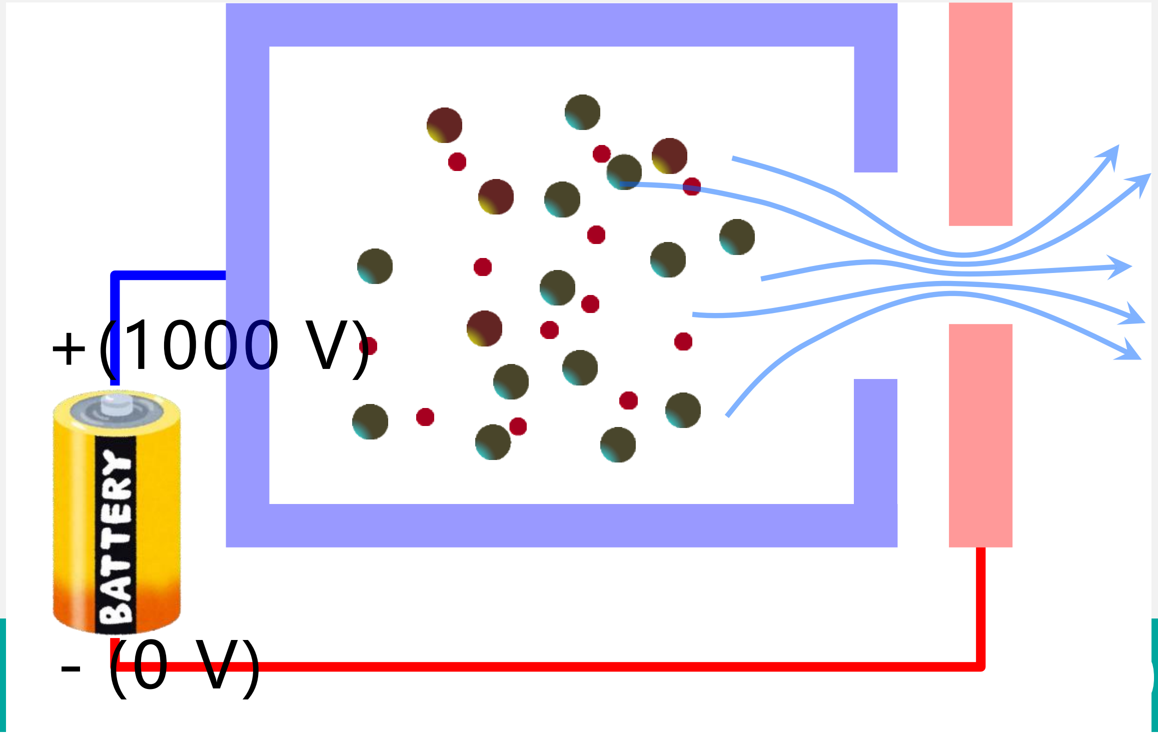
- Gridded Ion EP
  - Basic principle of an ion thruster: If you want to increase the thrust…



Which Gridded Ion Electric Propulsion Systems exist (19/70)?

Objective: To develop the basics of Gridded Ion EP

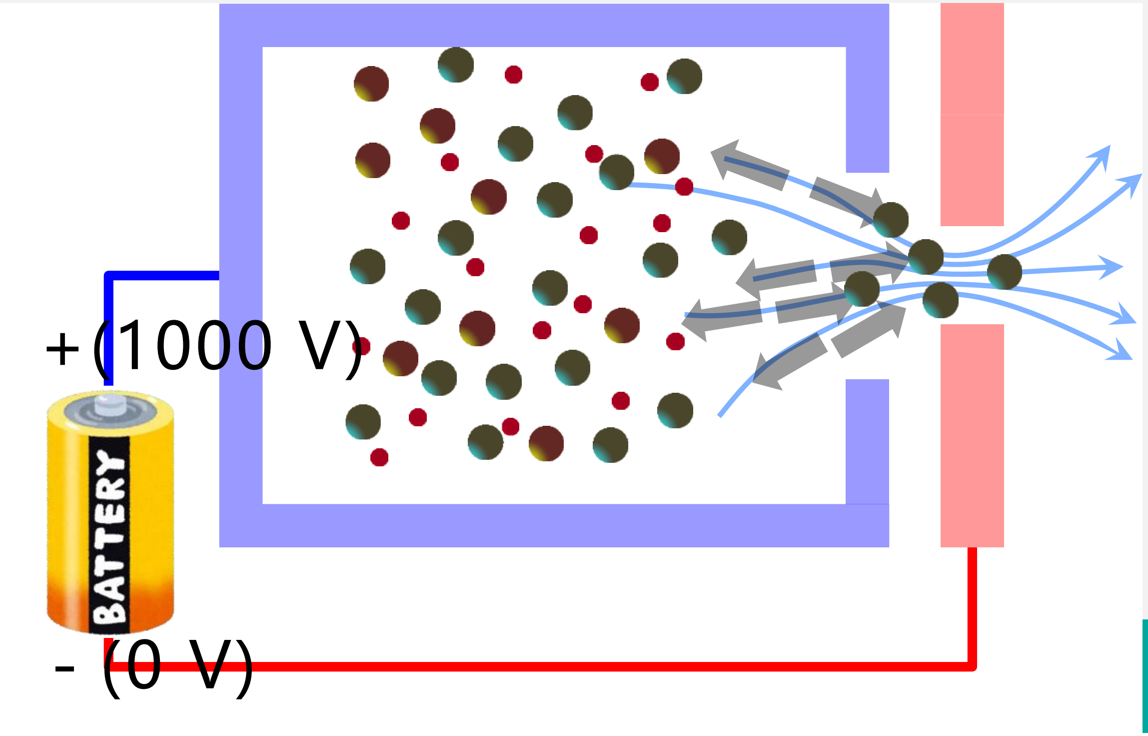
- Gridded Ion EP
  - Basic principle of an ion thruster: You need increase the number of ions flowing



Which Gridded Ion Electric Propulsion Systems exist (20/70)?

Objective: To develop the basics of Gridded Ion EP

- Gridded Ion EP
  - Basic principle of an ion thruster: But ions are repelling each other



10

Which Gridded Ion Electric Propulsion Systems exist (21/70)?

Objective: To develop the basics of Gridded Ion EP

- Gridded Ion EP
  - Basic principle of an ion thruster: Space Charge Limitation Current

e.g. 1D case

There is a theoretical limit for the current density of the ion thrusters (though actual current limit is different due to 3D & initial velocity)

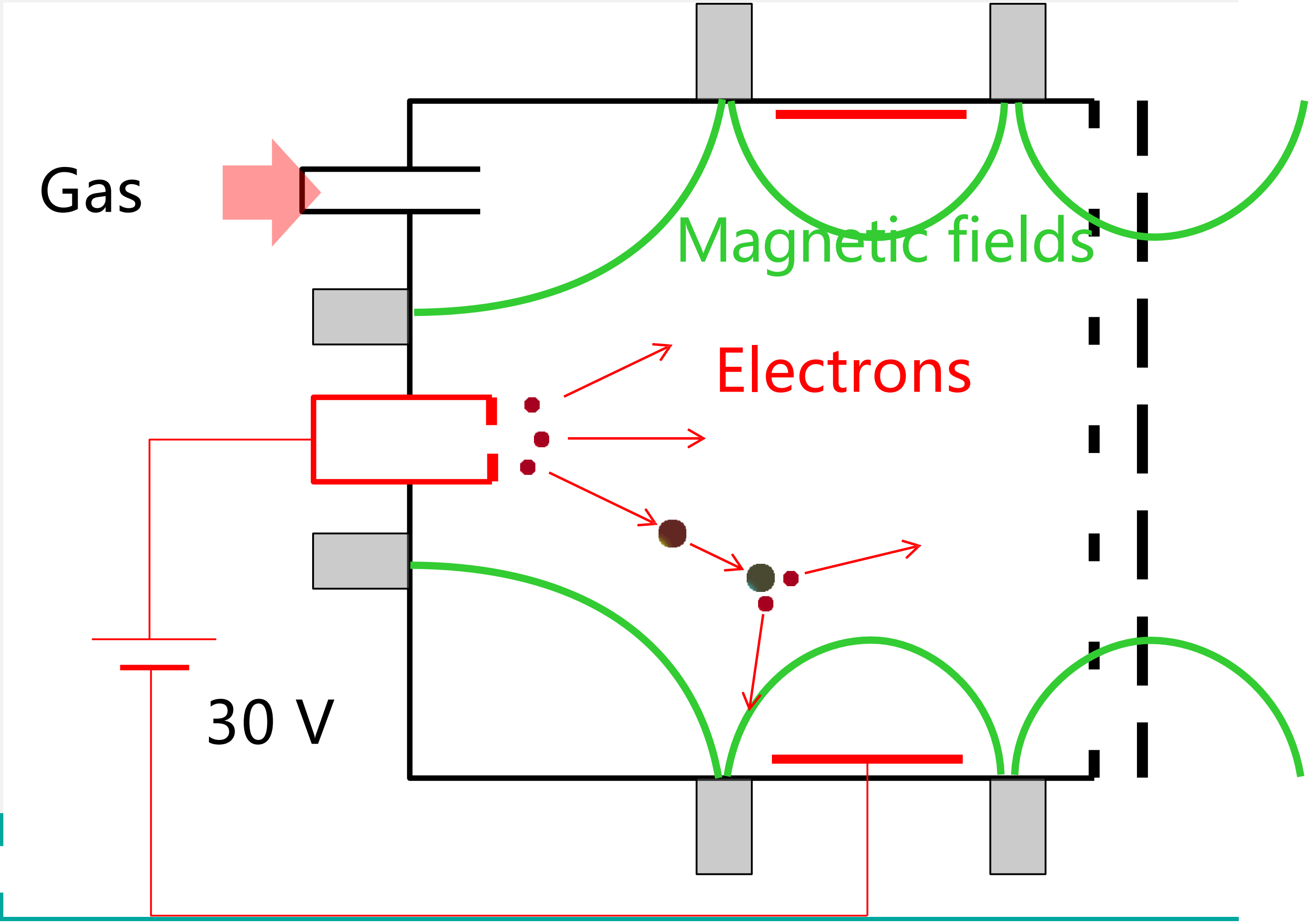
↓

Limitation for the thrust per unit area.
If you want high-thrust, it may be issue.

Which Gridded Ion Electric Propulsion Systems exist (24/70)?

Objective: To develop the basics of Gridded Ion EP

- Gridded Ion EP
  - DC discharge: Electron acceleration -> Ionization
  - Hollow cathode as electron source
  - Anode potential discharge chamber with magnetic multipole boundaries

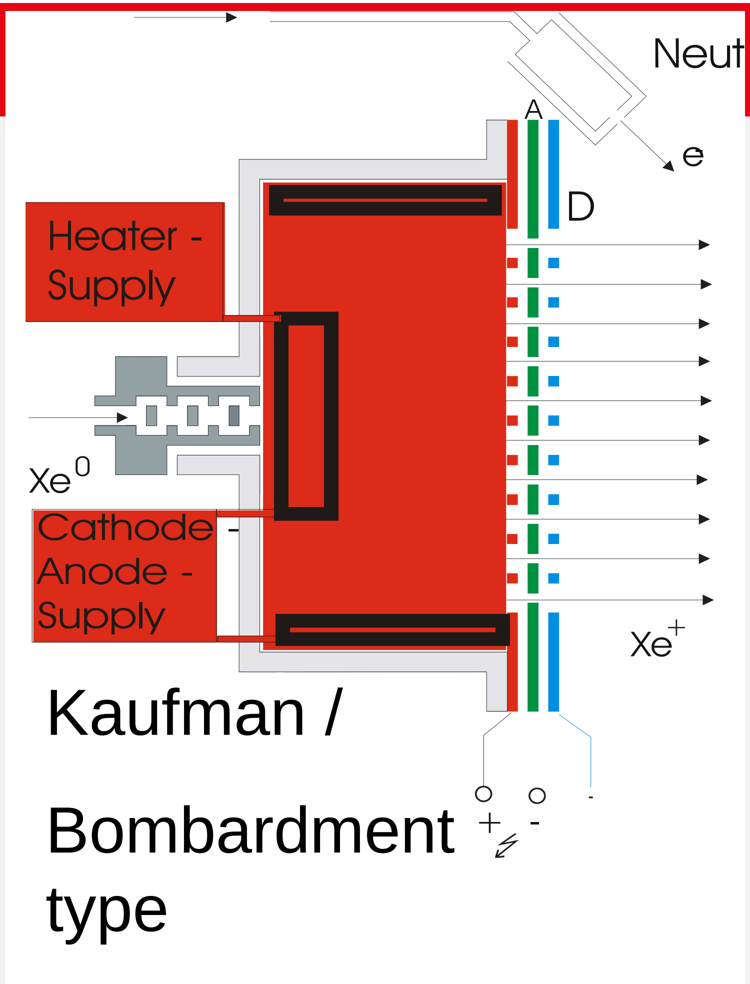


Space

Which Gridded Ion Electric Propulsion Systems exist (40/70)?

Objective: To develop … Ion EP

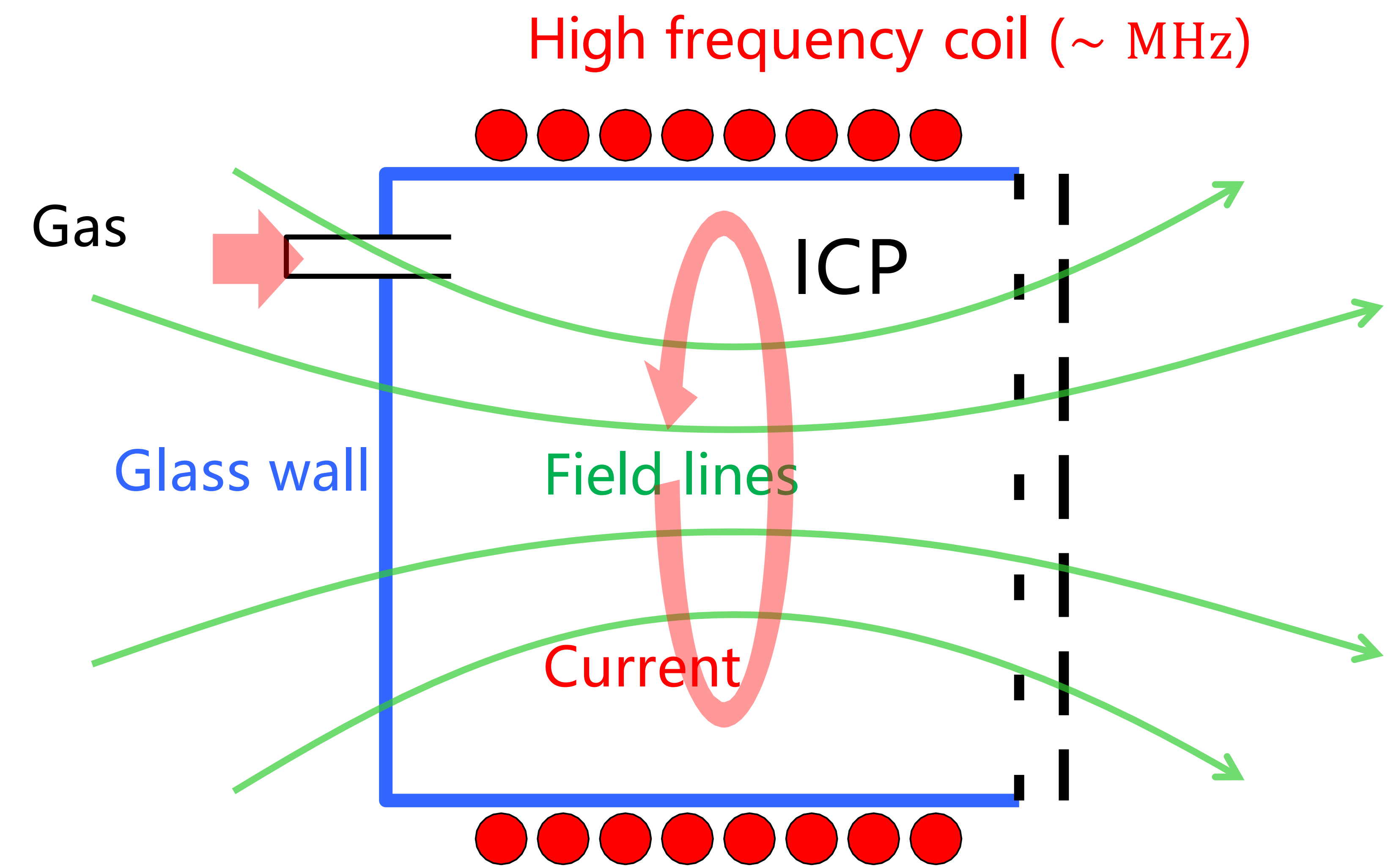
- Gridded Ion EP
  - Example: Kaufman thruster



Which Gridded Ion Electric Propulsion Systems exist (41/70)?

Objective: To develop the basics of Gridded Ion EP

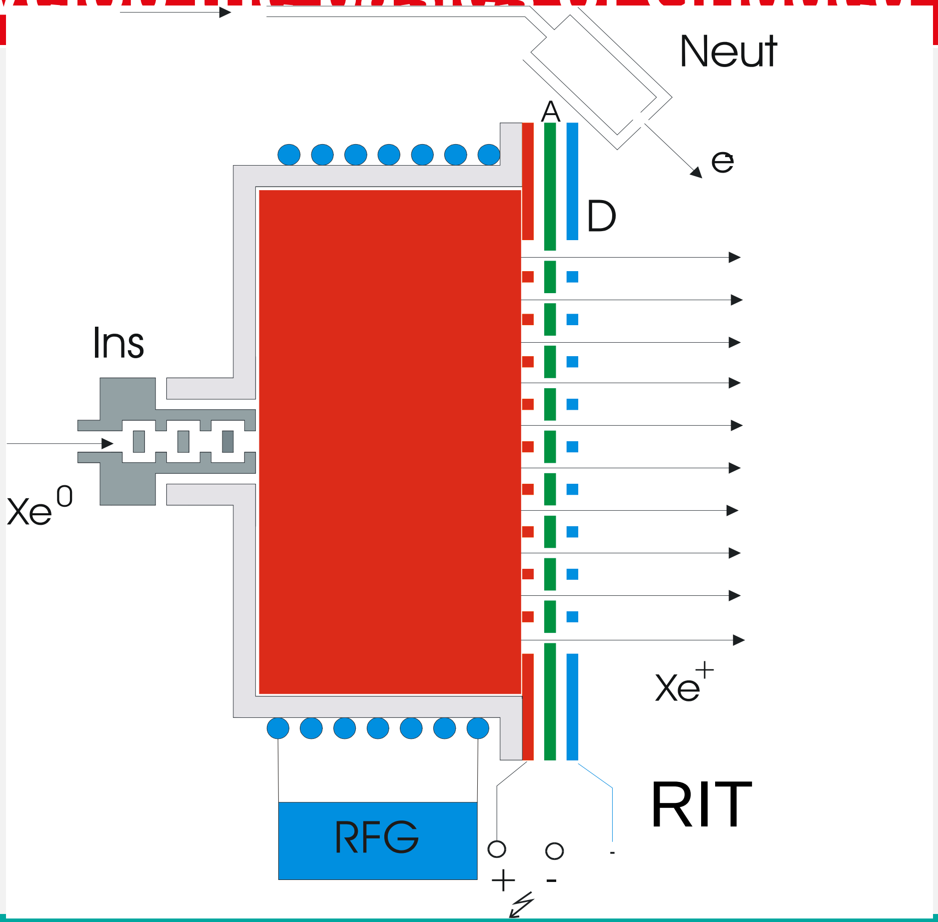
- Gridded Ion EP
  - RF discharge: RF current on outside coil -> Inducing current



Which Gridded Ion Electric Propulsion Systems exist (43/70)?

Objective: To develop the basics of Gridded Ion EP

- Gridded Ion EP
  - Example:
    AGG RIT thruster

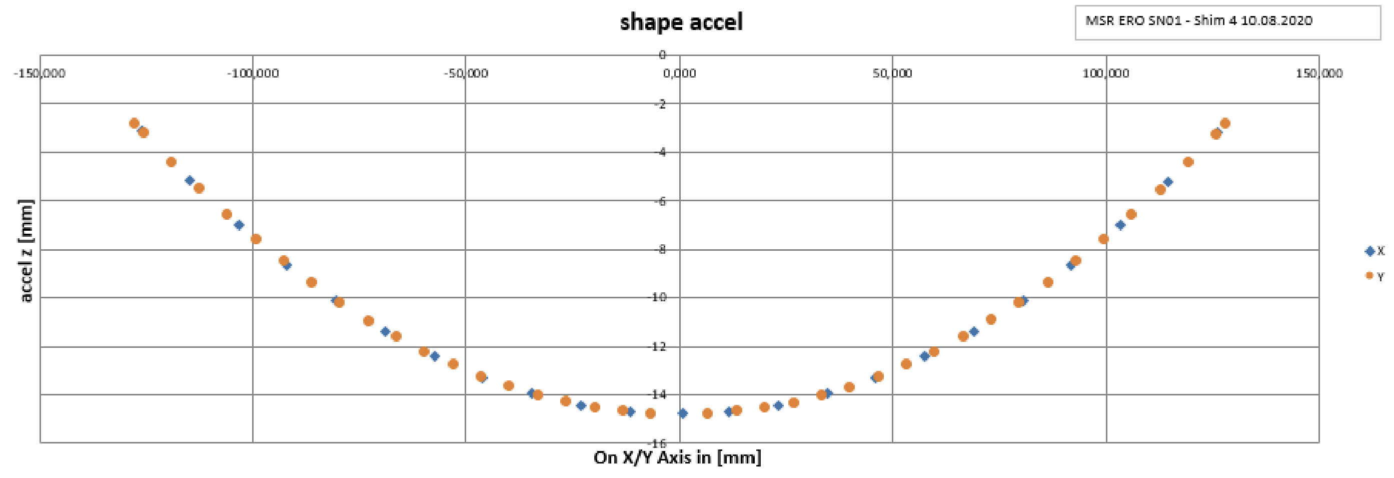


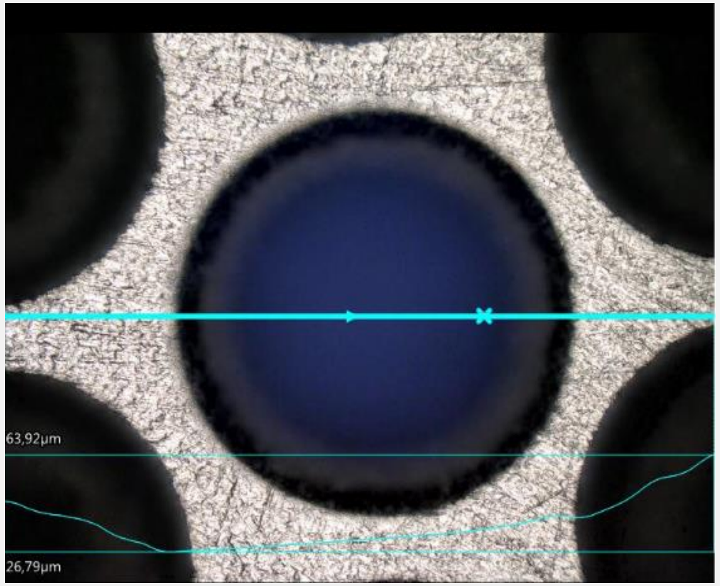

Huge thruster have the problem at
Grid systems

Which Gridded Ion Electric Propulsion Systems exist (45/70)?

Objective: To develop the basics of Gridded Ion EP

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

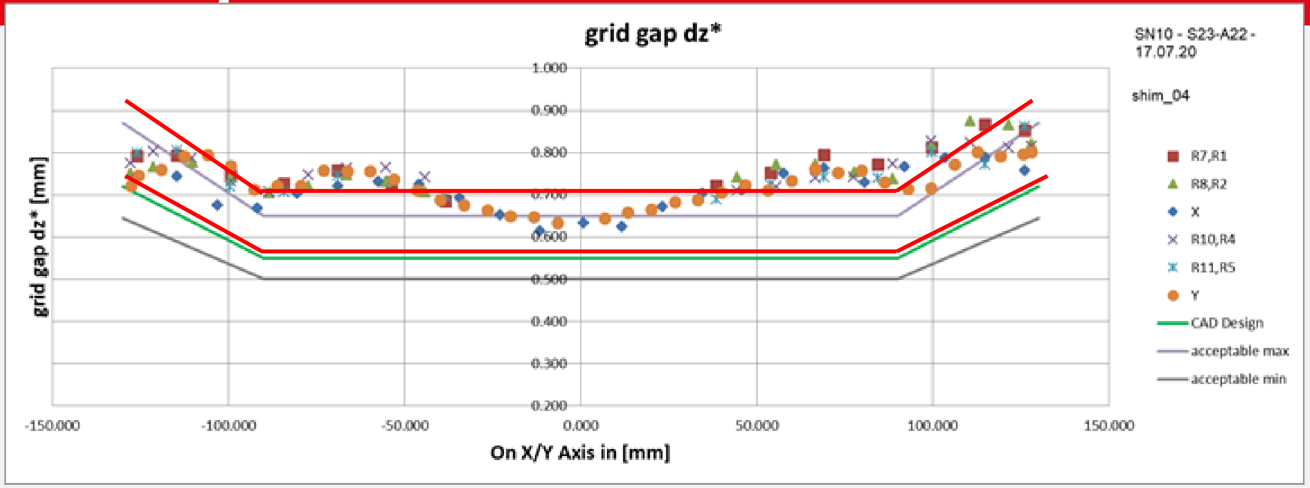


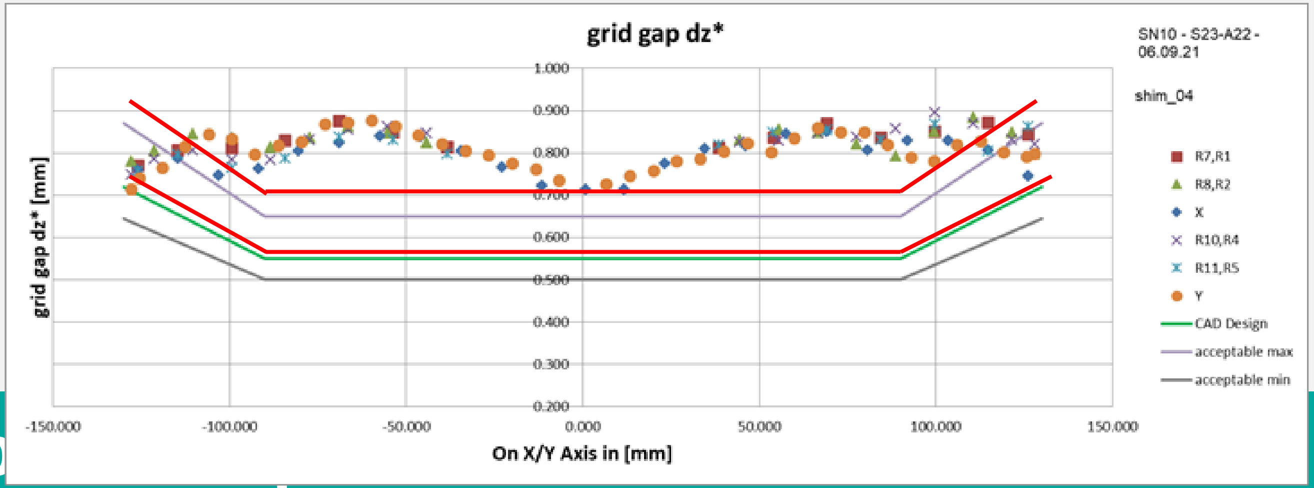


Which Gridded Ion Electric Propulsion Systems exist (46/70)?

Objective: To develop the basics of Gridded Ion EP

- Gridded Ion EP
  - Alignment
  - Hot conditions



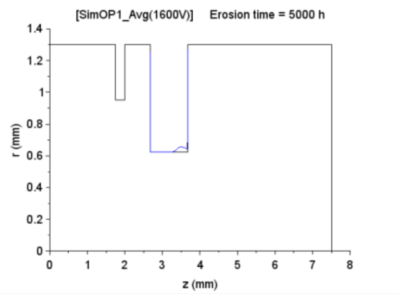
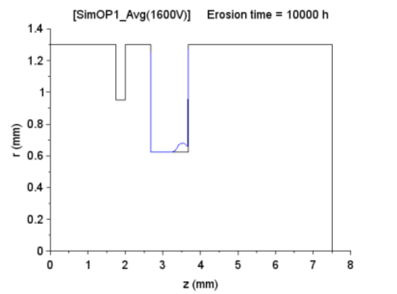
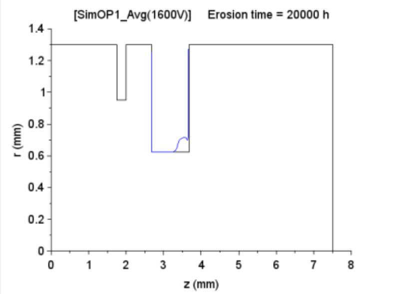


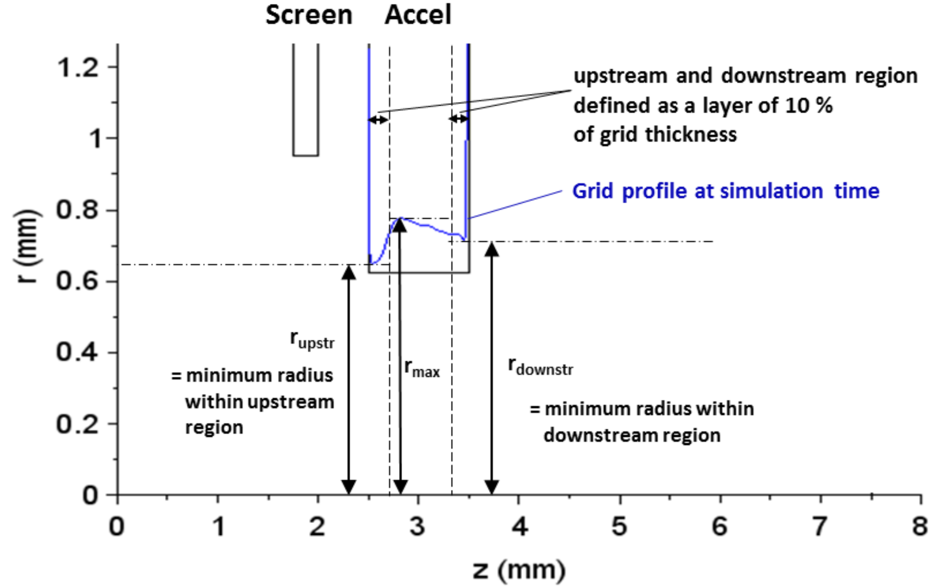
Sp

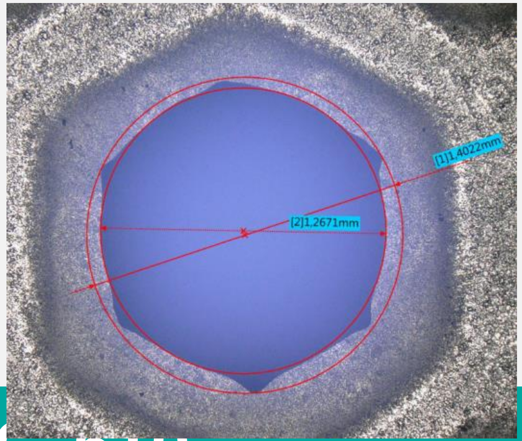
Which Gridded Ion Electric Propulsion Systems exist (47/70)?

Objective: To develop the basi

- Gridded Ion EP
  - Erosion

	5000h	10.000h	20.000h
OP1			

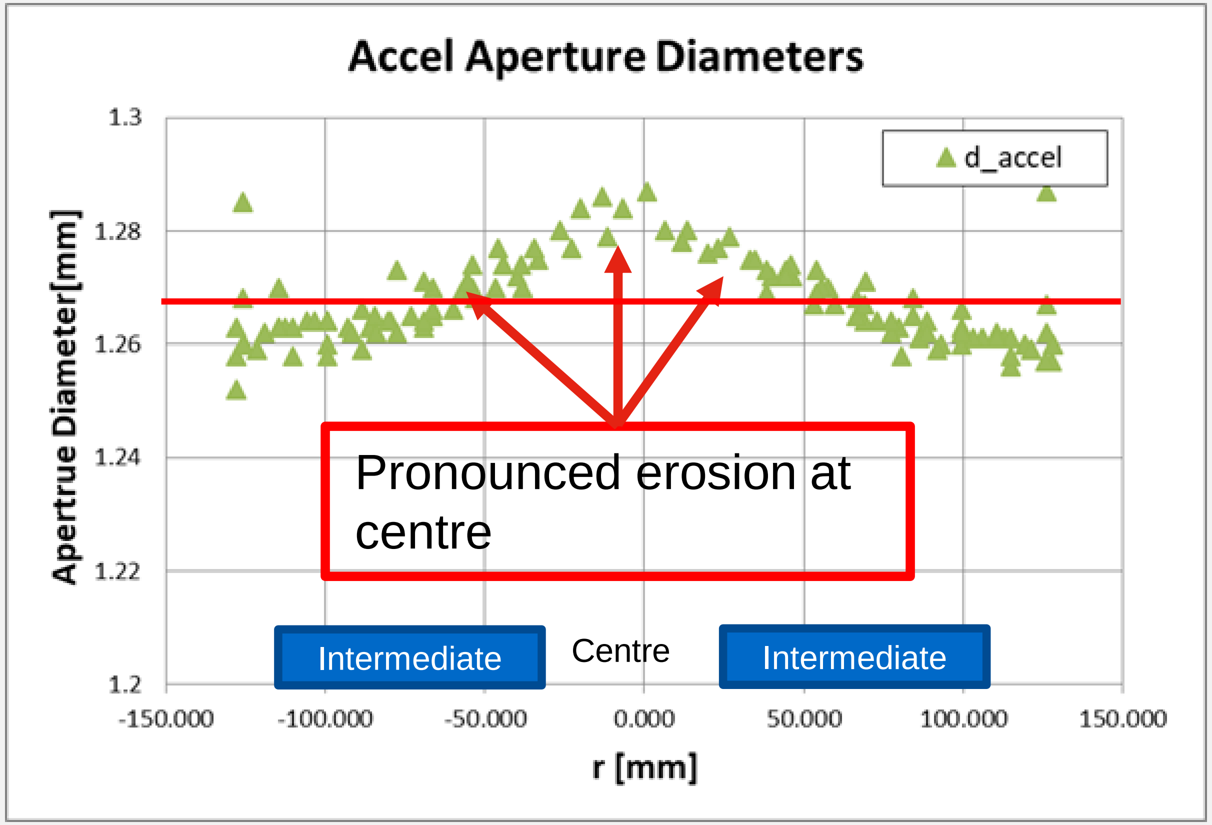




Which Gridded Ion Electric Propulsion Systems exist (48/70)?

Objective: To develop the basics of Gridded Ion EP

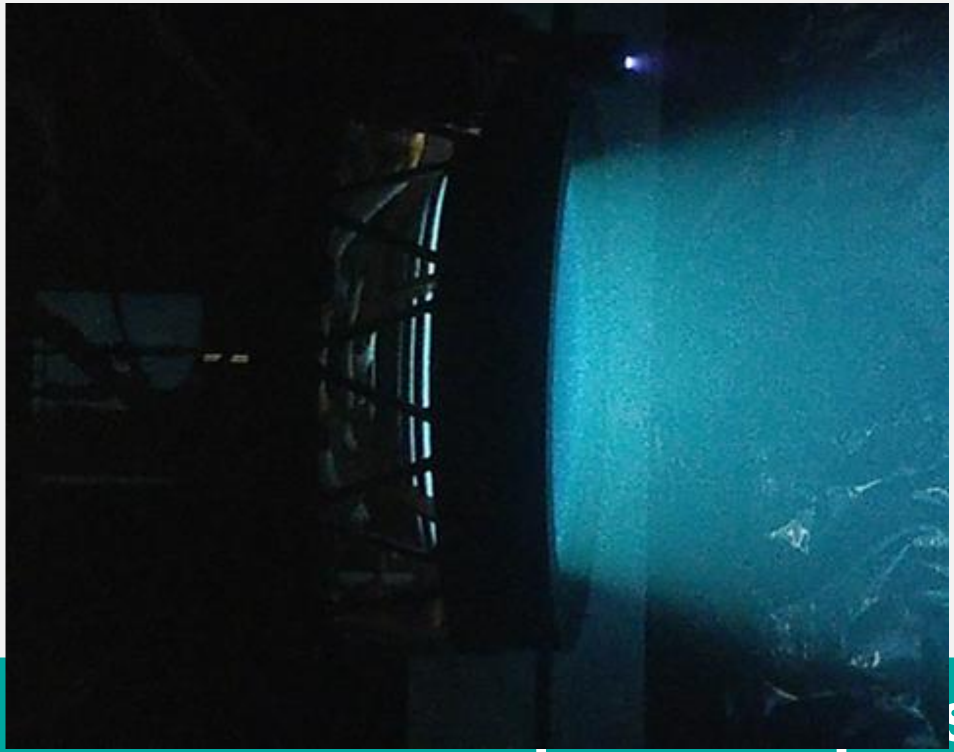
- Gridded Ion EP
  - Erosion linked to position…



Which Gridded Ion Electric Propulsion Systems exist (49/70)?

Objective: To develop the basics of Gridded Ion EP

- Gridded Ion EP
  - Arcs

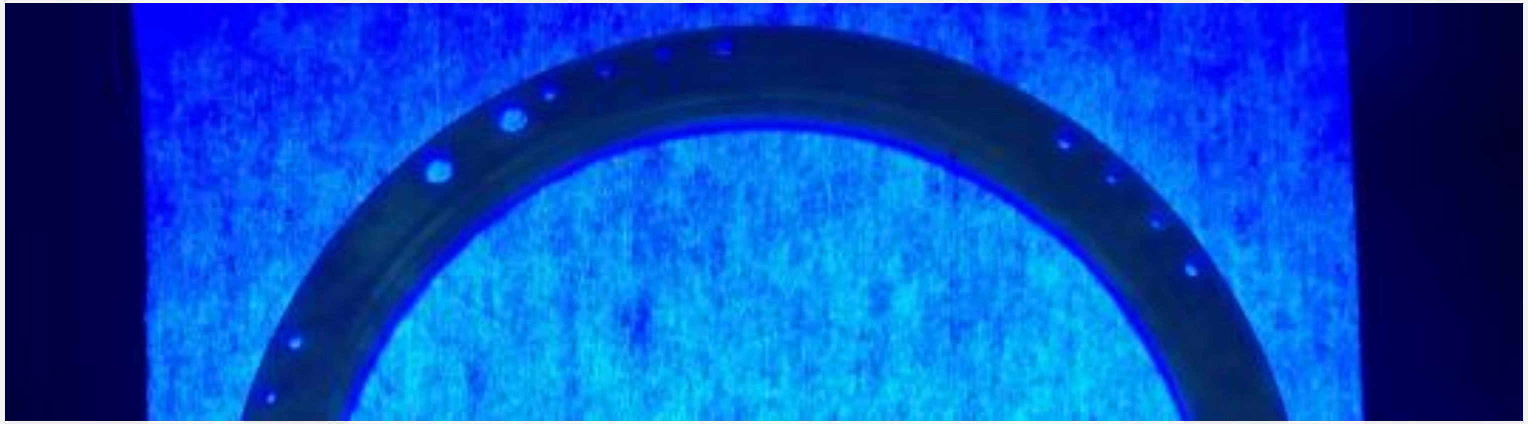



Huge thruster have the problem at
Grid systems
But not only as there is also

Which Gridded Ion Electric Propulsion Systems exist (51/70)?

Objective: To develop the basics of Gridded Ion EP

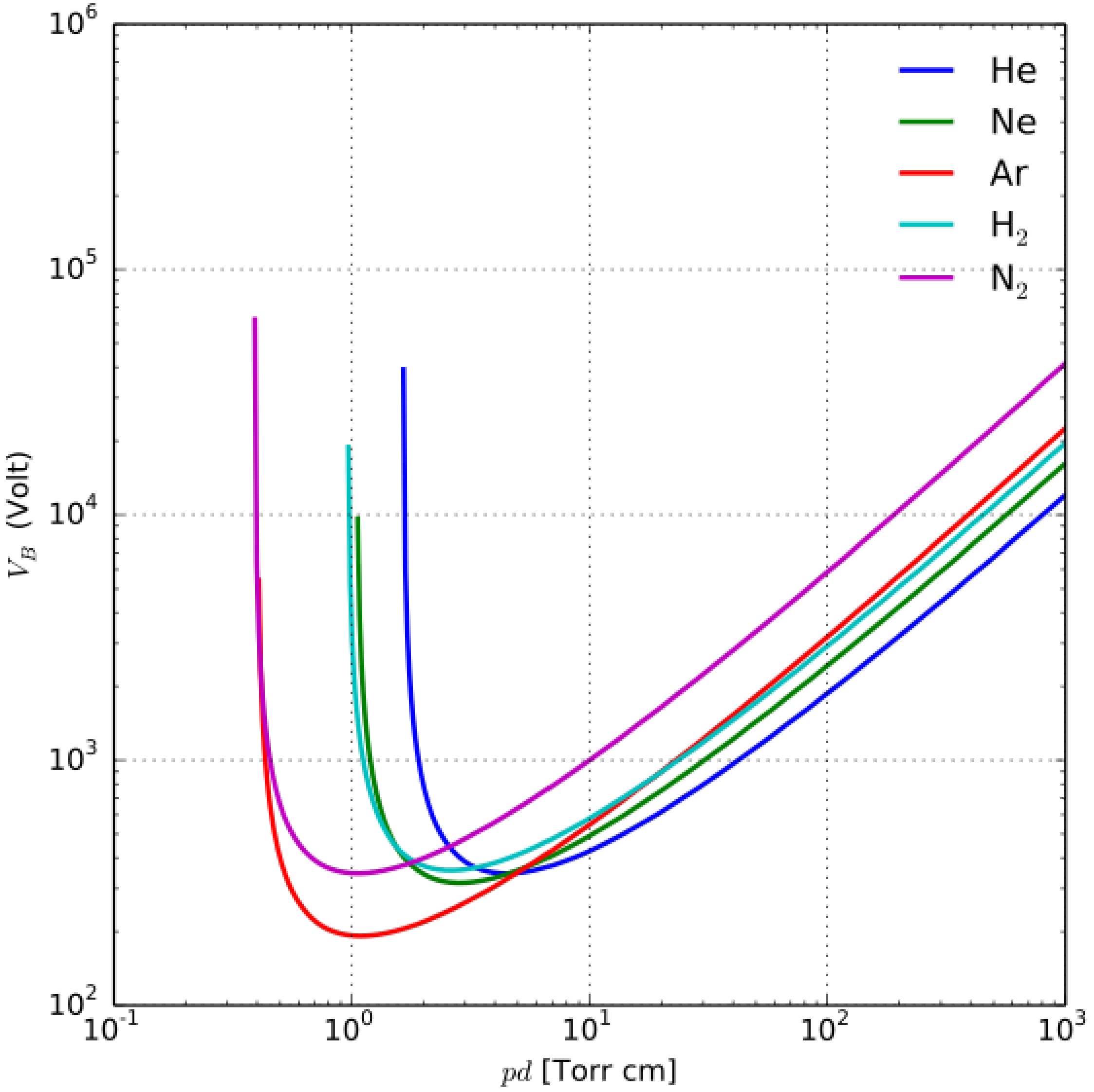
- Gridded Ion EP
  - Harness
  - RFG
  - Neutralizer
  - Ceramic
  - Testing on Ground (Vacuum level -> Paschen curve, sputter material)
  - Gas Inlet
  - …



Which Gridded Ion Electric Propulsion Systems exist (52/70)?

Objective: To develop the

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

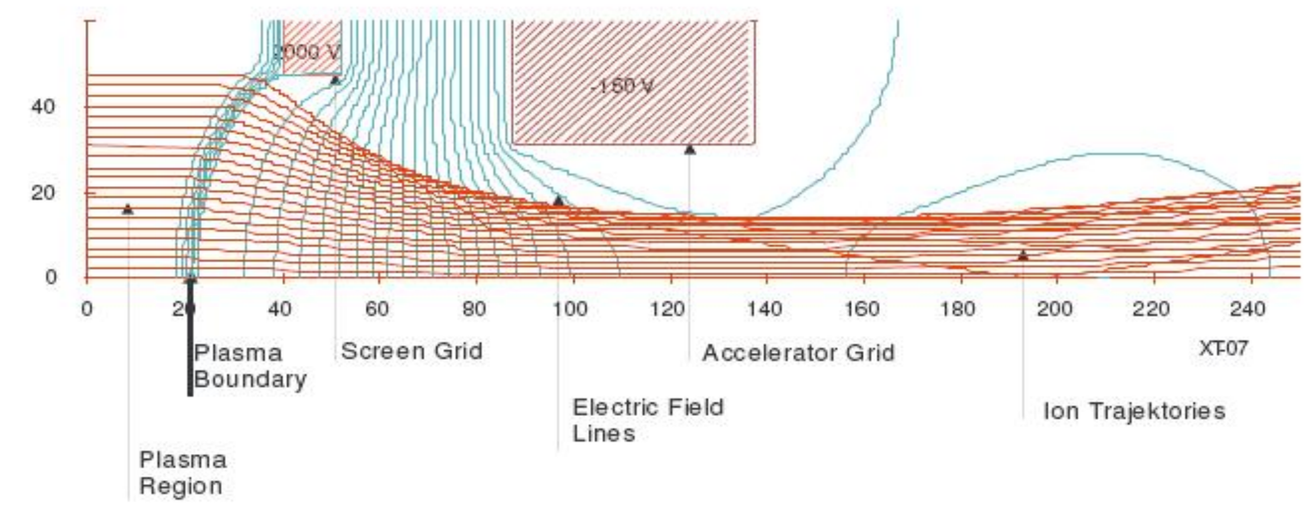


Space Propuls

Which Gridded Ion Electric Propulsion Systems exist (53/70)?

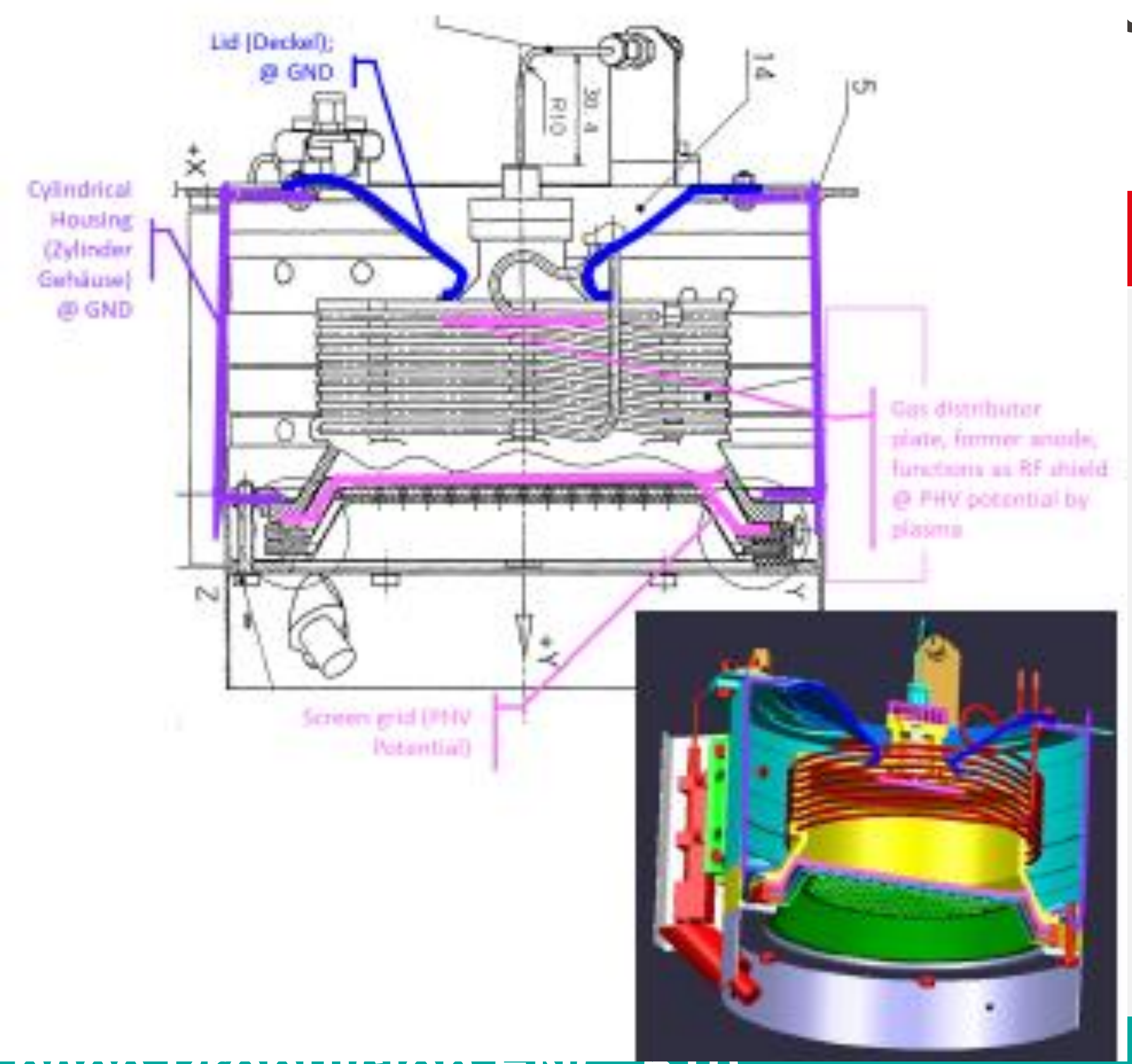
Objective: To develop the basics of Gridded Ion EP

- Gridded Ion EP
  - Testing on Ground (Sputter material)



Which Gridd… on Systems ex…

Objective: To…

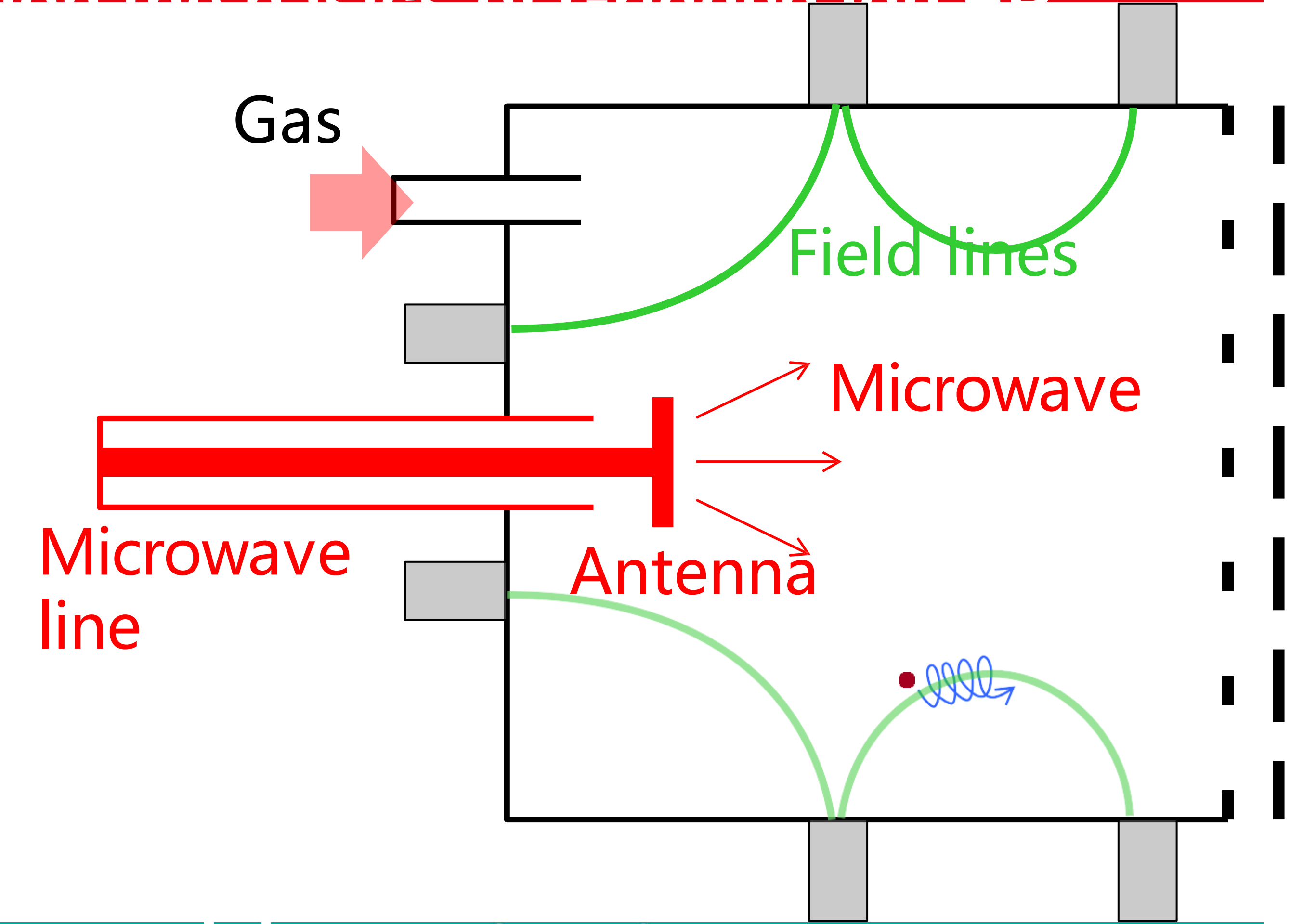


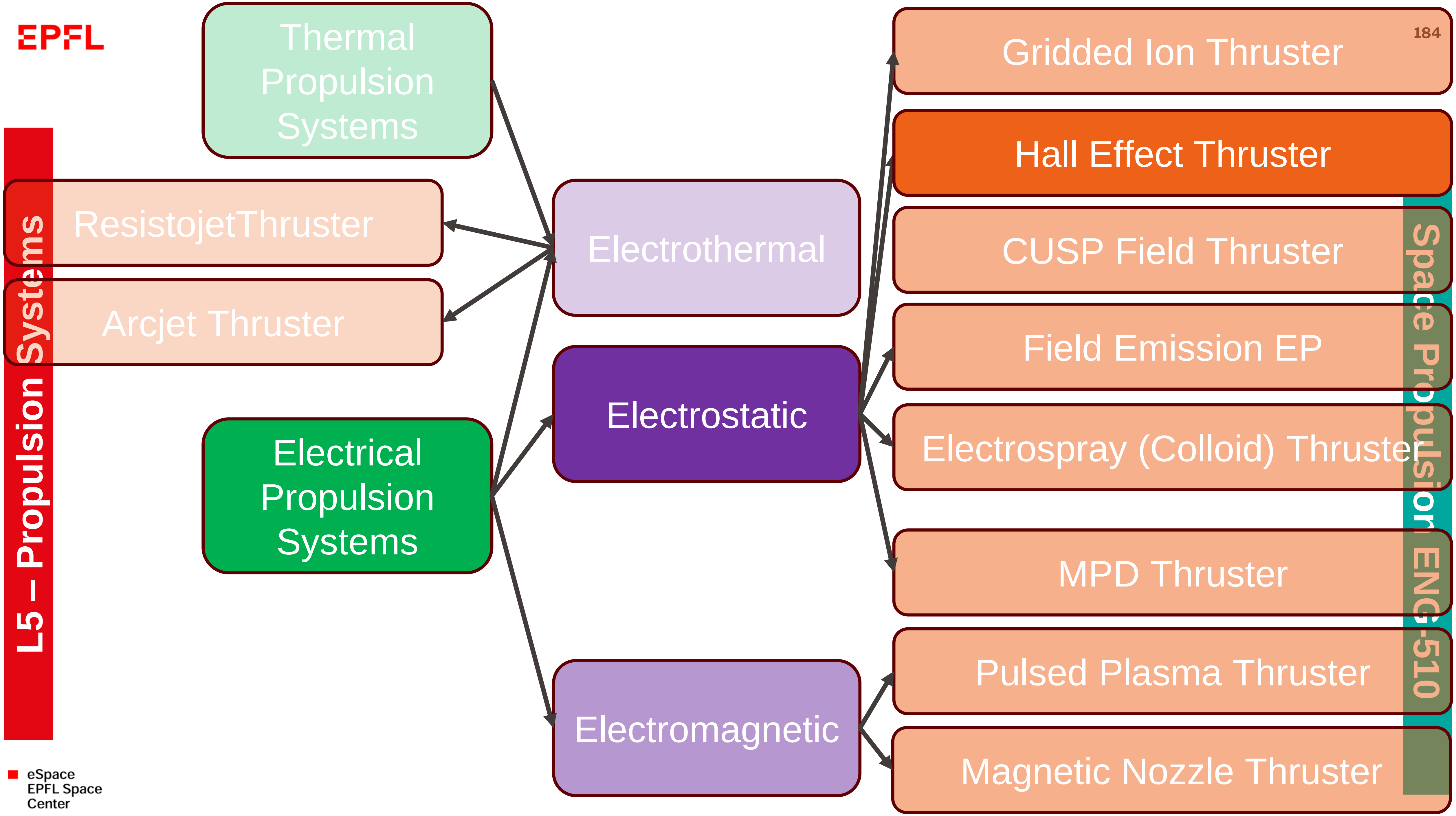
- Gridded Ion EP
  - Gas Inlet

Which Gridded Ion Electric Propulsion Systems exist (58/70)?

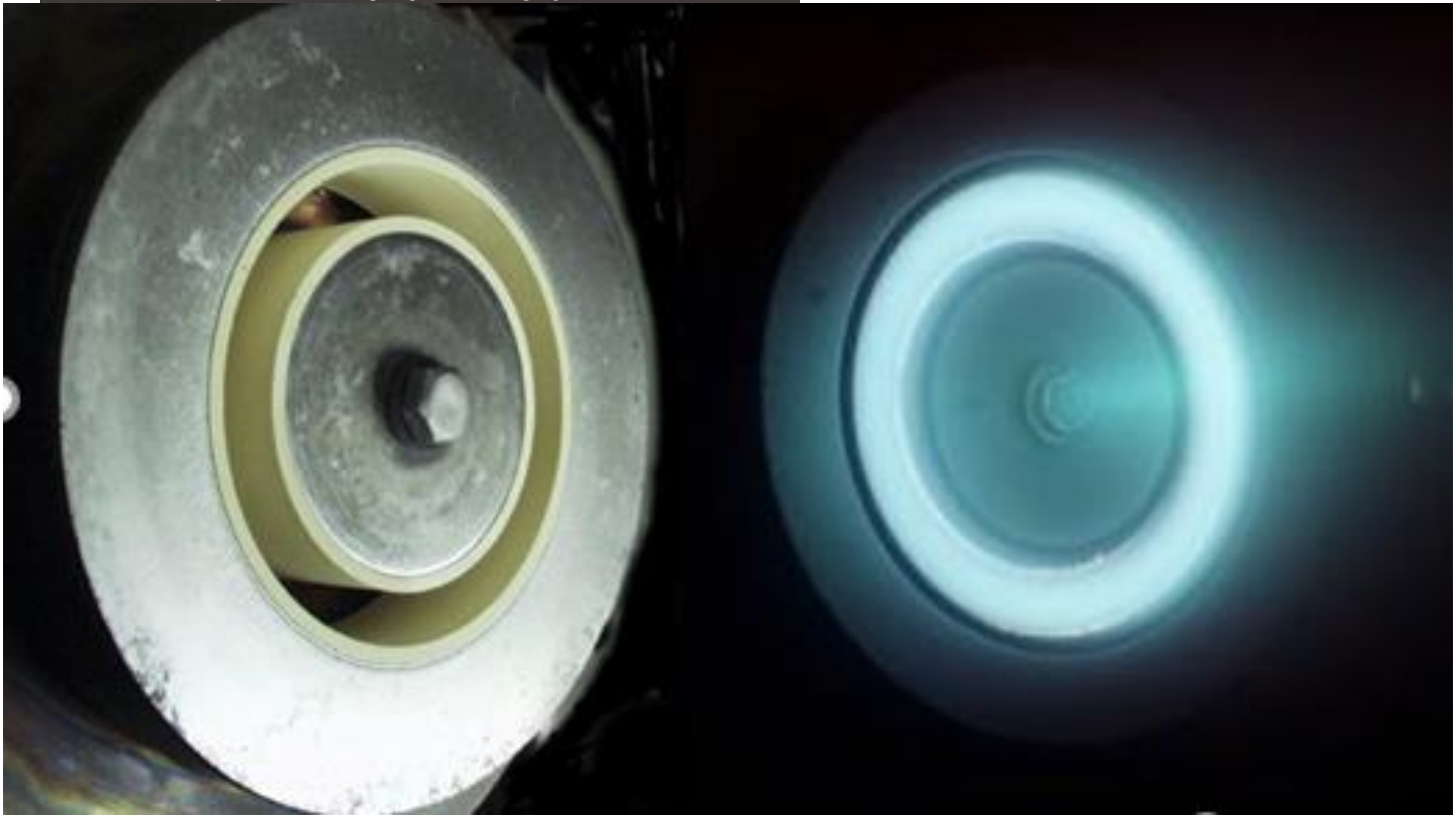
Objective: To develop the basics of Gridded Ion EP

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




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

Which Electrical



Which Electrical Propulsion Systems exist?

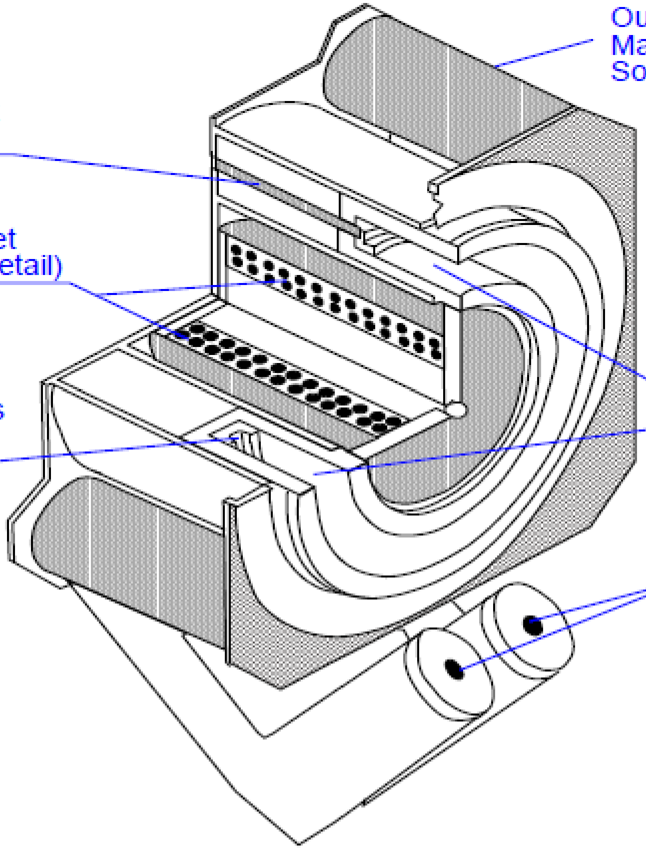
Electrostatic Propulsion Systems:

- 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

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:

- Hall Effect Thruster:
  - C
    - D

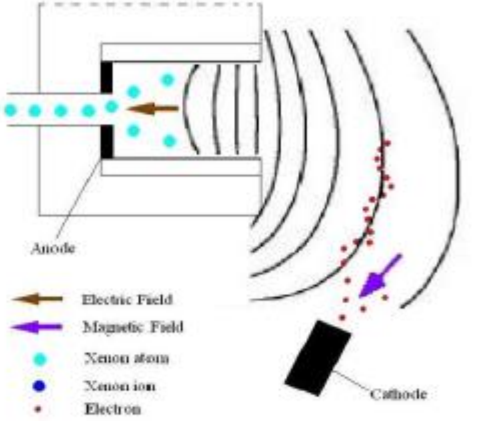


Which Electrical Propulsion Systems exist?

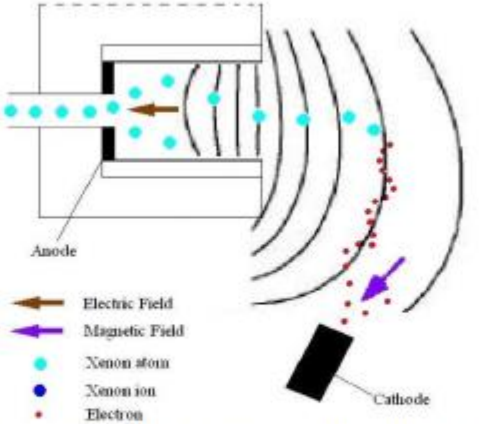
Electrostatic Propulsion Systems:

- 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)

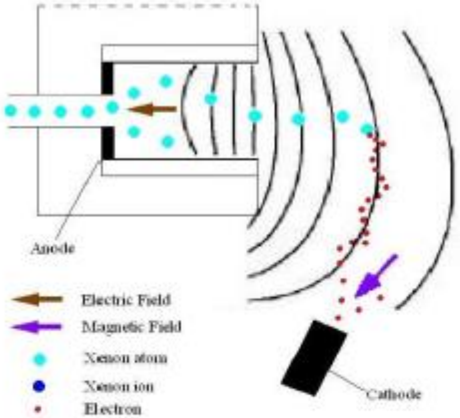
Which Electrical Propulsion Systems



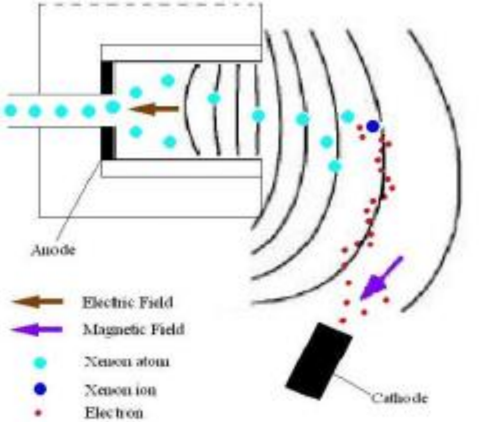
1/ Cathode electrons (e⁻) are trapped in the magnetic field



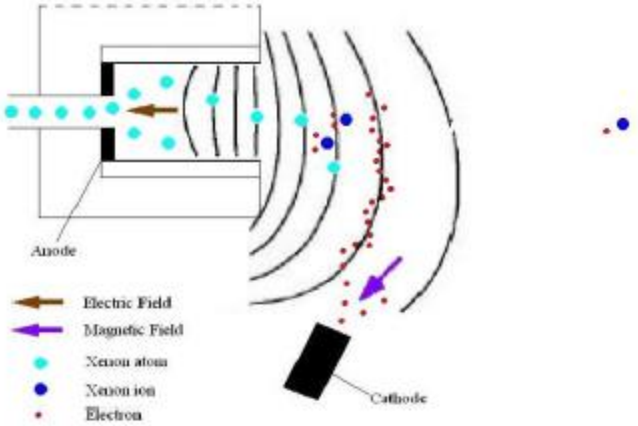
2/ Xenon (Xe) atoms are introduced in the anode



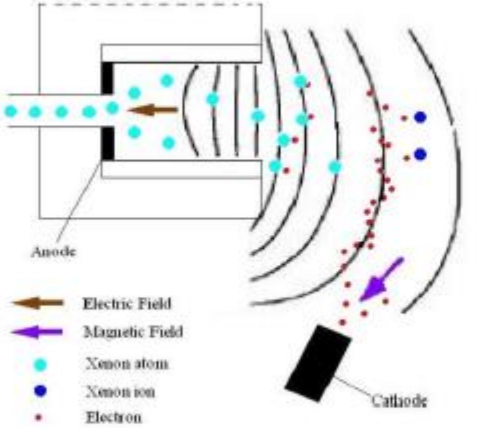
3/ One e⁻ collides with one Xe atom



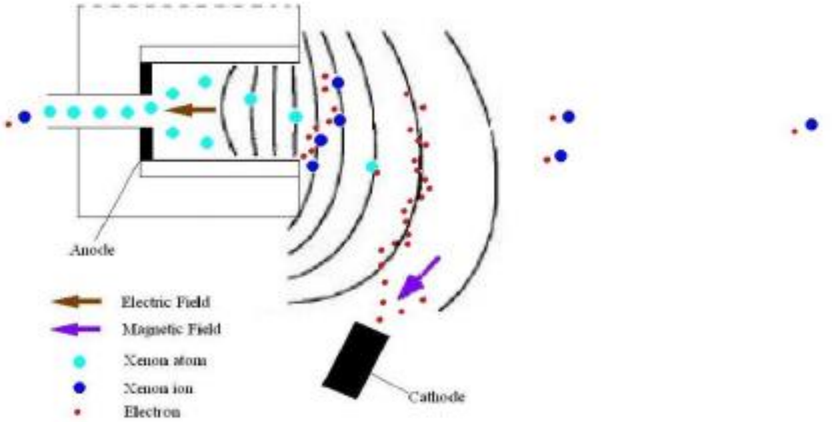
4/ When the colliding e⁻ has sufficient energy, the Xe atom is ionized: Xe + e⁻ -> Xe⁺ + 2e⁻



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

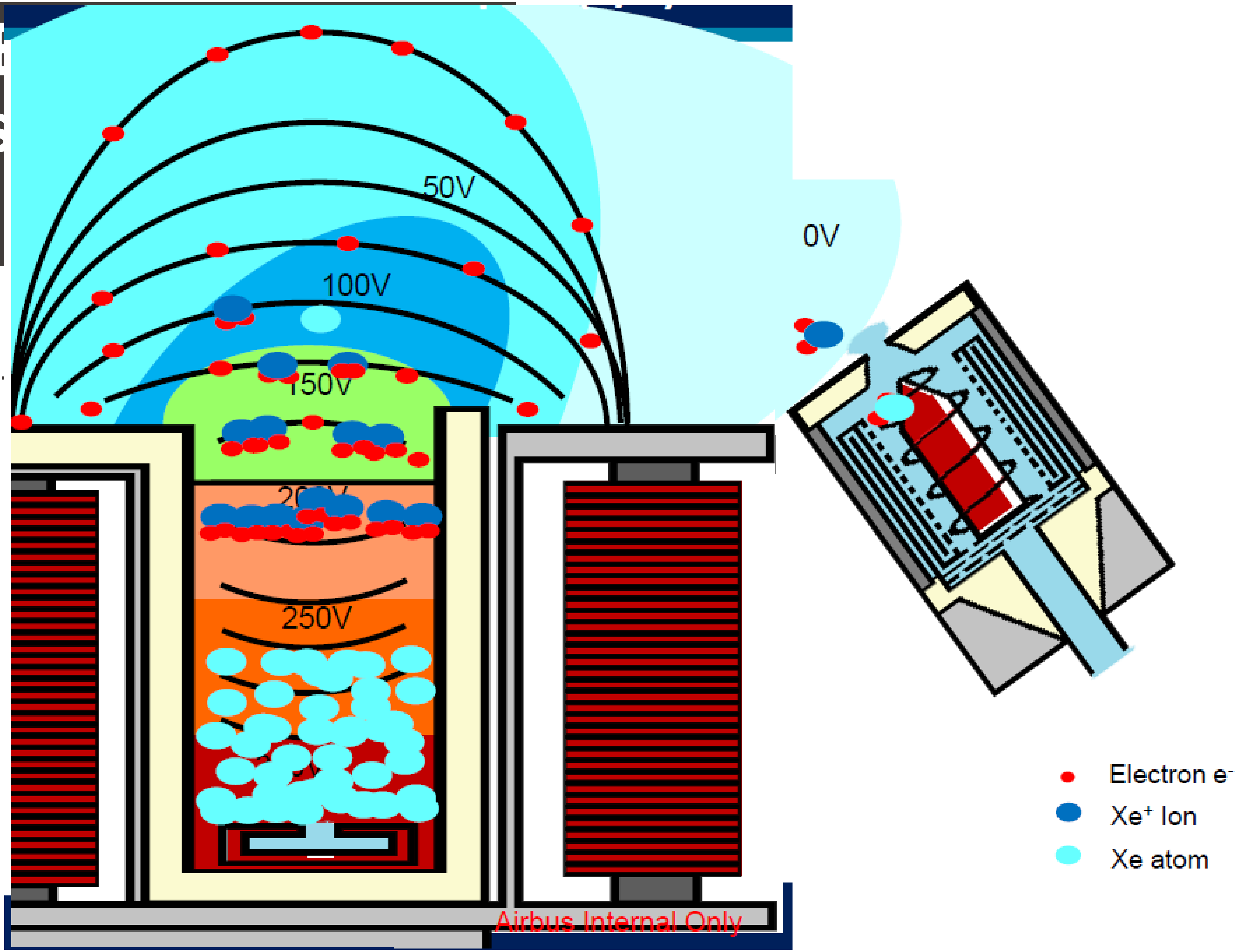


7/ The ionization process initiated by 1 e⁻ increases exponentially until the energy of generated e⁻ is insufficient to ionize Xe and they are collected by the anode

Which E
Propuls
exist?

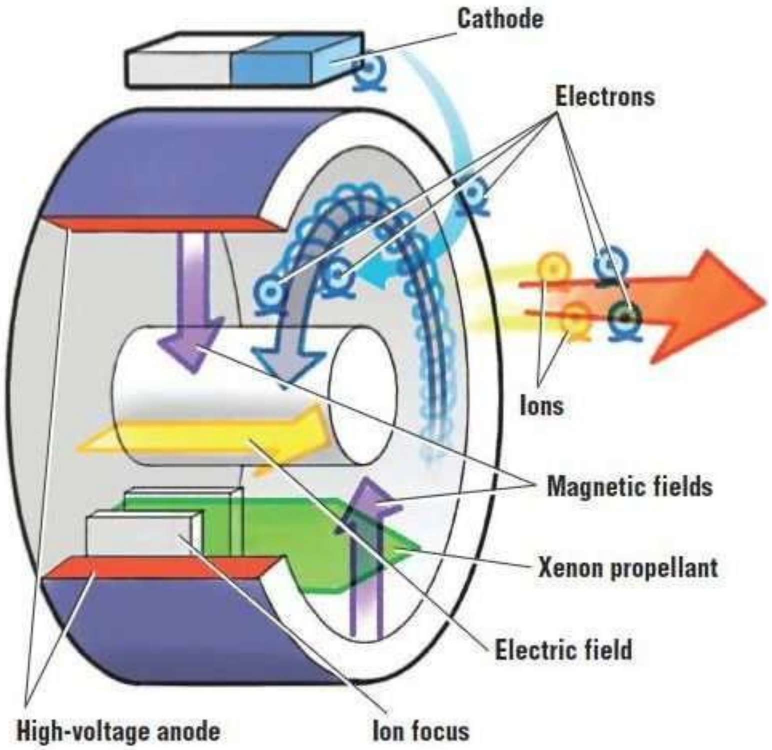
Electrostatic

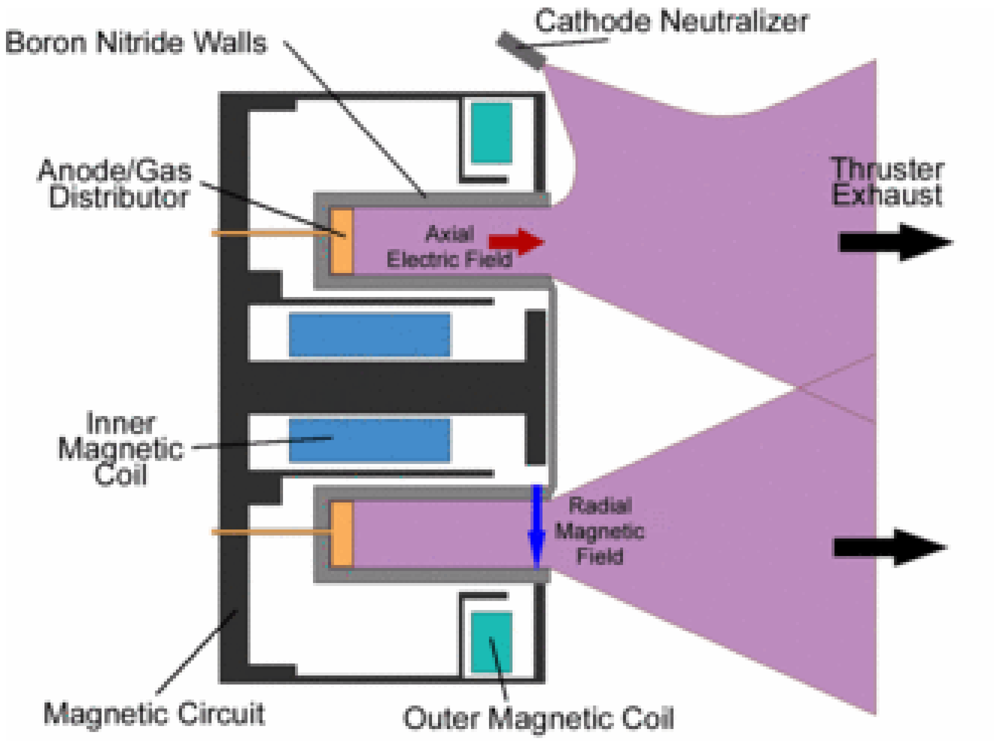
- Hall Effect

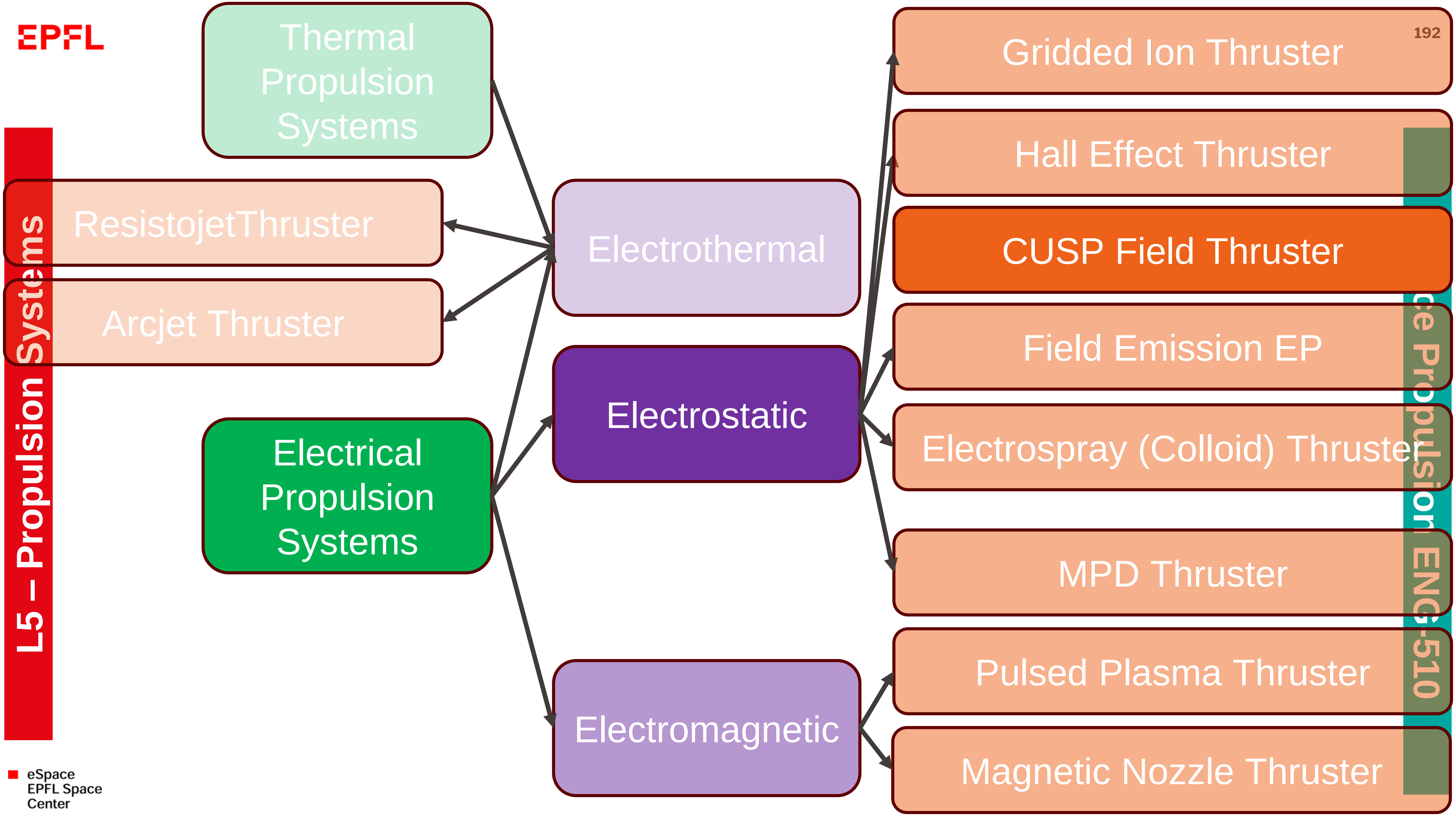


Which Electrical Propulsion Systems exist?

Electrostatic Propulsion Systems:






L5 – Propulsion Systems
Thermal Propulsion Systems
Electrical Propulsion Systems
Electrothermal
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Electromagnetic
ResistojetThruster
Arcjet Thruster
Gridded Ion Thruster
Hall Effect Thruster
CUSP Field Thruster
Field Emission EP
Electrospray (Colloid) Thruster
MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster
ce Propulsion ENG-510

Which Electrical Propulsion Systems exist?

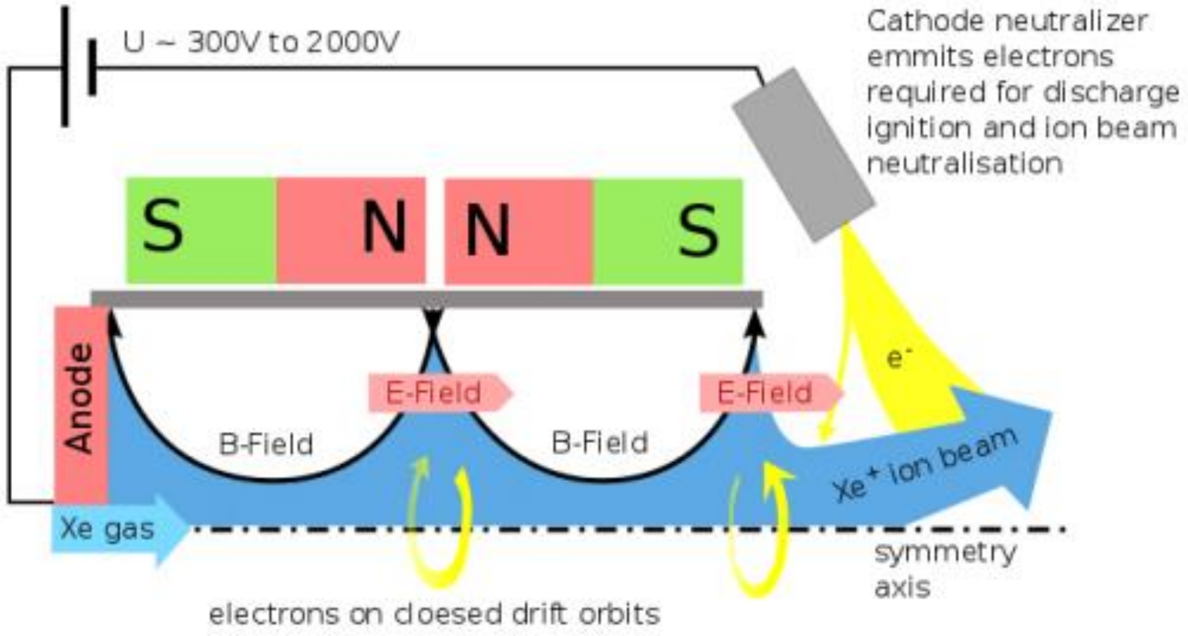
Electrostatic Propulsion System:

- 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?

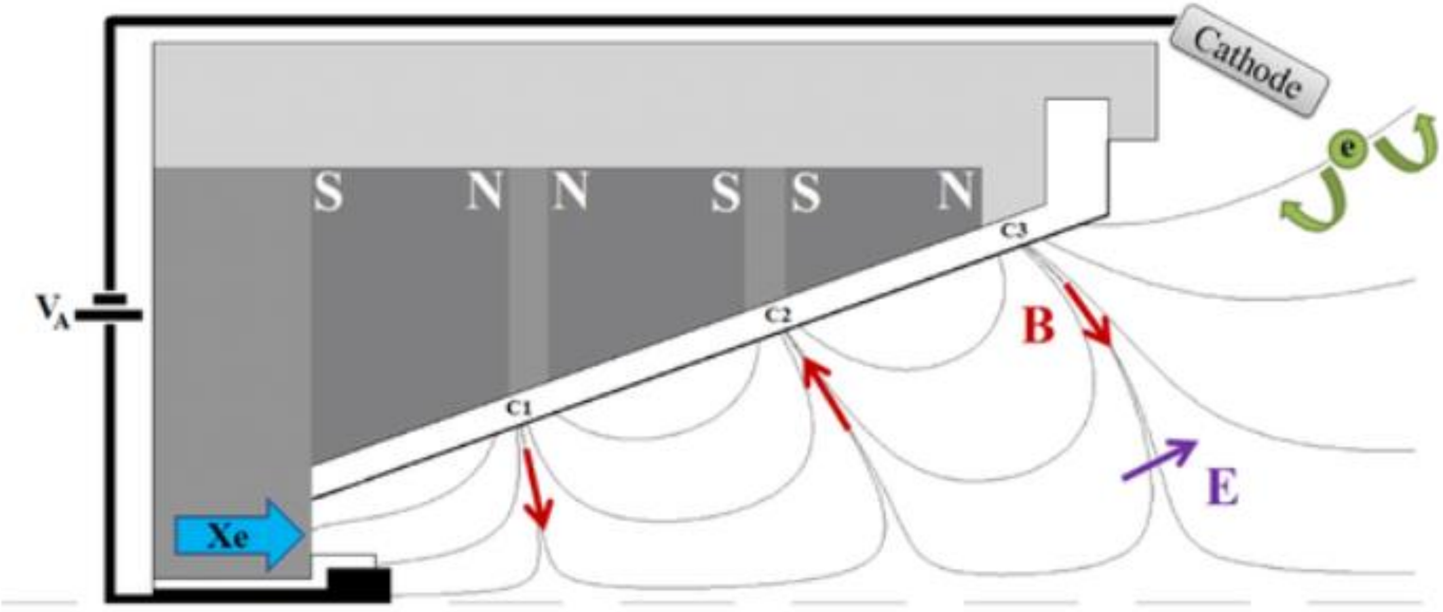
Electrostatic Propulsion System:

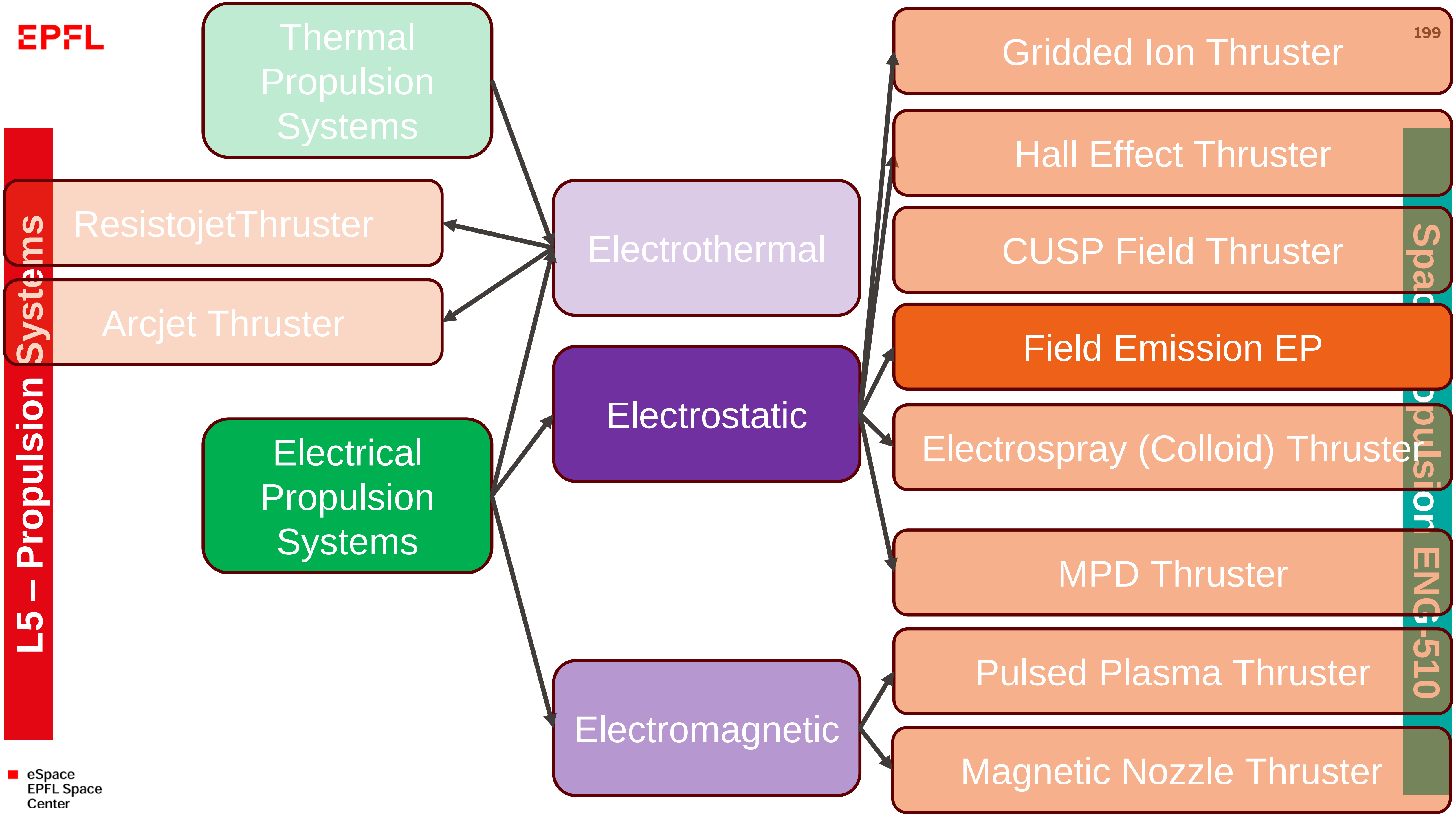
- ACFT (Advanced Cusp Field Thruster) / HEMPT (High Efficiency Multistage Plasma Thruster) EP
  - The magnetic rings create a magnetic field almost perpendicular to the electric field, which forces the electrons towards the anode in spiral trajectories which allows more propellant atoms to be ionised, 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

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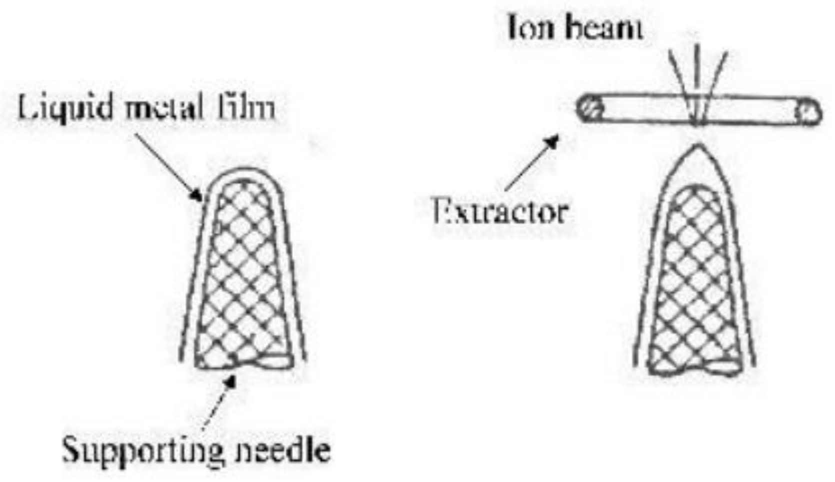
CUSP Field Thruster
Field Emission EP
Electrospray (Colloid) Thruster
MPD Thruster
Pulsed Plasma Thruster
Magnetic Nozzle Thruster

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?

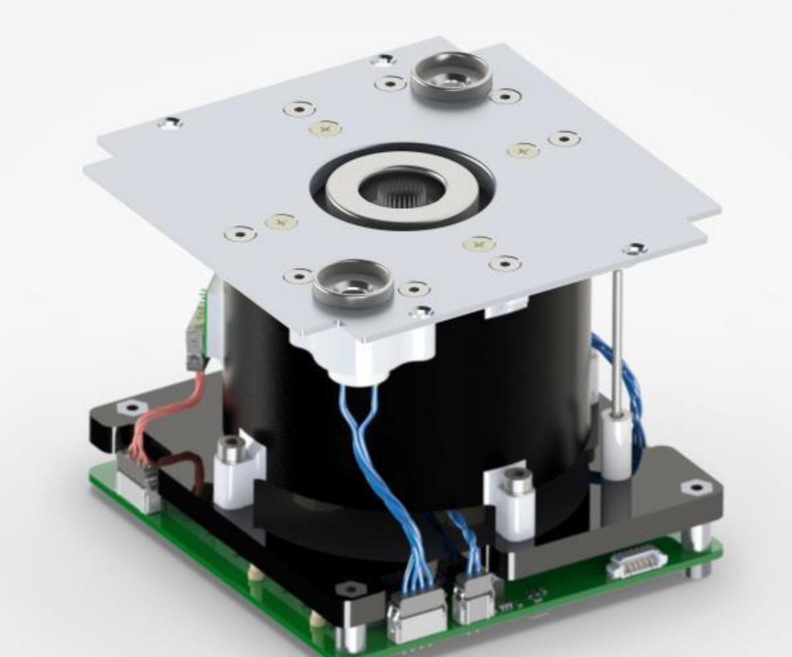


Electrostatic Propulsion System:

- 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:



IFM nano thruster by ENPULSION

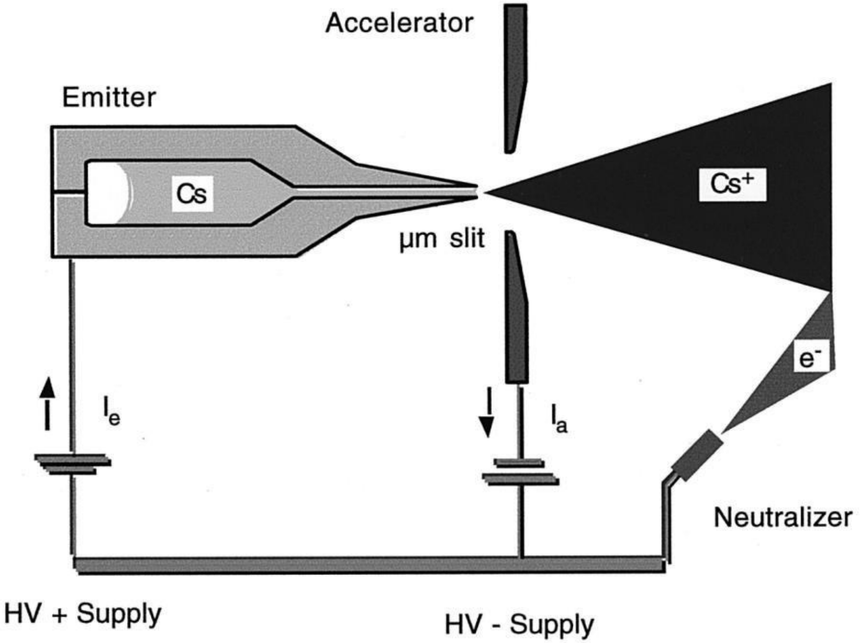


FIGURE 6 Schematic of a field emission electric propulsion

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?

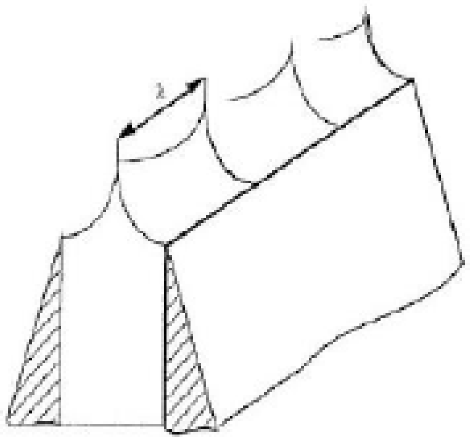
Electrostatic Propulsion System:

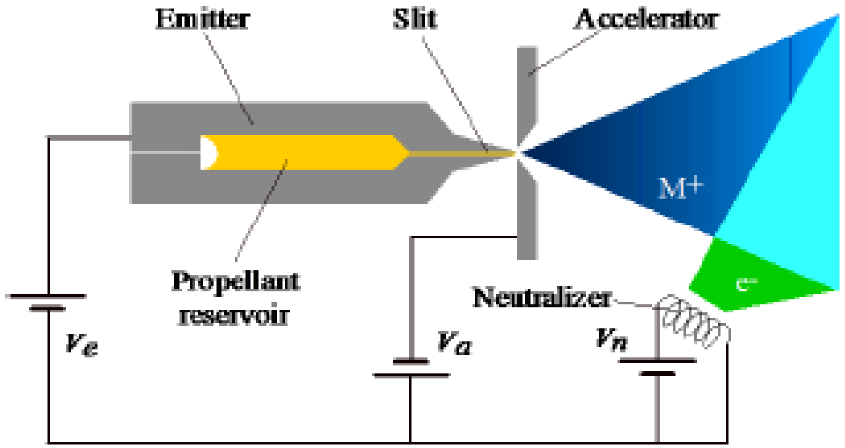
- Field Emission Electric Propulsion
  - Single needle can provide thrust levels up to around 10 µN
    - Above this level ion current is so large that emission geometry is disrupted, and droplets are emitted at lower efficiency
  - 2 main developments aimed at increasing thrust level up to > 100 µN:
    - 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

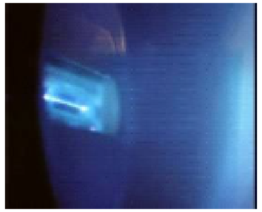
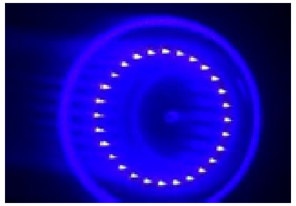


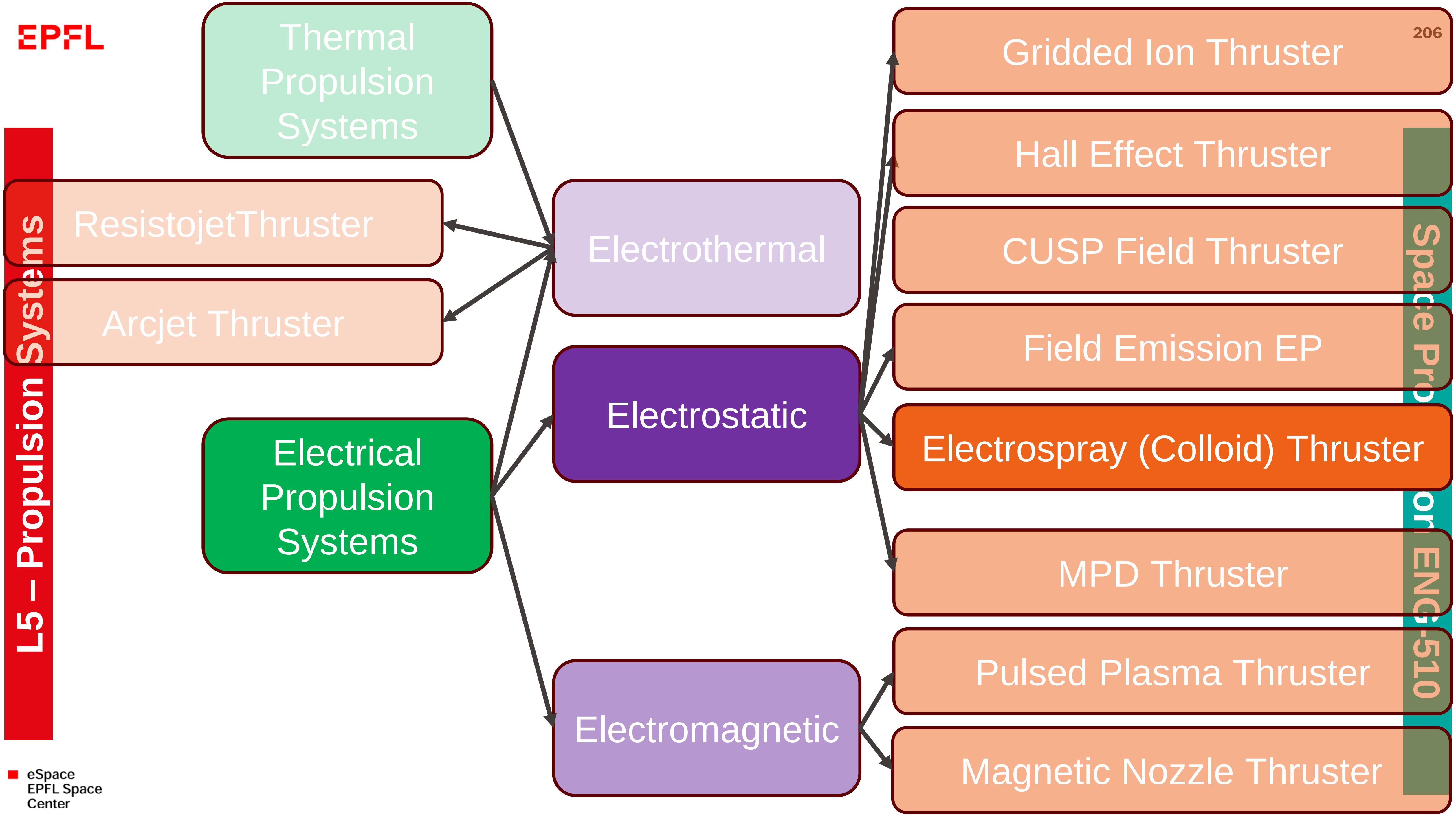


Which Electrical Propulsion Systems exist?

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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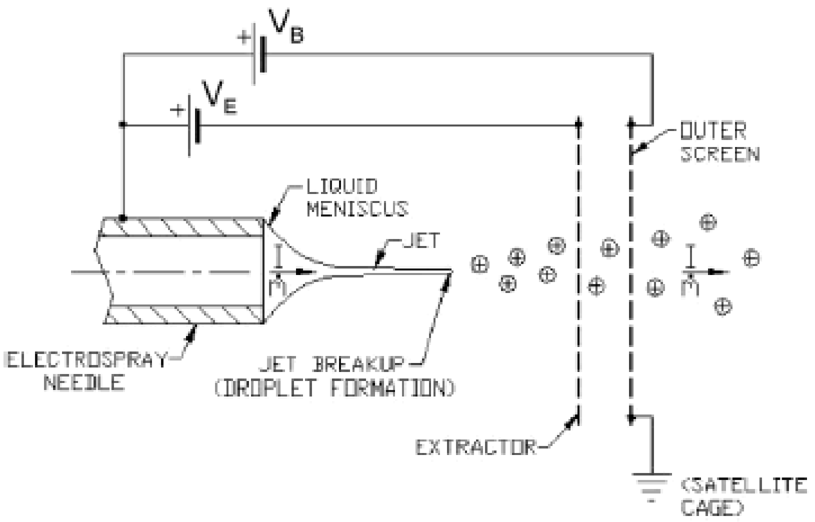
Magnetic Nozzle Thruster

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

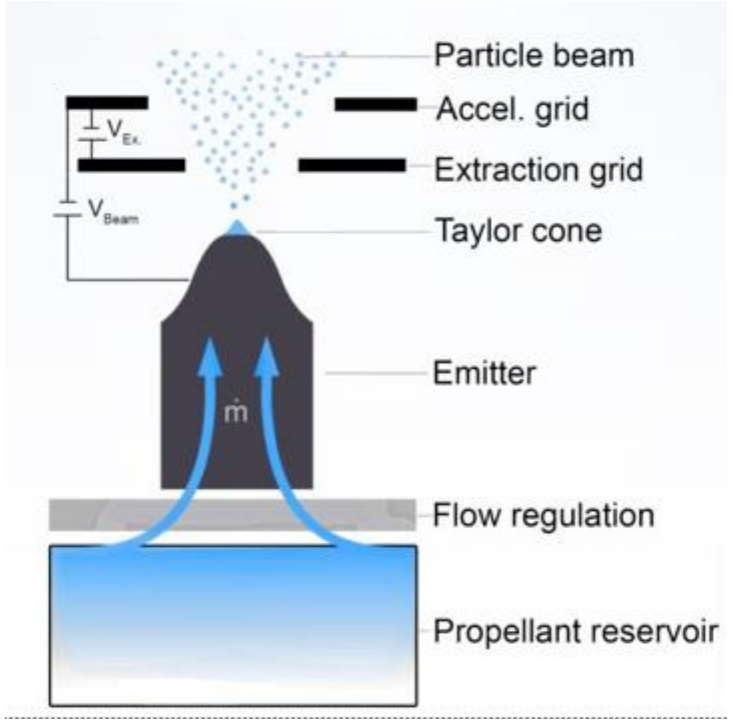
Which Electrical Propulsion Systems exist?



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:

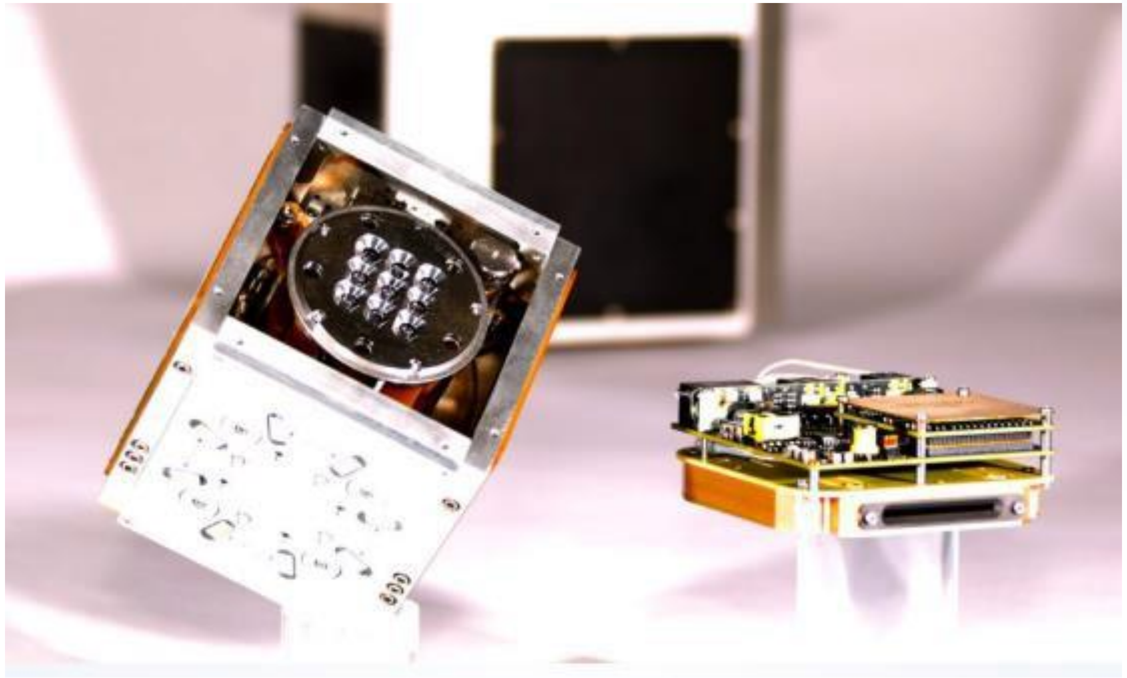
- Electrospray Thruster
  - Single needle can provide only a few μN
    - Array of needles used to provide higher thrust levels
  - Thrust controlled by acceleration voltage and / or propellant flow rate
    - Propellant feed is typically at constant pressure
  - Beam voltages up to 10 kV
  - Typical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

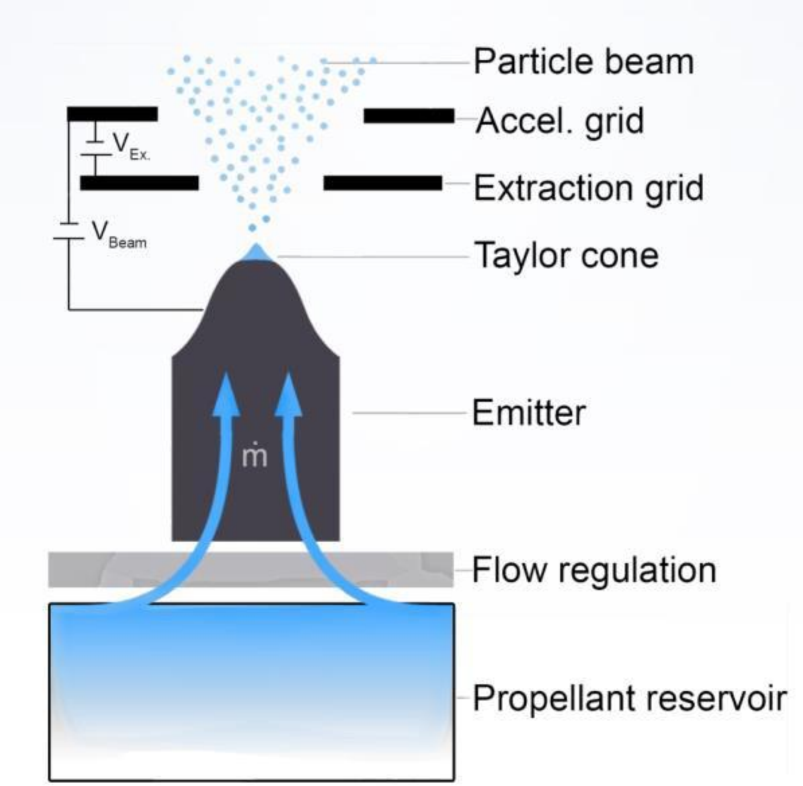
Requirement	Performance
Thrust range	4.5 to 35 μN
Thrust resolution	<0.1 μN
Thrust noise	<0.1 μN/√Hz
Specific Impulse	500 to 1500 s
Power at 35 μN	1.75 W

Which Electrical Propulsion Systems exist?

Electrostatic Propulsion System:

- Electrospray Thruster





EPFL

Back-up

Brief overview on all space propulsion systems