



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Nuovi materiali e nuove tecniche di propulsione tra meccanica e spazio

Teaching Hub – 11 Aprile 2025



Department of industrial engineering

Alma Propulsion Laboratory

Topics:

- About propulsion
- Plasma Thrusters simulation and modeling
- BOOST project
- Aerospike simulation and geometry optimization
- Aeronautical engine modeling and testing
- Solid Rocket Booster performance evaluation

People:

- Fabrizio Ponti – Full Professor
- Enrico Corti – Associate Professor
- Vittorio Ravaglioli – Associate Professor
- Giacomo Silvagni - Researcher
- Nabil Souhair – Research Fellow
- Antonella Caldarelli– Post-doc
- Lorenzo Suozzi– PhD Candidate
- Raoul Andriulli – PhD Candidate
- Francesco Felicioni – PhD Candidate
- Mattia Magnani– PhD Candidate



Chemical Propulsion

Chemical

Power: up to 50 GW

Exit speed: up to 4.5 km/s

Mass flow rate: up to 10000 kg/s

Thrust: 15000 kN

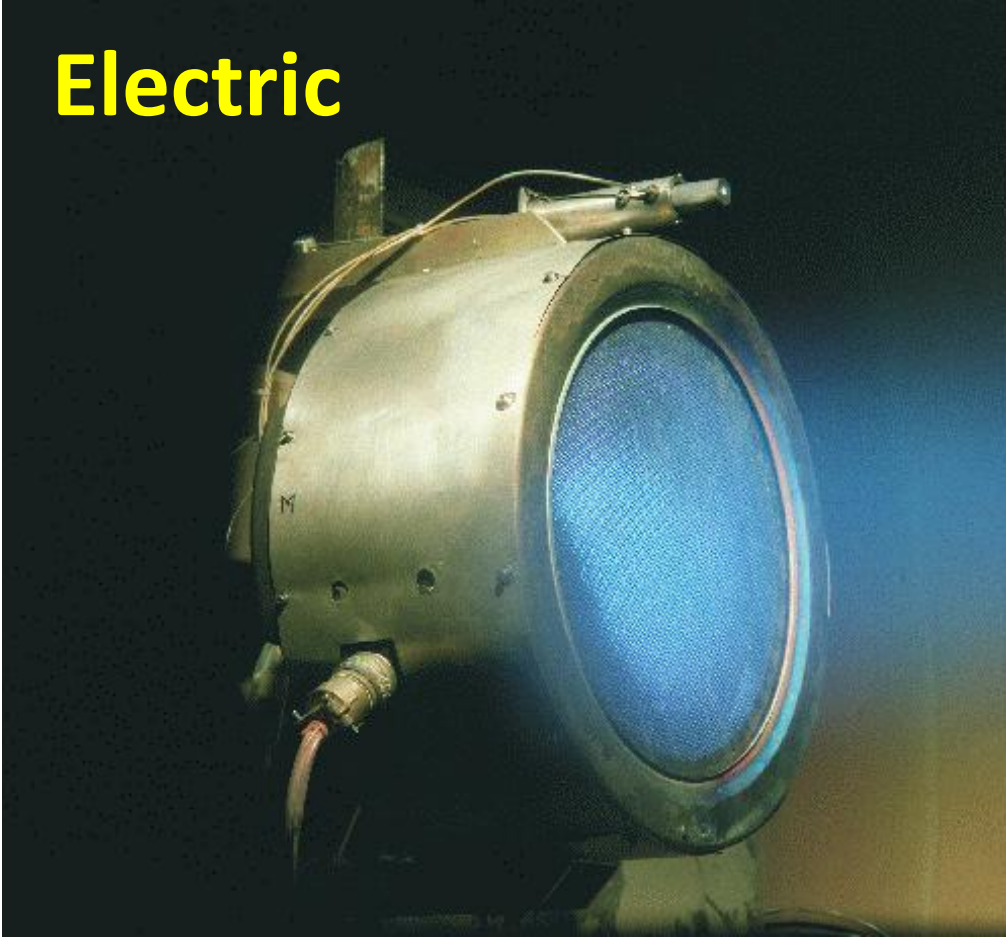


Energy conversion is efficient if the exhaust is composed by light molecules

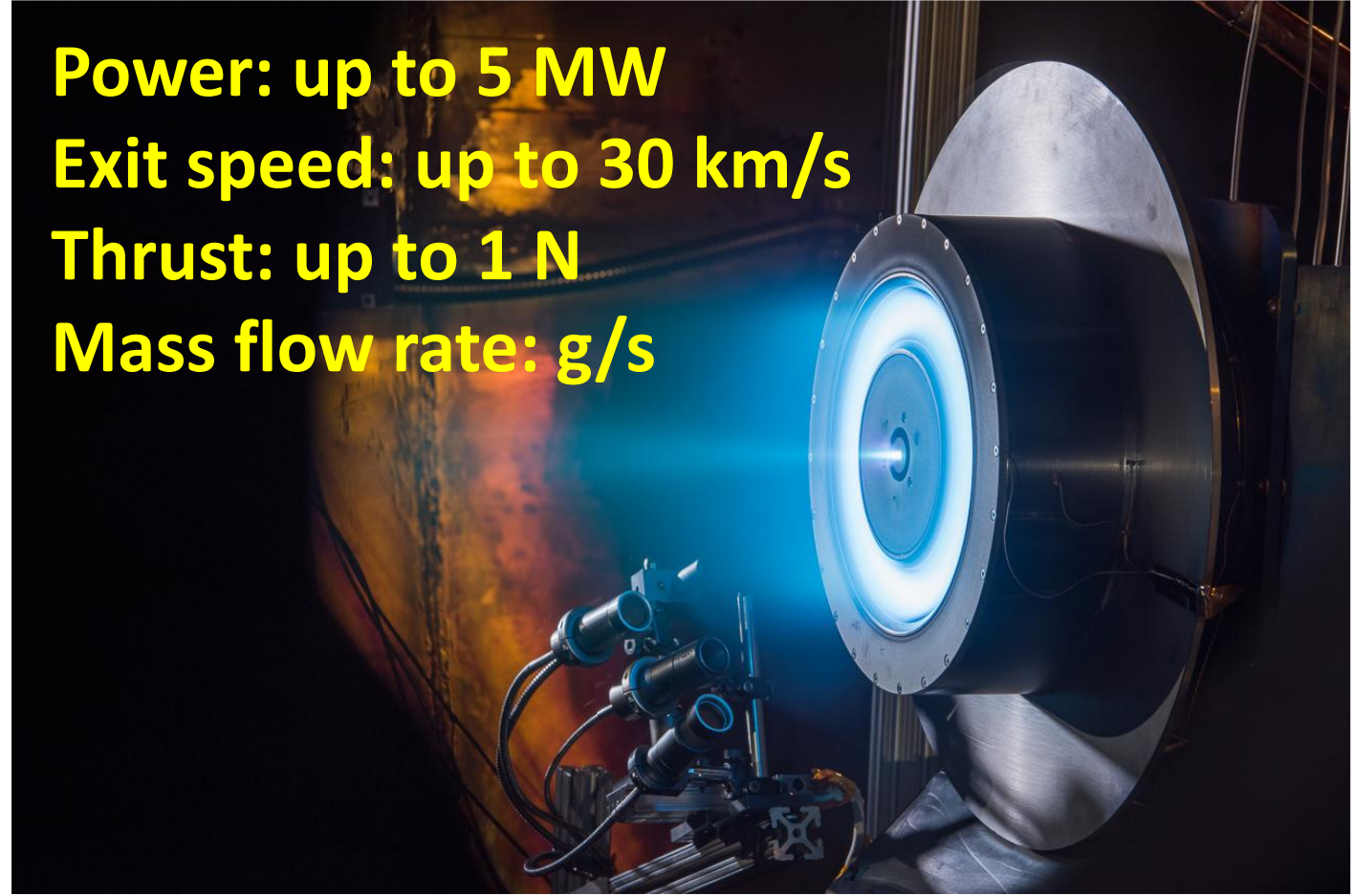


Electric Propulsion

Electric



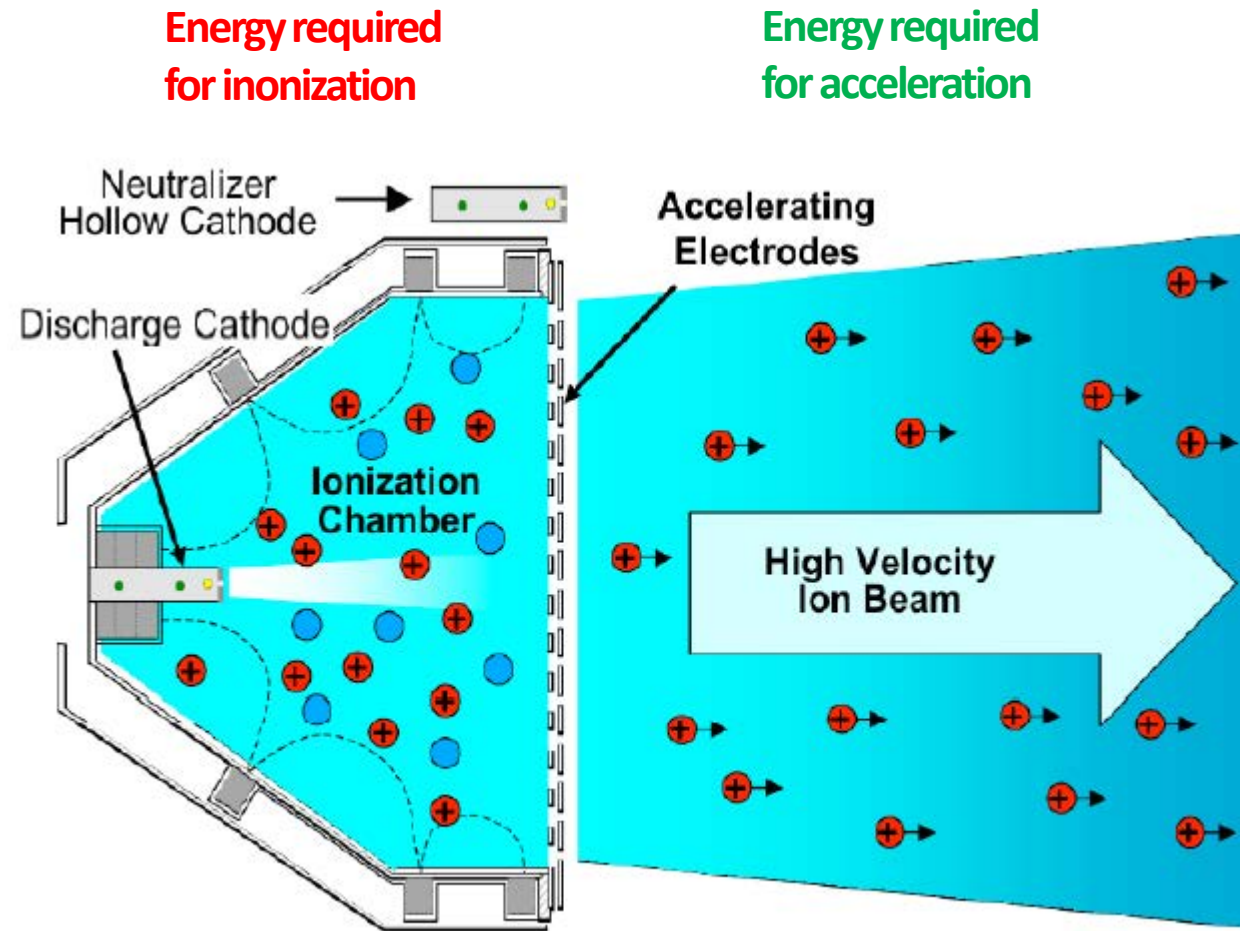
Power: up to 5 MW
Exit speed: up to 30 km/s
Thrust: up to 1 N
Mass flow rate: g/s



Energy conversion is efficient if the exhaust is composed by heavy atoms



Electric Propulsion



Main limitation is the maximum power available

Simulation strategy for Helicon Plasma Thrusters

PRODUCTION STAGE (3D-VIRTUS):

- EM module (ADAMANT) coupled with FLUID module (OpenFoam)
- Iterative convergence

ACCELERATION STAGE:

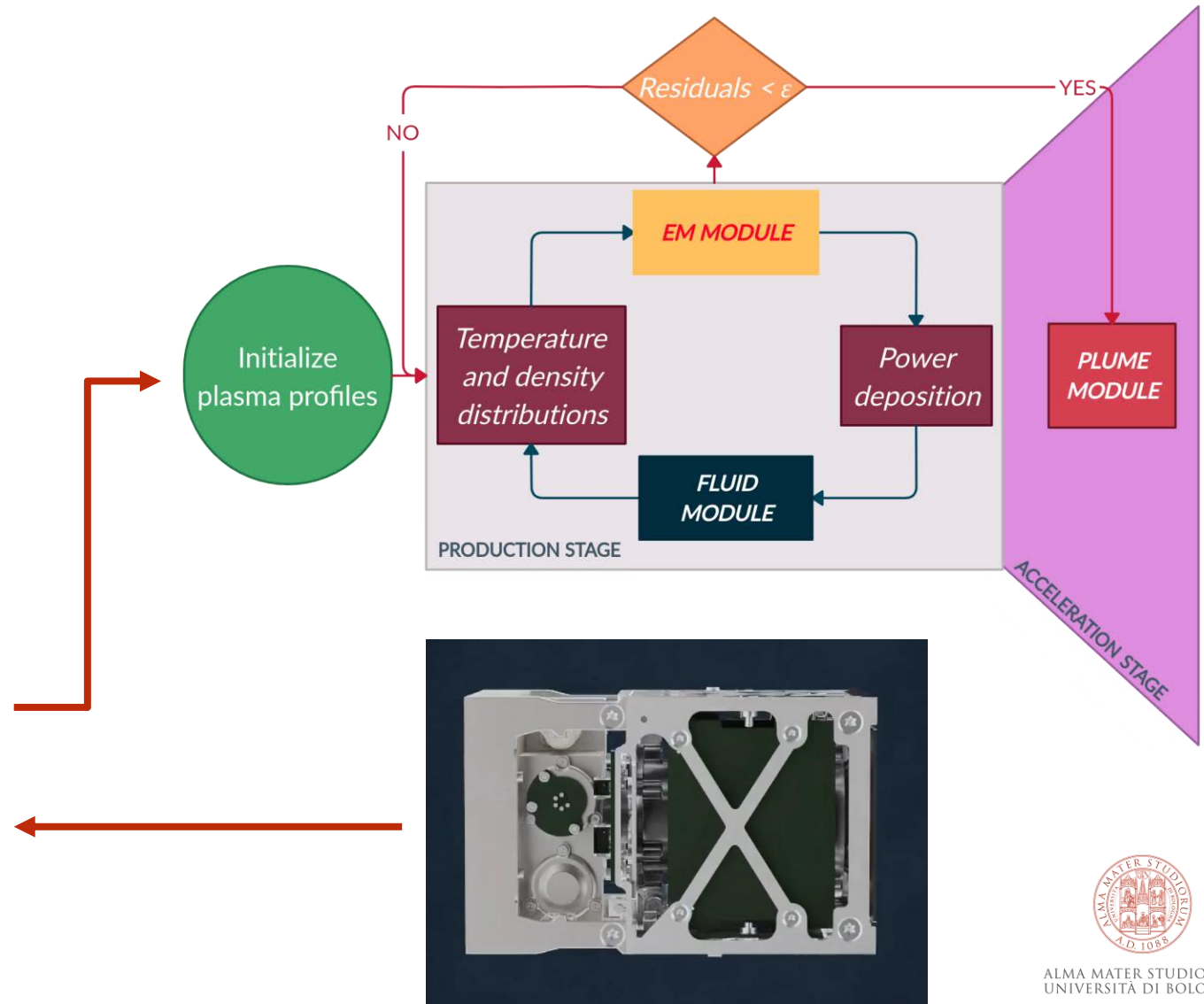
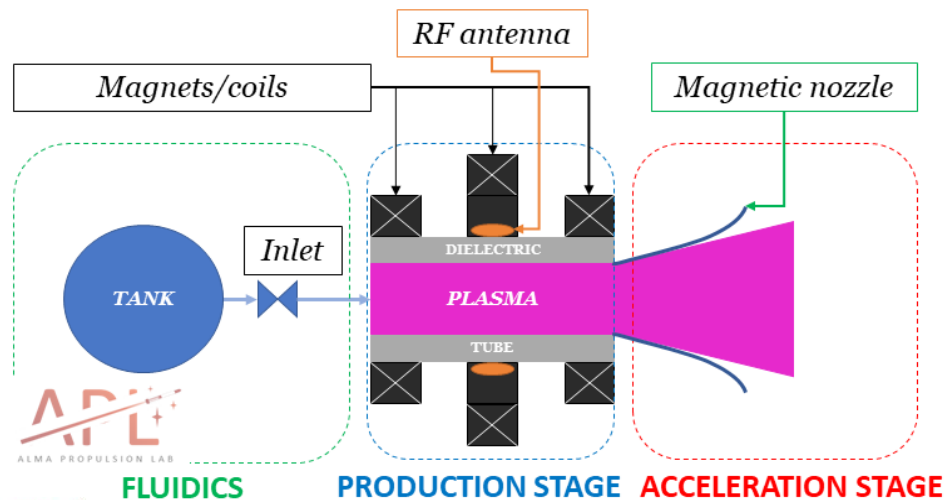
- Analytical PLUME model [Lafleur 2011]
- PIC 2D (STARFISH)
- PIC 3D (PROPIC)

COUPLING STRATEGY:

- MUPETS (integration of Fluid Model and PIC)

HYBRID MODELING:

- Development of a Hybrid Model (Fluid-PIC)



Satellite life

(and increasing number of satellites)



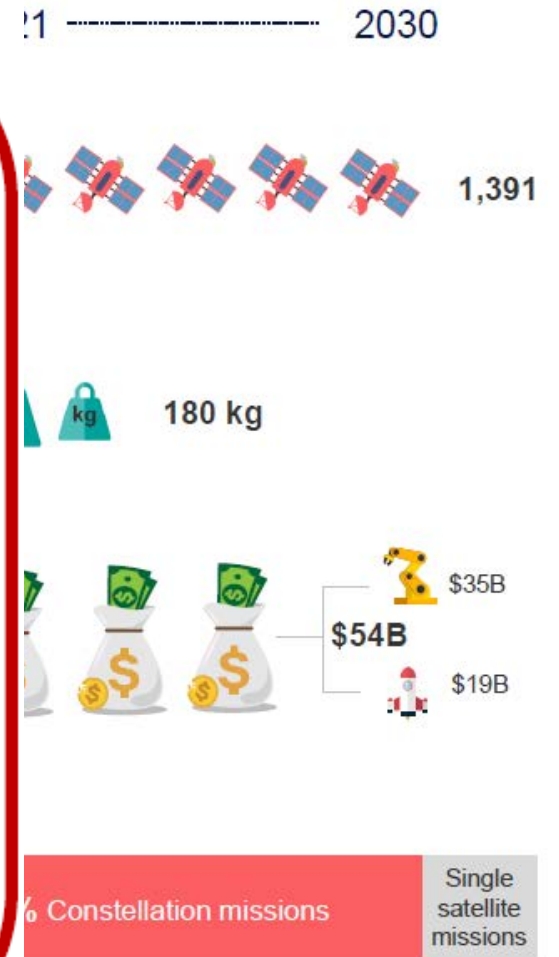
End-of-Life Disposal

According to international standards, CubeSats shall re-enter within 25 years from launch.



De-orbiting from above 2000 km might be required.

- Δv up to 400 m/s
- CubeSats larger than 12U are going to enter the market



The periodic table

PERIODIC TABLE OF THE ELEMENTS

Too light

Radioactive or synthetic

1 H 1.0079 HYDROGEN																	2 He 4.0026 HELIUM						
3 Li 6.941 LITHIUM	4 Be 9.0122 BERYLLIUM																	5 B 10.811 BORON	6 C 12.011 CARBON	7 N 14.007 NITROGEN	8 O 15.999 OXYGEN	9 F 18.998 FLUORINE	10 Ne 20.180 NEON
11 Na 22.990 SODIUM	12 Mg 24.305 MAGNESIUM																	13 Al 26.982 ALUMINUM	14 Si 28.086 SILICON	15 P 30.974 PHOSPHORUS	16 S 32.065 SULFUR	17 Cl 35.453 CHLORINE	18 Ar 39.948 ARGON
19 K 39.098 POTASSIUM	20 Ca 40.078 CALCIUM	21 Sc 44.956 SCANDIUM	22 Ti 47.867 TITANIUM	23 V 50.942 VANADIUM	24 Cr 51.996 CHROMIUM	25 Mn 54.938 MANGANESE	26 Fe 55.845 IRON	27 Co 58.933 COBALT	28 Ni 58.693 NICKEL	29 Cu 63.546 COPPER	30 Zn 65.38 ZINC	31 Ga 69.723 GALLIUM	32 Ge 72.64 GERMANIUM	33 As 74.922 ARSENIC	34 Se 78.96 SELENIUM	35 Br 79.904 BROMINE	36 Kr 83.798 KRYPTON						
37 Rb 85.468 RUBIDIUM	38 Sr 87.62 STRONTIUM	39 Y 88.906 YTRIUM	40 Zr 91.224 ZIRCONIUM	41 Nb 92.906 NIOBIUM	42 Mo 95.96 MOLYBDENUM	43 Tc 98 TECHNETIUM	44 Ru 101.07 RUTHENIUM	45 Rh 102.91 RHODIUM	46 Pd 106.42 PALLADIUM	47 Ag 107.87 SILVER	48 Cd 112.41 CADMIUM	49 In 114.82 INDIUM	50 Sn 118.71 TIN	51 Sb 121.76 ANTIMONY	52 Te 127.6 TELLURIUM	53 I 126.9 IODINE	54 Xe 131.29 XENON						
55 Cs 132.91 CAESIUM	56 Ba 137.33 BARIUM	57-71 Lanthanide	72 Hf 178.49 HAFNIUM	73 Ta 180.95 TANTALUM	74 W 183.84 TUNGSTEN	75 Re 186.21 RHENIUM	76 Os 190.23 OSMIUM	77 Ir 192.22 IRIDIUM	78 Pt 195.08 PLATINUM	79 Au 196.97 GOLD	80 Hg 200.59 MERCURY	81 Tl 204.38 THALLIUM	82 Pb 207.20 LEAD	83 Bi 208.98 BISMUTH	84 Po 209 POLONIUM	85 At 210 ASTATINE	86 Rn 222 RADON						
87 Fr 223 FRANCIUM	88 Ra 226 RADIUM	89-103 Actinide	104 Rf 261 RUTHERFORDIUM	105 Db 262 DUBNIUM	106 Sg 266 SEABORGIUM	107 Bh 264 BOHRHIUM	108 Hs 277 HASSIUM	109 Mt 268 MEITNERIUM	110 Ds 285 DARMSTADTIUM	111 Rg 281 ROENTGENIUM	112 Cn 285 COPECNICIUM	113 Uut 284 UNUNTRIUM	114 Fl 289 FLEROVIUM	115 Uup 288 UNUNPENTIUM	116 Lv 293 LIVERTONIUM	117 Uus 294 UNUNSEPTIUM	118 Uuo 294 UNUNOCTIUM						
			57 La 138.91 LANTHANUM	58 Ce 140.12 CELESIUM	59 Pr 140.91 PRASEODYMIUM	60 Nd 144.24 NEODYMIUM	61 Pm 145 PROMETHIUM	62 Sm 150.36 SAMARIUM	63 Eu 151.96 EUROPEUM	64 Gd 157.25 GADOLINIUM	65 Tb 158.93 TERBIUM	66 Dy 162.50 DYSprosIUM	67 Ho 164.93 HOLMIUM	68 Er 167.26 ERBIUM	69 Tm 168.93 THULIUM	70 Yb 173.05 YTERBIUM	71 Lu 174.97 LUTETIUM						
			89 Ac 227 ACTINIUM	90 Th 232.04 THORIUM	91 Pa 231.04 PROTACTINIUM	92 U 238.03 URANIUM	93 Np 237.05 NEPTUNIUM	94 Pu 239.05 PLUTONIUM	95 Am 243.06 AMERICIUM	96 Cm 247.07 CURIUM	97 Bk 247.07 BERKELEIUM	98 Cf 251.08 CALIFORNIUM	99 Es 252.08 EINSTEINIUM	100 Fm 257.10 FERMIUM	101 Md 258.10 MEITNERIUM	102 No 259.10 NOBELIUM	103 Lr 262.10 LAWRENCIUM						

Legend:

- Alkali metal
- Alkaline earth metal
- Metal
- Transition metal
- Lanthanide
- Metalloid
- Non-metal
- Halogen
- Noble gas
- Actinide

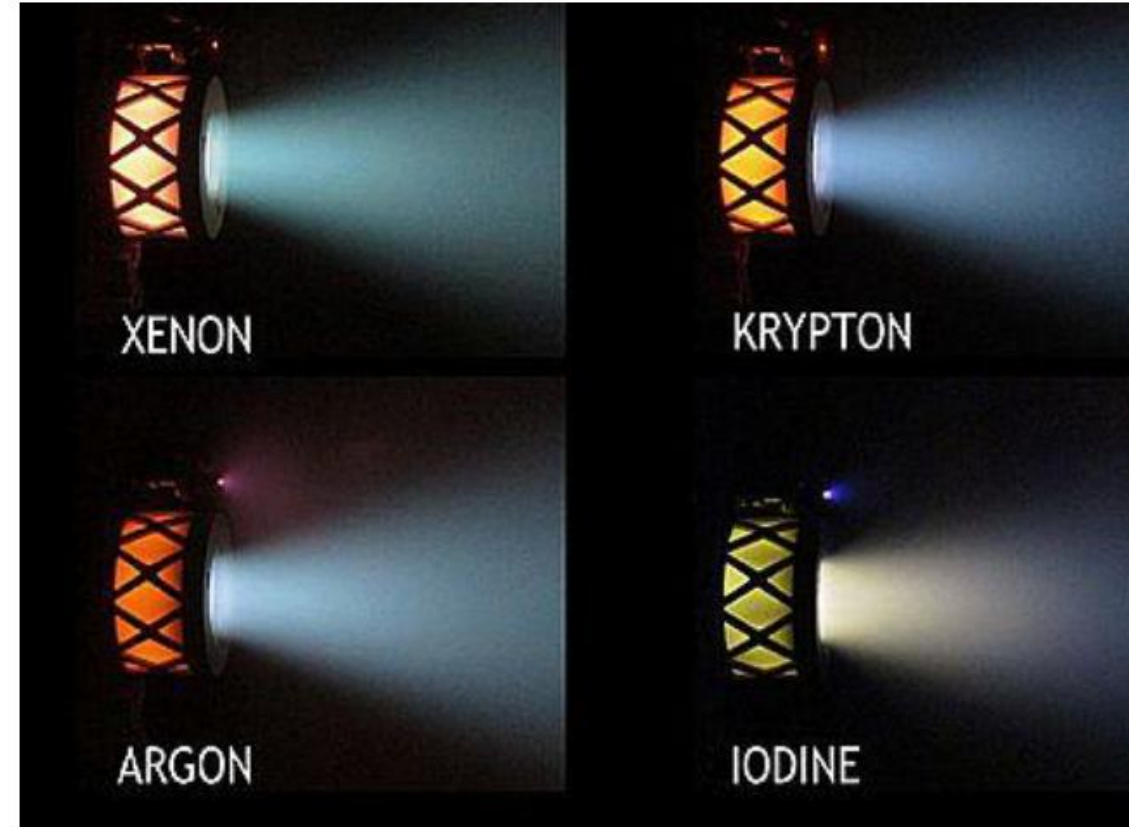
Callout for Boron (B):

Atomic number: 5
Atomic mass: 10.811
Name: BORON
Symbol: B

Propellant choice (1)

Properties of a good propellant for plasma-based systems are related to

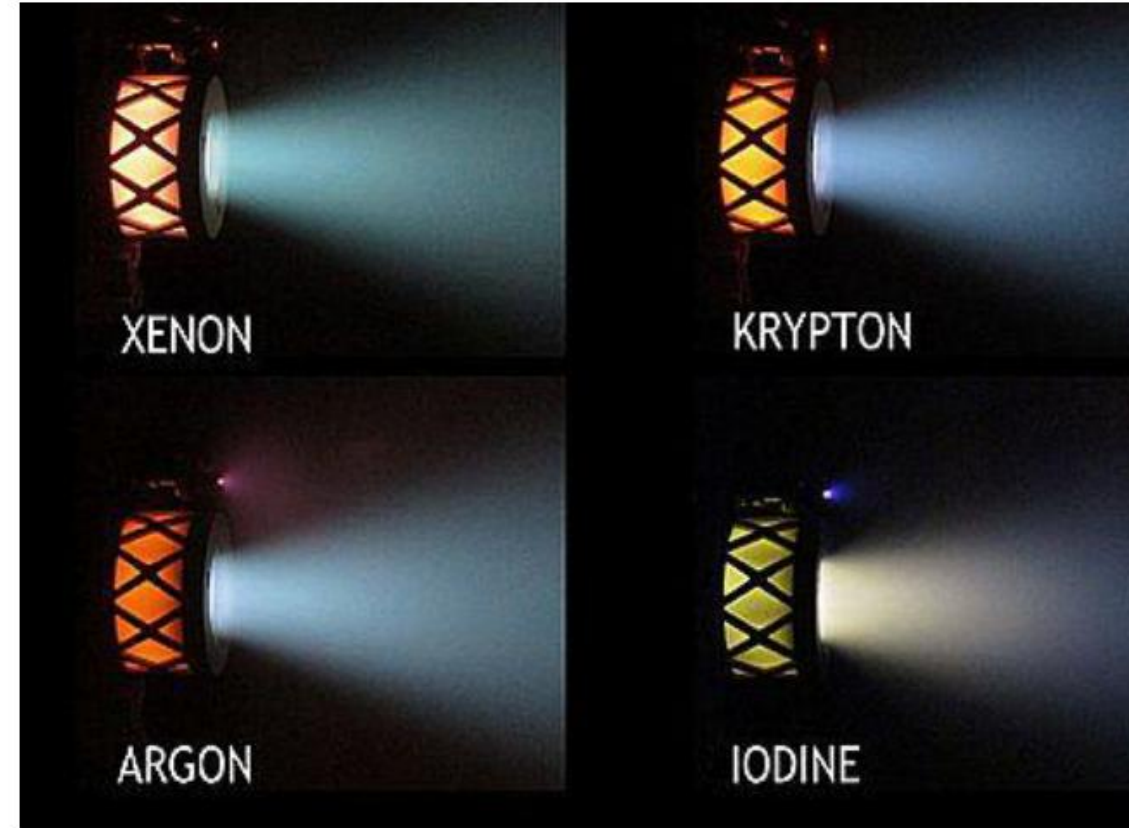
- **Physical** considerations
 - Appropriate molecular weight
 - Low ionization and dissociation (if a molecular compound) energies
- **Practical** considerations
 - Easily storable
 - Non-corrosive and non-condensable
 - Non-toxic



Propellant choice (2)

Solid and **liquid** propellants in respect to classical gaseous solutions have

- **Pros**
 - Can be stored in non-pressurized tanks (mandatory for secondary payloads)
 - Higher density than gases
- **Cons**
 - Higher power budget for phase transition
 - Accurate thermal and chemical design to avoid condensation and corrosion



Propellant choice (3)

	Xe		Kr		I ₂	
Cost [\$ / kg]	1000		100		100	
Tank pressure [bar]	200-300		200-300		0	
Condensable						
Corrosive						
Performance						

Refuelling mission – Scenarios

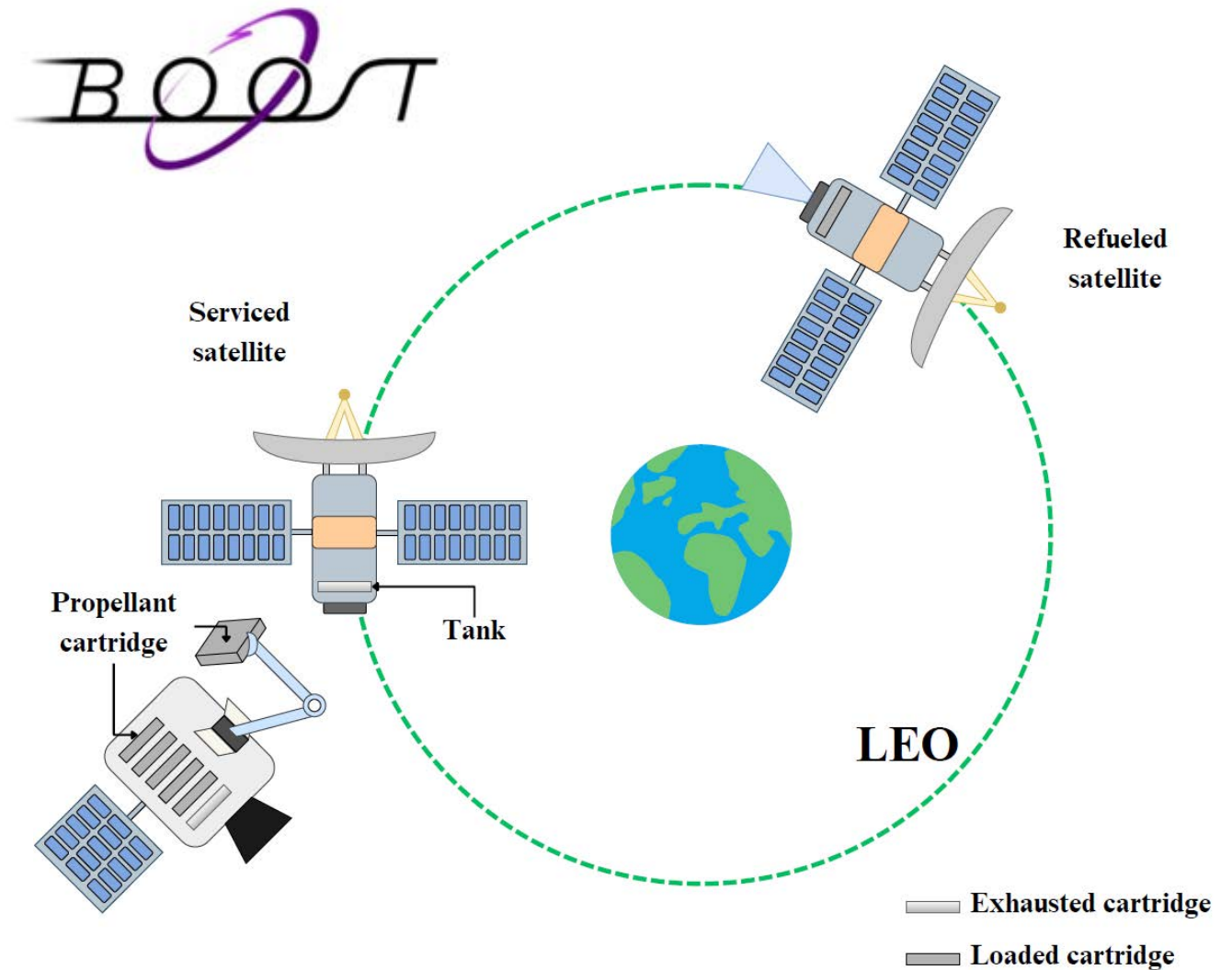
The following scenarios are being taken into account for the refuelling missions:

- Refuelling of a single satellite
- Refuelling of a constellation
- Servicer able to refuel more targets
- Storage set in a suitable point to be reached by targets

The economic feasibility takes into account the manoeuvres need to dock.

The output of the mission analysis will be a set of suitable scenarios/orbits that will benefit the most from refuelling operations.

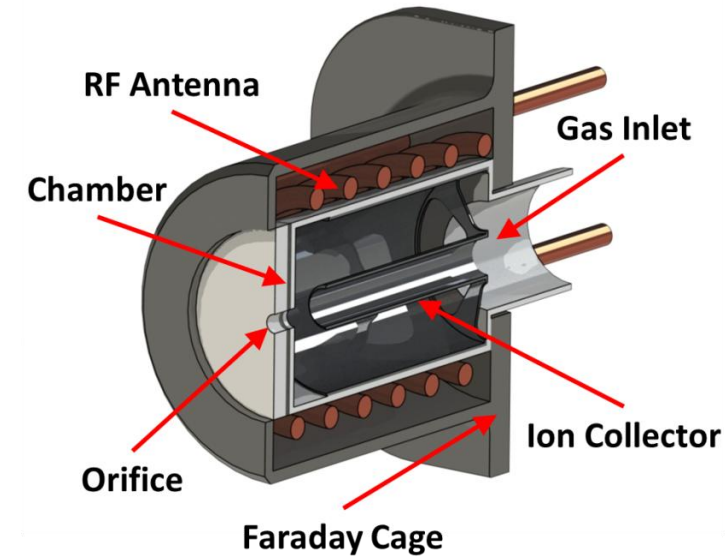
The output will become a set of target values to be used for the definition and design of the building blocks.



BOOST – Specific Objective 1

Development of a RF cathode to improve the thruster's neutralization capabilities

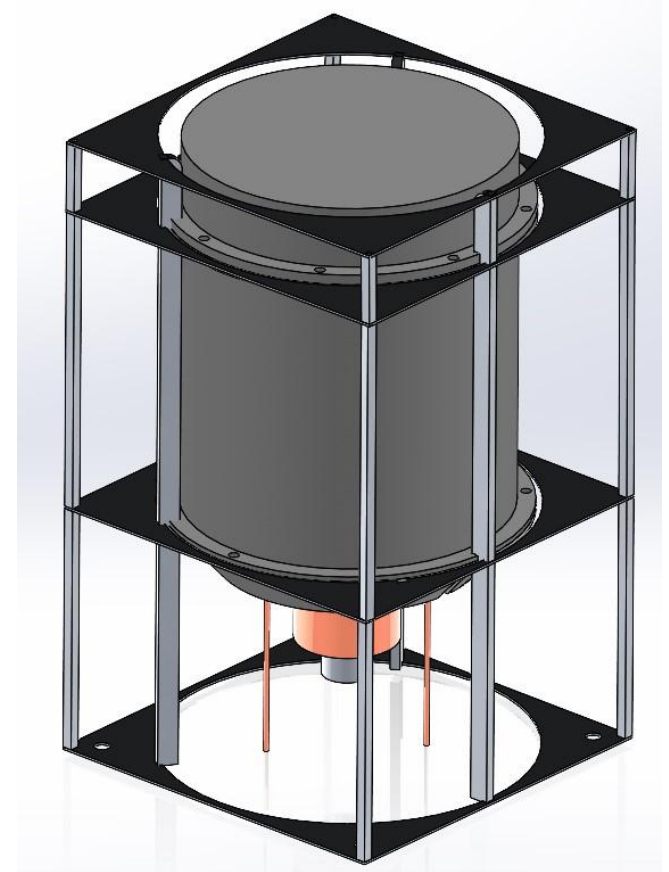
- RF cathode **propelled with iodine**.
 - **Numerical analysis** and **experimental characterization** to deepen the physical understanding of the plasma dynamics in a RF cathode.
 - **Scale the cathode** at a generic current rate.
 - Analysis and definition of the **thermal, mechanical and electrical interfaces**. Realize a **building-block** applicable on a generic concept of electric thruster.
 - **Lower contamination and erosion** compared to other types of cathodes.
- **KPI-1**: Neutralization current ≥ 100 mA.
 - **KPI-2**: Scaled design for increased current applications.



BOOST – Specific Objective 2

Development of a smart propellant storage system compatible with future mission of on-orbit-refueling

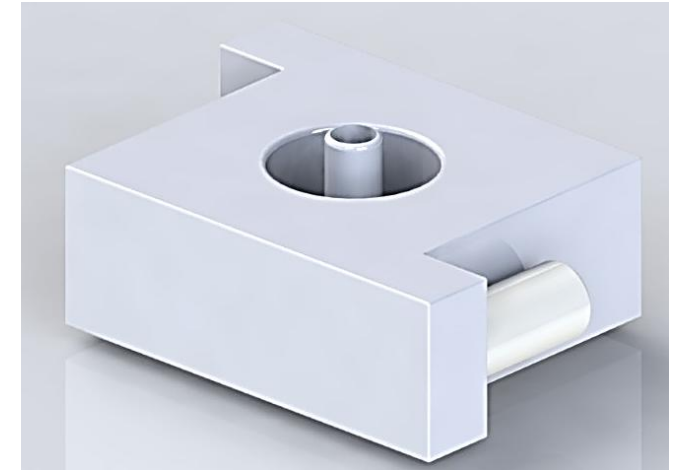
- **Tank** filled with **solid iodine cartridges**.
- The storage system will consist of
 - the **tank**,
 - the **electro-thermo-mechanical interfaces** with the thruster's fluidic subsystem,
 - the **propellant cartridge**.
- A **mission analysis**, performed by ASTOS based on satellite platforms defined by TYVAK, will provide a proof-of-concept of the **on-orbit refueling concept** for various target satellites and constellations and will provide **sizing rules** for an economic concept.
 - **KPI-3**: Economic evaluation of on-orbit refueling.
 - **KPI-4**: Leak proof of the tank with cartridges.
 - **KPI-5**: Capability to vaporize at least 0.2 mg/s of iodine mass flow rate.



BOOST – Specific Objective 3

Improvement of an iodine compatible fluidic subsystem at TRL 6

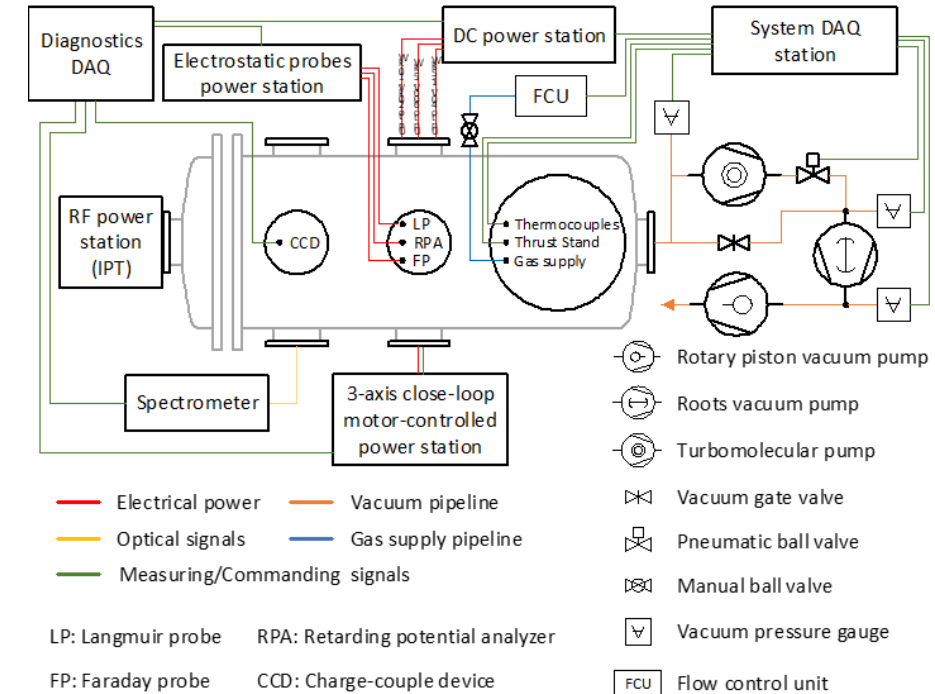
- Improvements targeted:
 - 1) Employment of **custom-made actuators** specifically designed to be used with gaseous iodine.
 - 2) Improvement of printability, repeatability, and cost effectiveness of **Additive Manufacturing (AM) processes** by means of an iterative design & manufacture process.
 - 3) **Reduction of fluidic system mass** by using advanced materials and surface treatments.
 - 4) **Optimization of the thermal paths** towards the mechanical interfaces.
- **KPI-6:** Mass reduction of the fluidic sub-system $\geq 10\%$.
 - **KPI-7:** Production of ≥ 2 pieces tested and validated to demonstrate mass production capabilities.



BOOST – Specific Objective 4

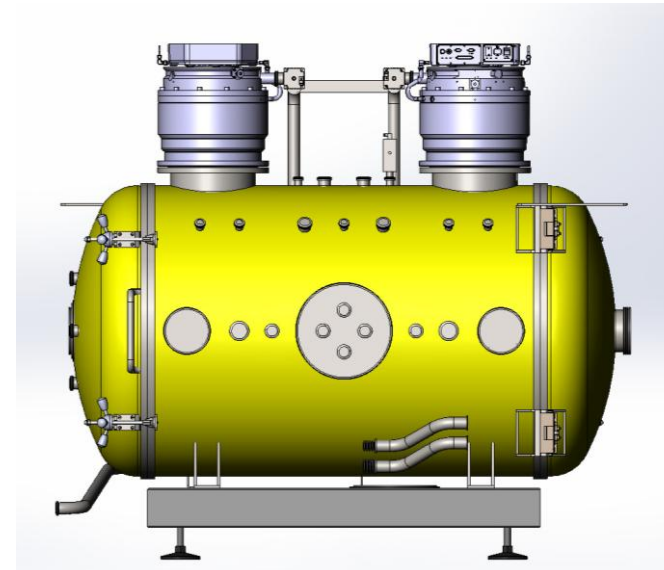
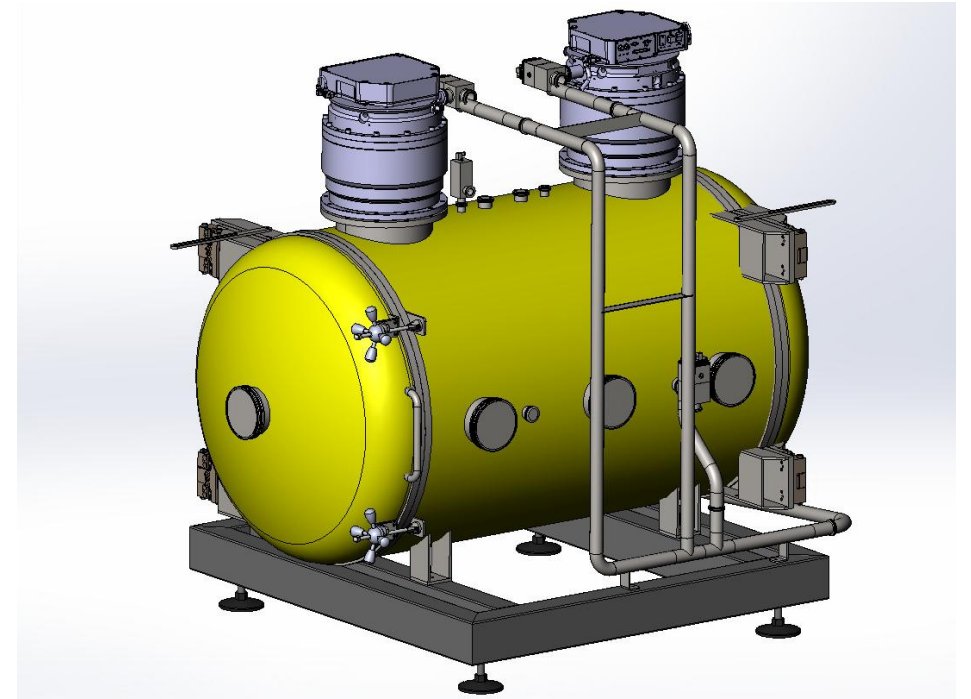
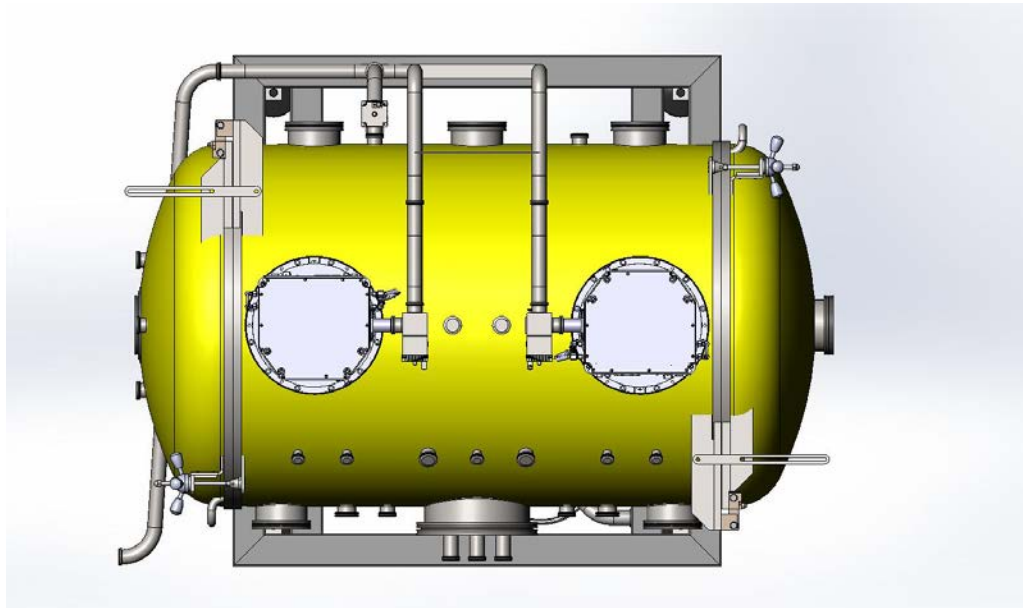
Adaptation of the testing facilities and diagnostic capabilities improvement

- USTUTT **facilities** will be adjusted to allow the operation of Iodine.
 - Vacuum pumps
 - Sealings
 - Instruments and materials (Langmuir Probes, Faraday Probes, back-vacuum Retarding Potential Analyzer, Laser Absorption Spectroscopy)
- CNRS will develop **dedicated diagnostic tools**
 - Laser Induced Fluorescence Spectroscopy to allow detection of singly charged ion velocity distribution function
 - Optical Emission Spectroscopy to observe ionic and molecular emission lines
- **KPI-8:** Iodine compatibility for the entire facility.
- **KPI-9:** Development of dedicated diagnostic tools compatible with iodine accompanied by an upgrade and an enhancement of existing tools (e.g. OES).
- **KPI-10:** Correlation of plasma plume and thrust measurements to reduce uncertainty below 5% in presence of RF disturbances.



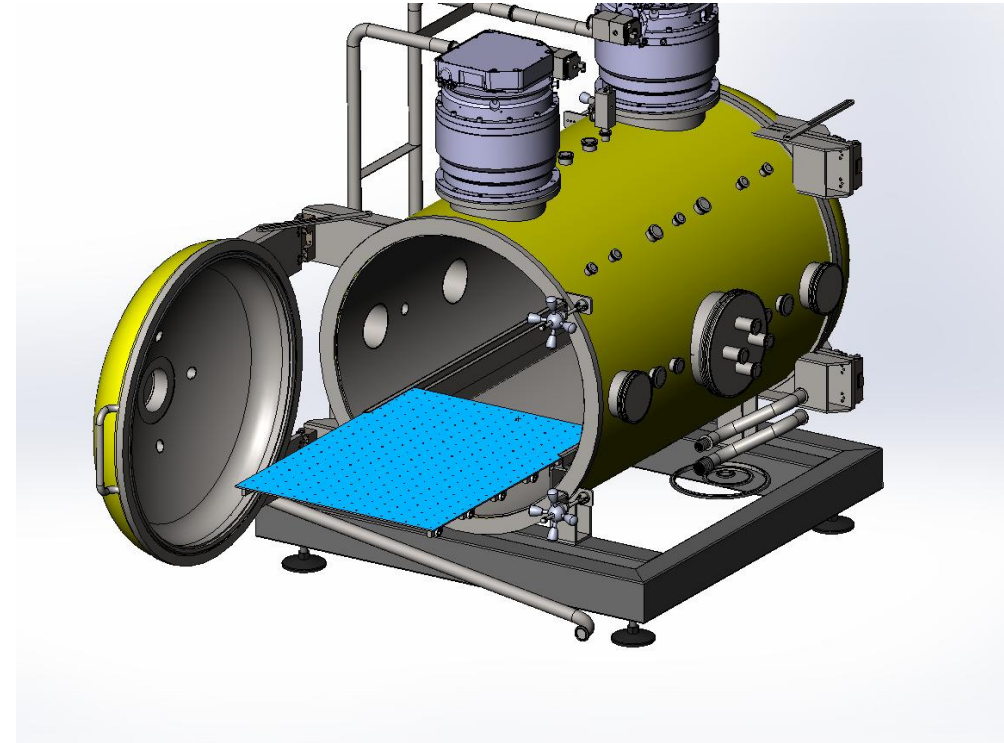
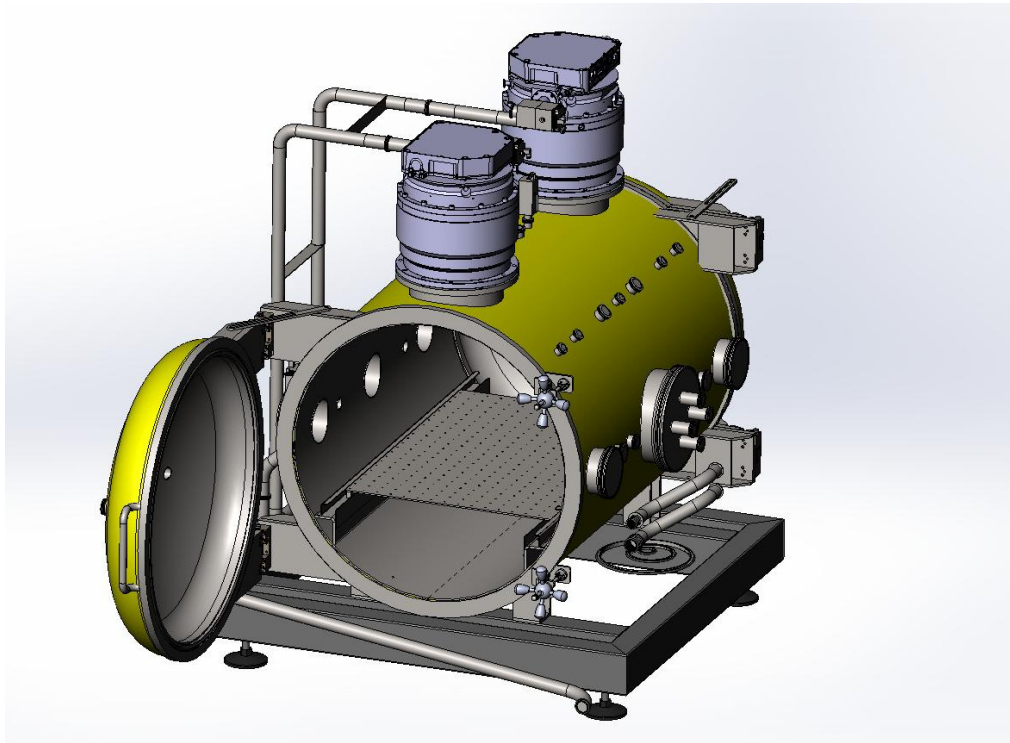
Vacuum chamber

- Custom-designed 2m long, 1m diameter stainless steel vacuum chamber manufactured by 5Pascal
- Pumping system allowing a base pressure of 10^{-6} mbar using a magnetically levitated 4,000 l/s turbo pump
- Initially equipped with only one turbo pump, but a second one can be mounted in a following stage

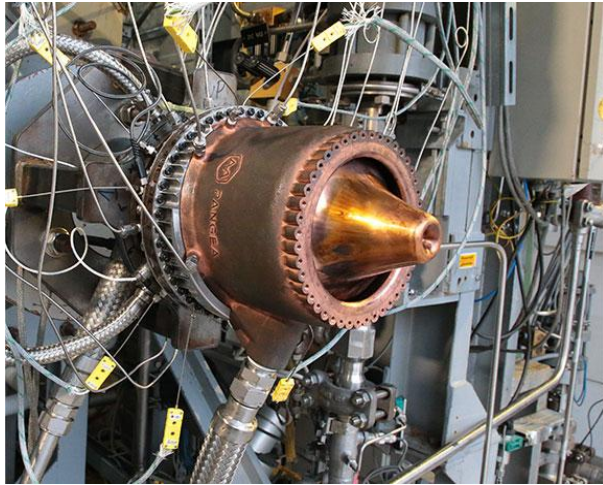


Vacuum chamber

- Safe testing of iodine will be achieved with the implementation of a heating system around the chamber
- An activated carbon vapor trap will be installed to suppress iodine dispersion in the chamber
- A stainless-steel railing system will allow easy mounting/dismounting operations of the cartridge/tank system
- Custom-made flanges and electrical feedthroughs to allow easy installation of power supplies and measuring equipment



Aerospike simulations and geometry optimization



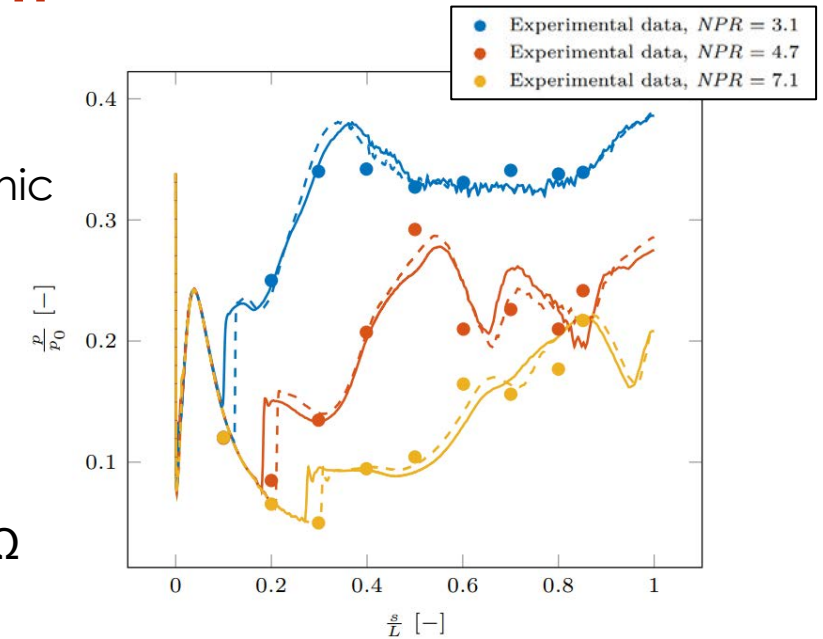
Pangea Aerospace , DemoP1 –
aerospike demonstrator additively
manufactured

openFOAM solver

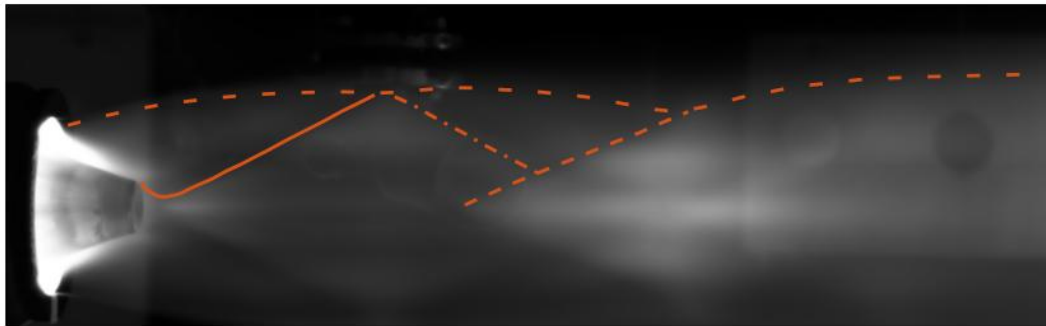
- Compressible viscous flow solver
- HLLC scheme designed for supersonic flow
- $k-\Omega$ SST turbulence model
- Open source

Solver validation

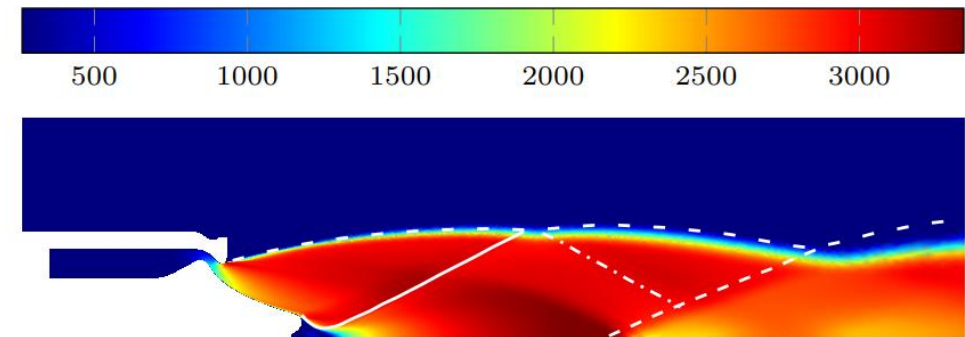
- Experimental data at different NPR
- Solver tested changing the base $k-\Omega$ SST parameters



DemoP1 experimental data and simulation



PANGAEATM
AEROSPACE



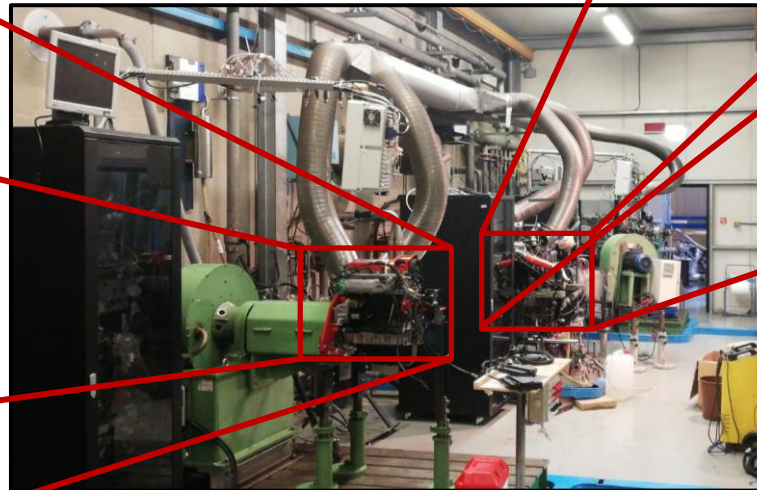
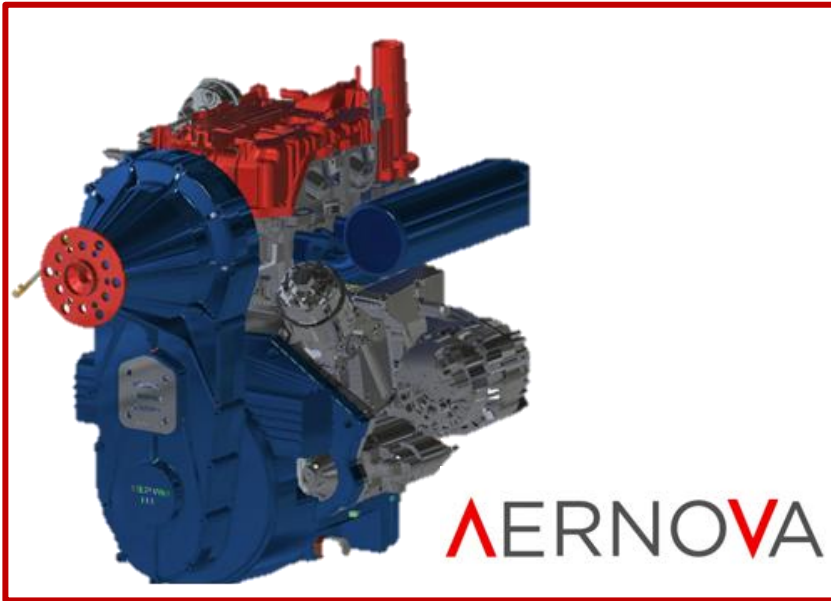
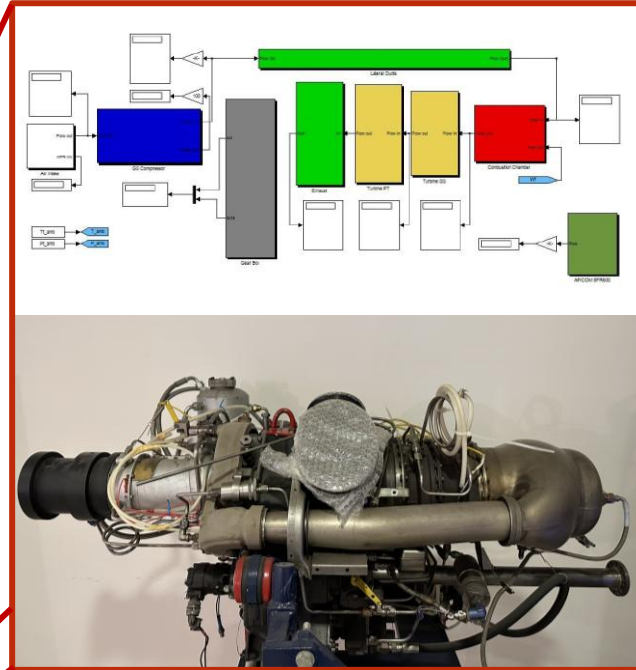
Internal Combustion Engine and Gas Turbine testing facilities

Aeronautical engines:

- Gas turbine characterisation and conversion for hydrogen
- Fuel-cell application for helicopter and aircrafts

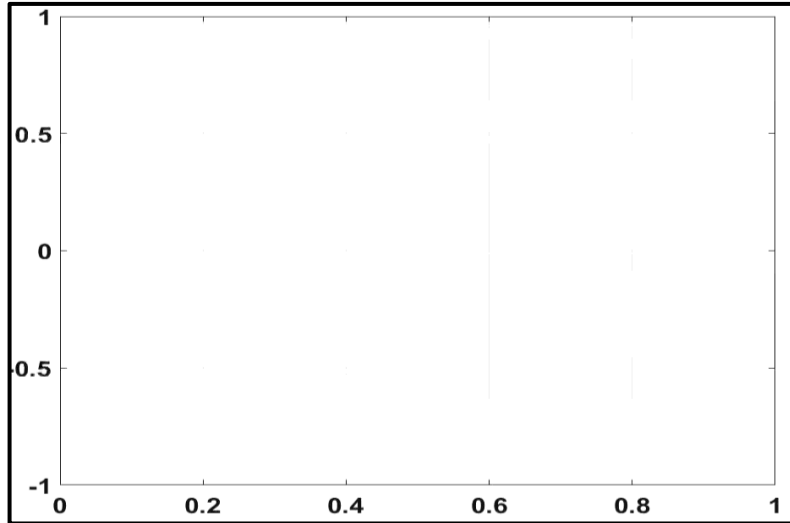
Piston engines activities:

- Calibration of piston engines for aeronautic application
- Control strategies development based on in-cylinder pressure measurement

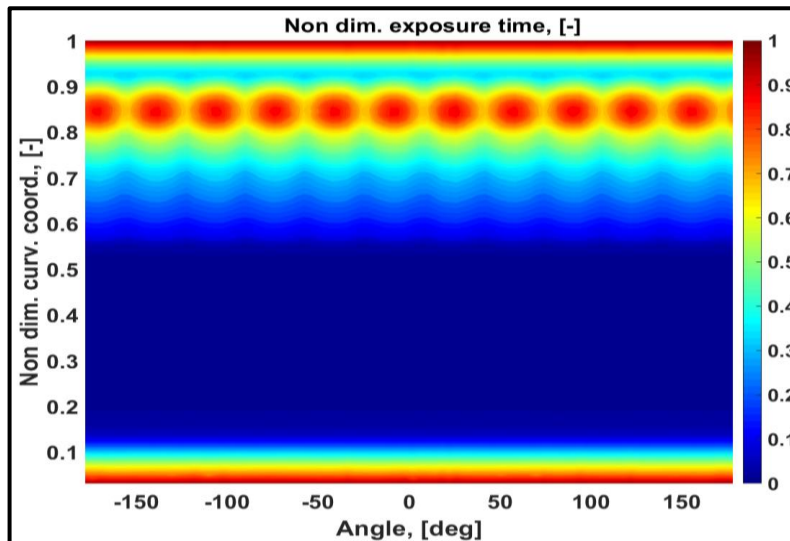


ROcket BOOst Simulation Tool – ROBOOST (1)

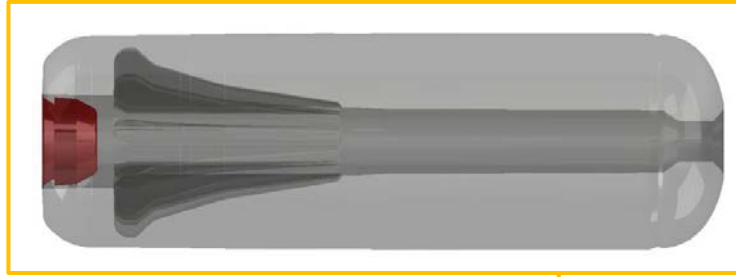
1D Internal ballistics computation



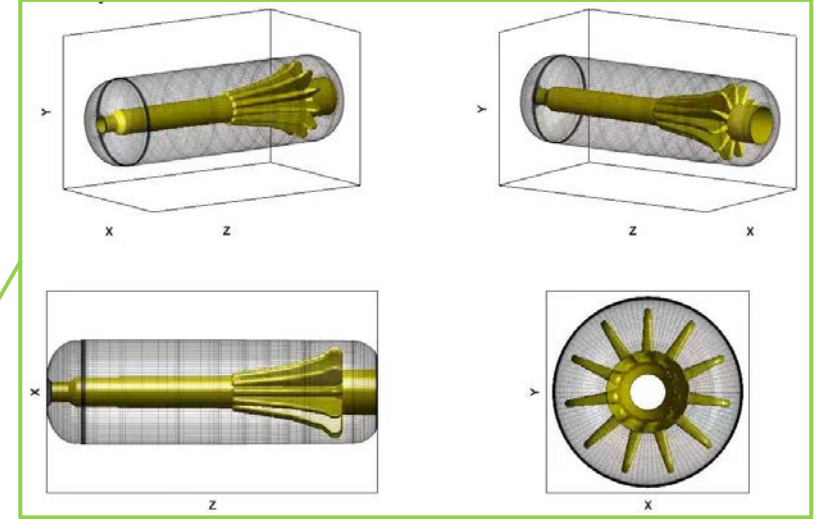
Thermal protection exposure



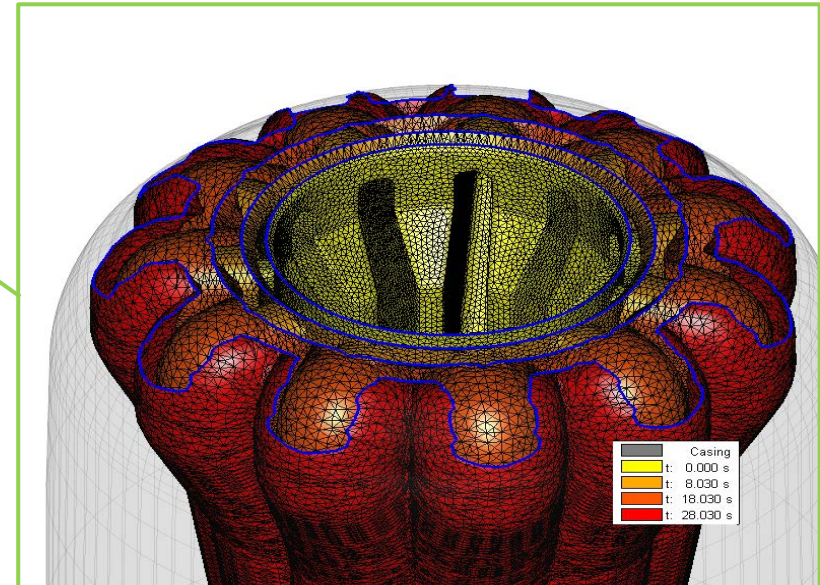
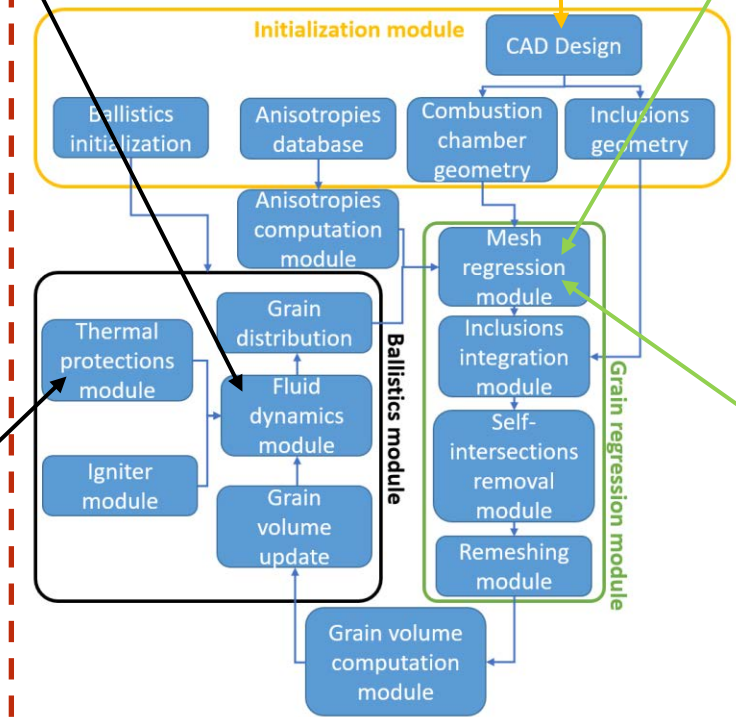
Generic CAD geometry



3D Burning surface regression

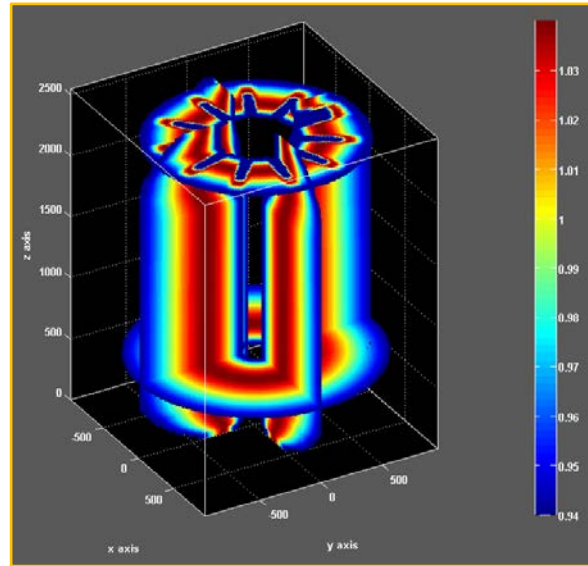


ROBOOST

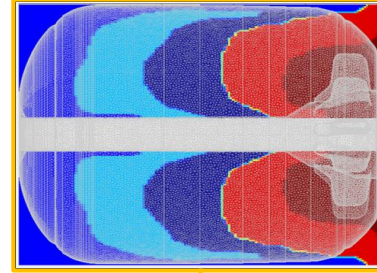


ROcket BOOst Simulation Tool – ROBOOST (2)

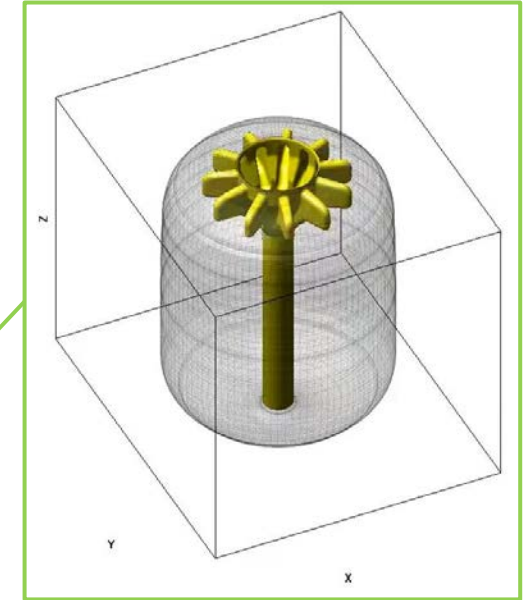
Burn rate anisotropy tables



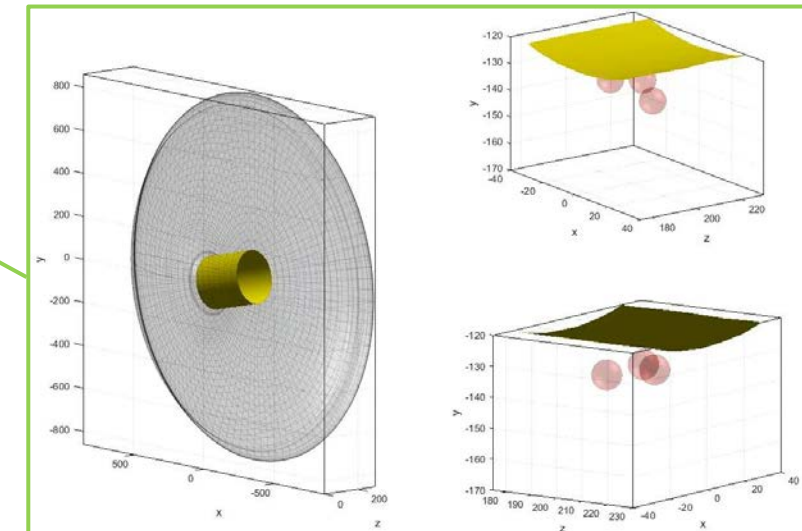
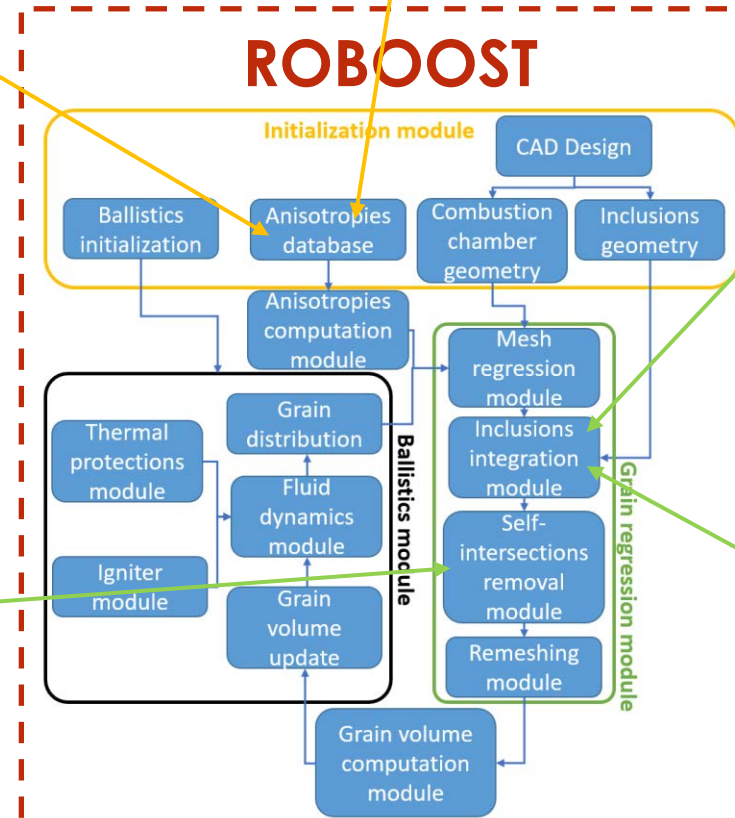
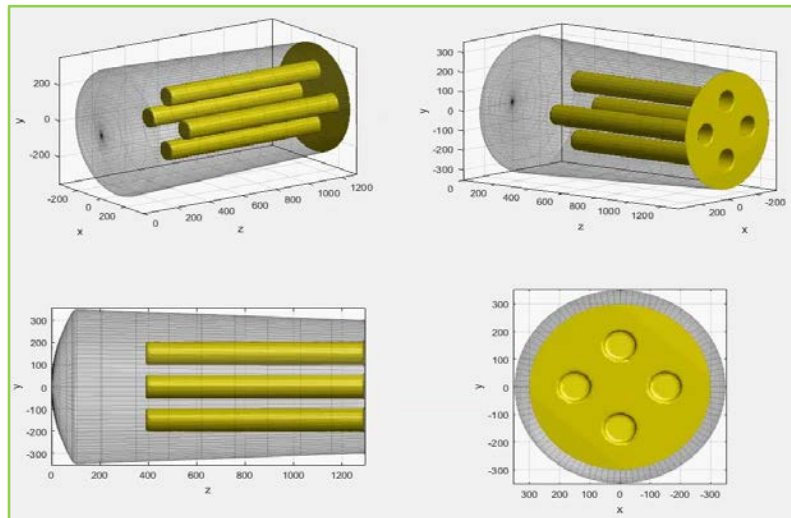
Burn rate anisotropy-multibatch



Inclusions-debondings



Self-intersections handling





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