ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Nuovi materiali e nuove tecniche di propulsione tra meccanica e spazio

Teaching Hub – 11 Aprile 2025

ALMA PROPULSION LAB

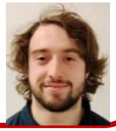
Department of industrial engineering

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

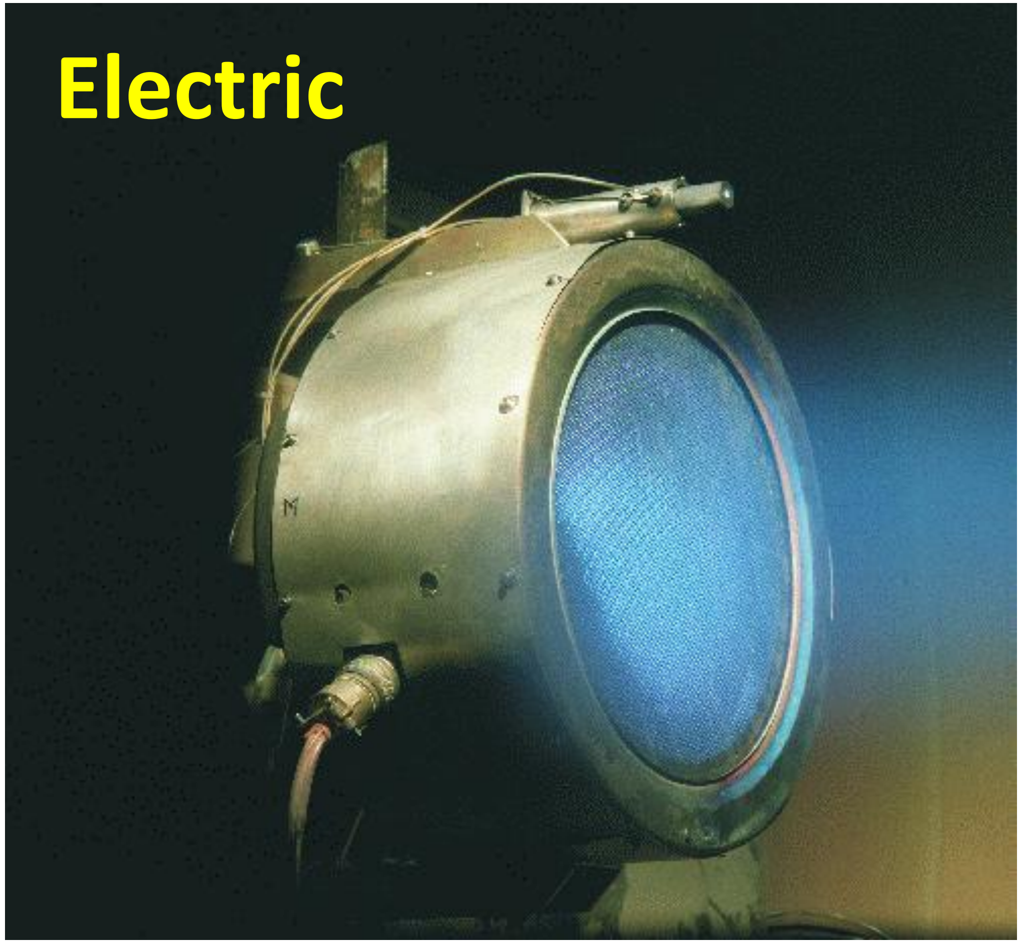
People:

- 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

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

Electric Propulsion

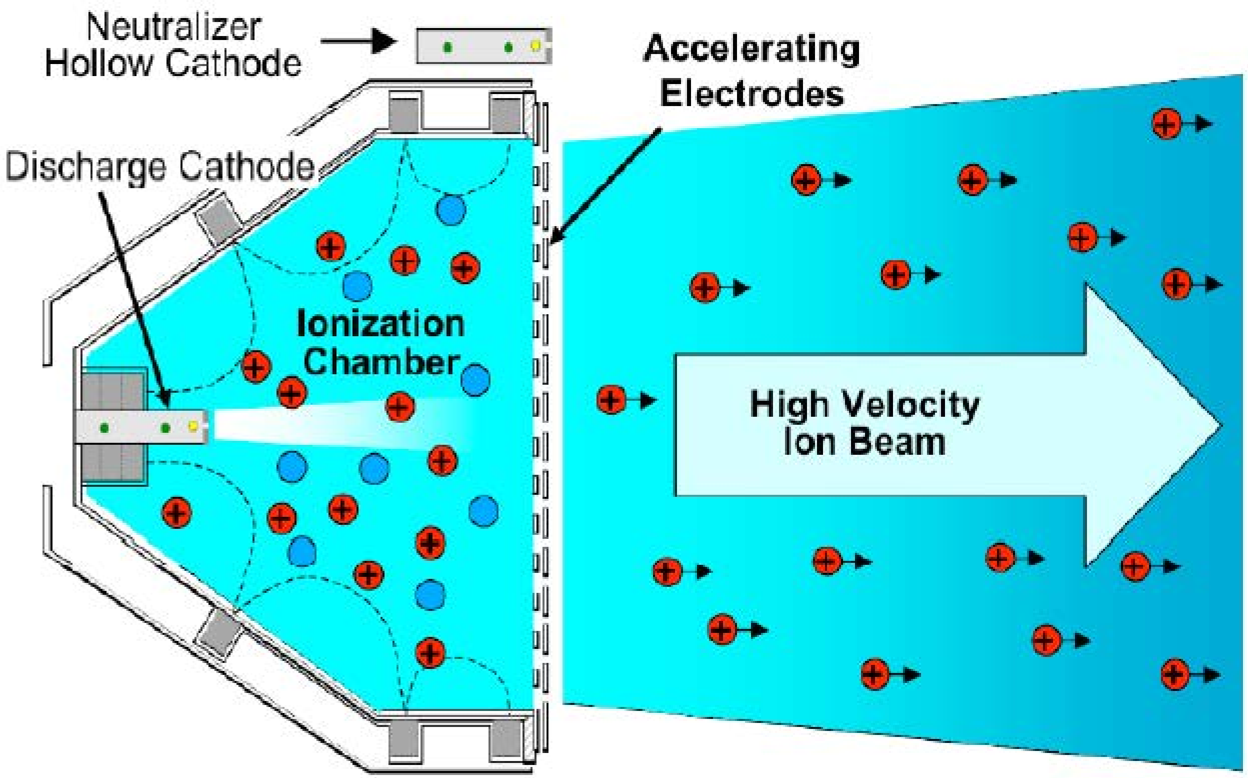


Energy conversion is efficient if the exhaust is composed by heavy atoms

Electric Propulsion

Energy required
for inonization

Energy required
for acceleration



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:

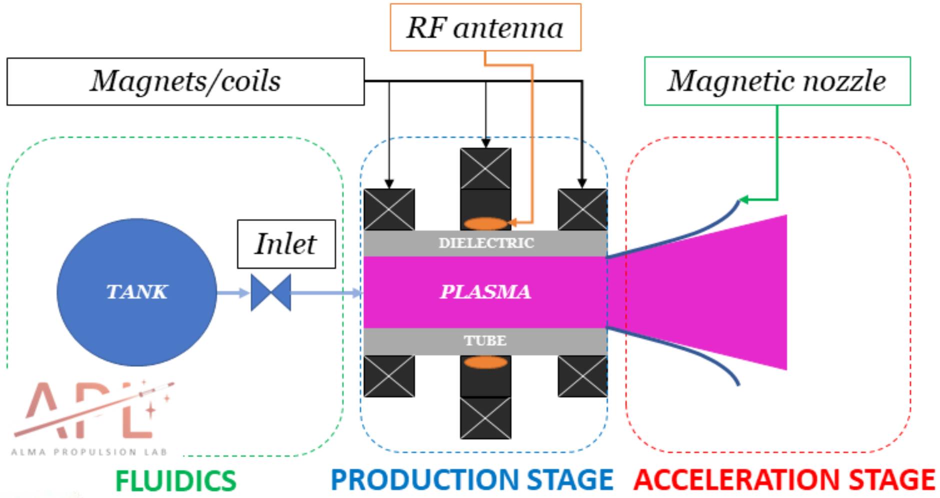
- Analytical PLUME model [Lafleur 2011]
- PIC 2D (STARFISH)
- PIC 3D (PROPIC)

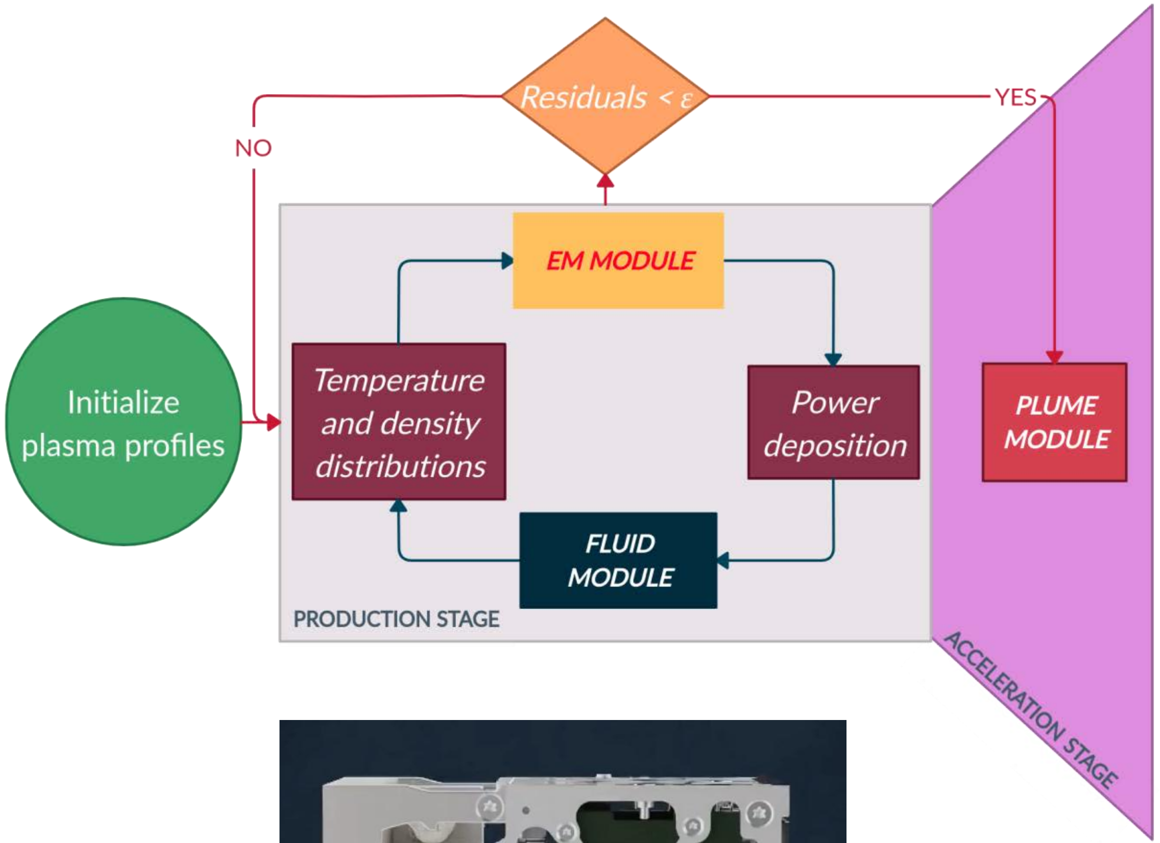
COUPLING STRATEGY:

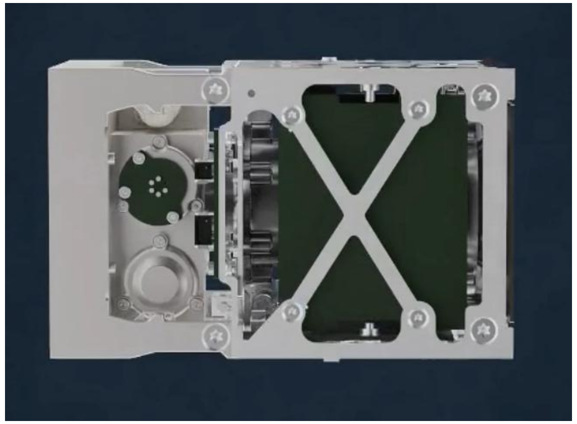
- MUPETS (integration of Fluid Model and PIC)

HYBRID MODELING:

- Development of a Hybrid Model (Fluid-PIC)







Satellite life

(and increasing number of satellites)

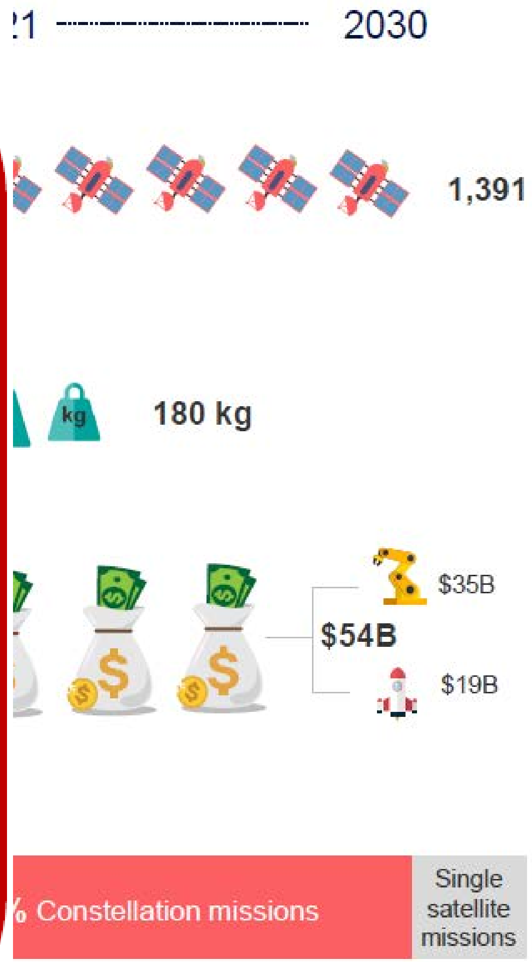
End-of-Life Disposal

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

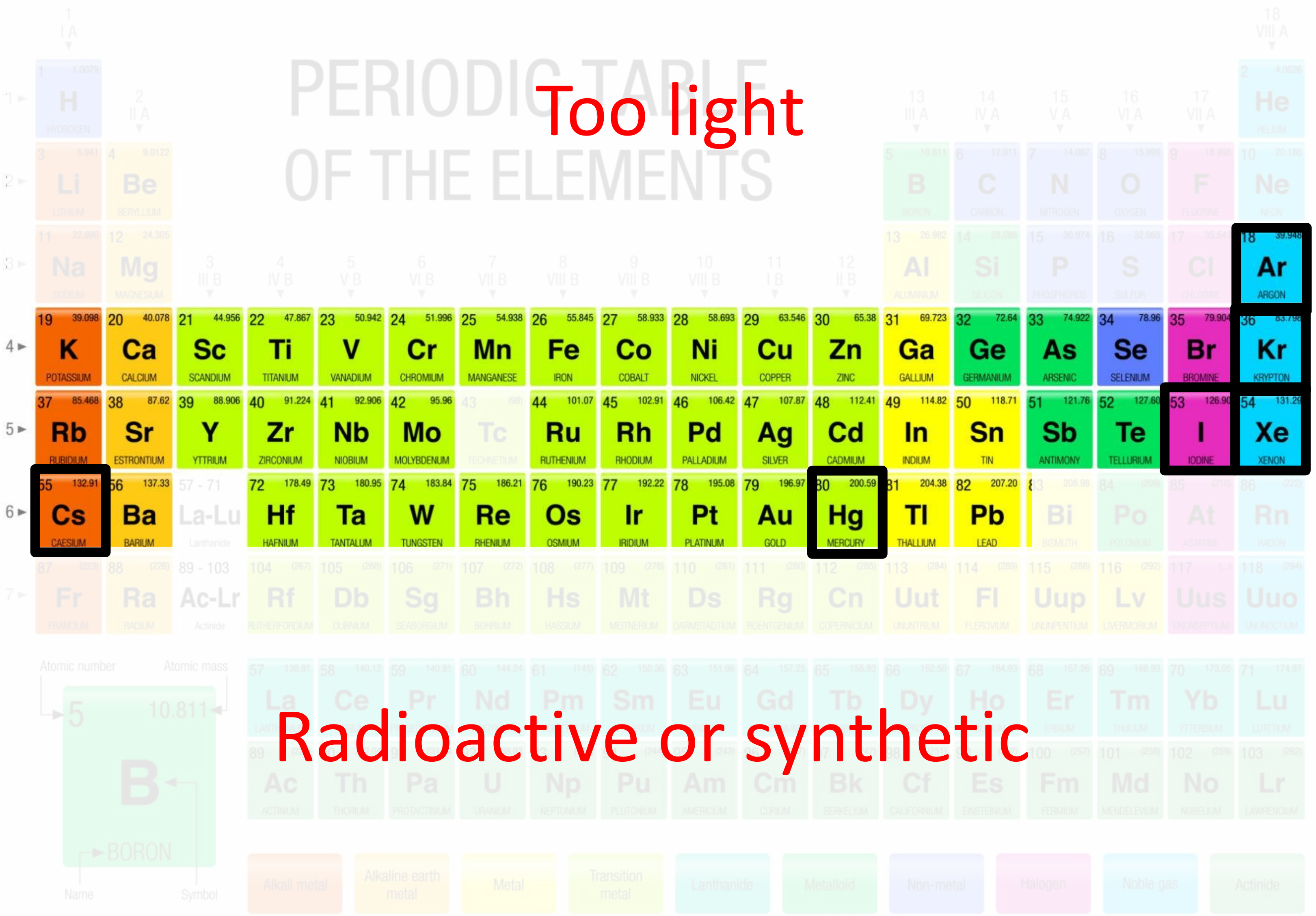
⬇

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



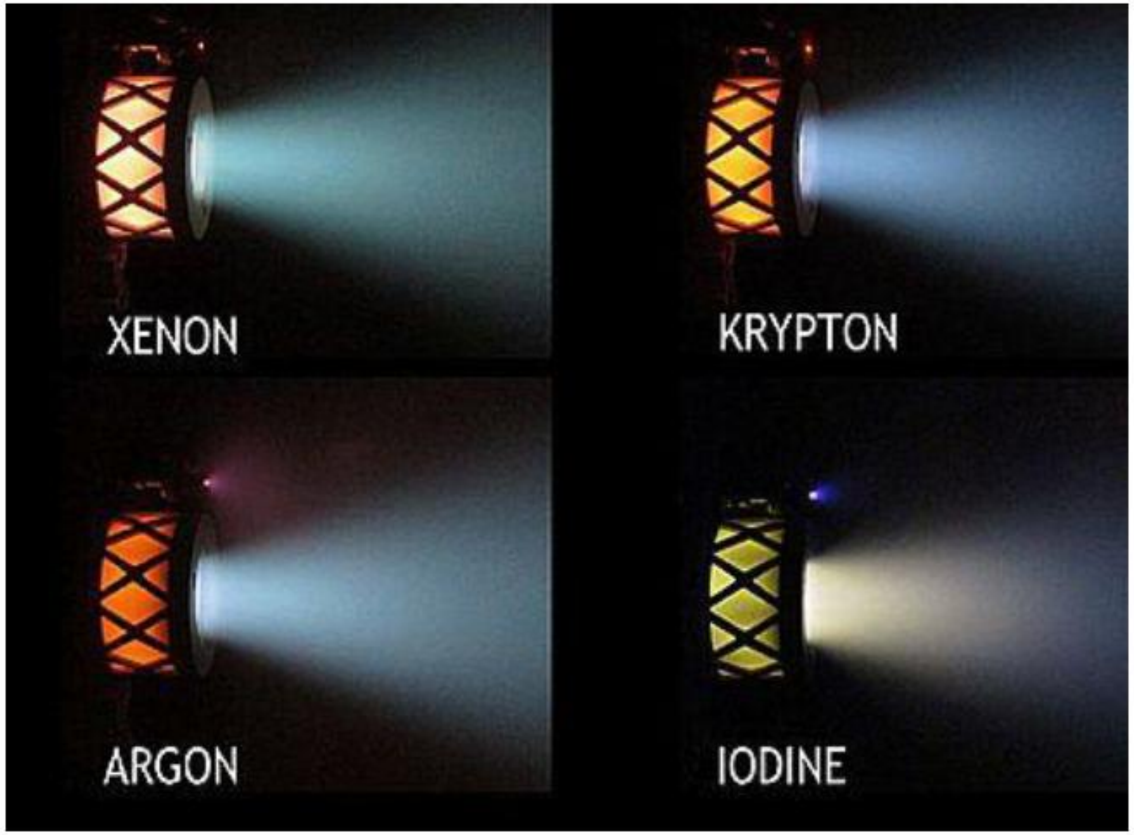
The periodic table



Propellant choice (1)

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

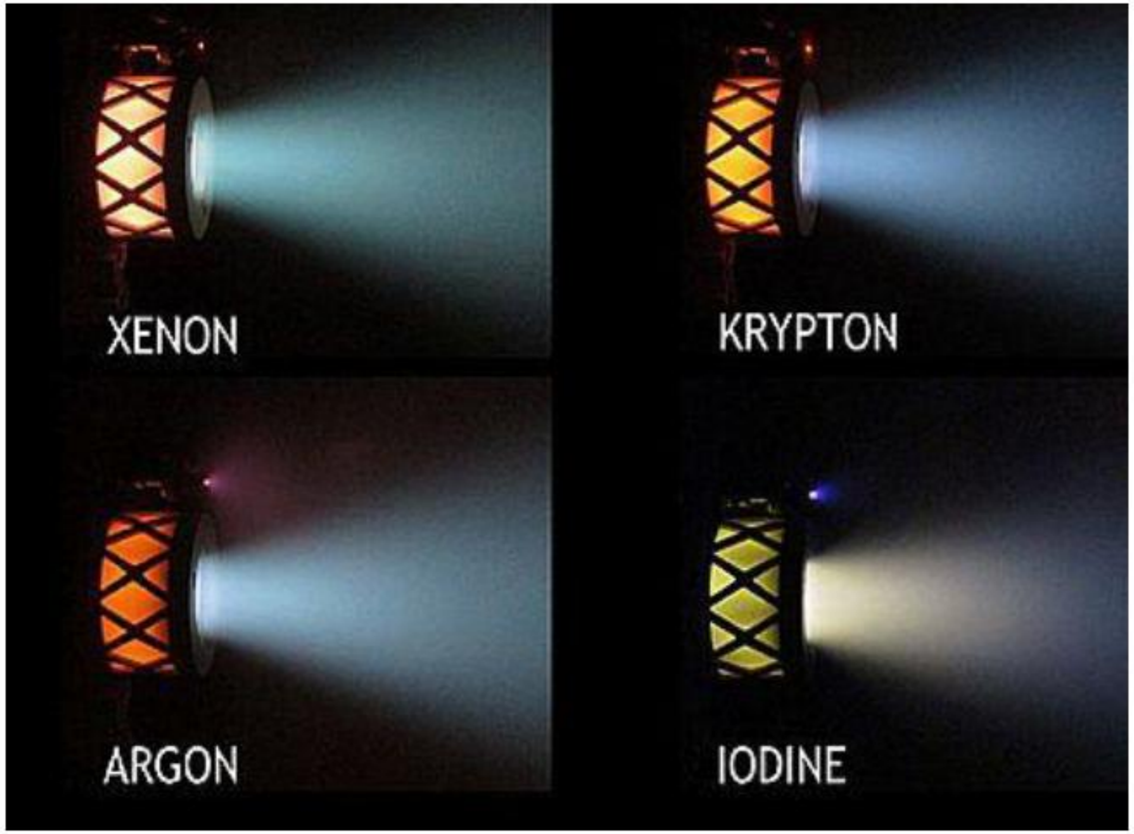
- **Physical** considerations
  - Appropriate molecular weight
  - Low ionization and dissociation (if a molecular compound) energies
- **Practical** considerations
  - Easily storable
  - Non-corrosive and non-condensable
  - Non-toxic



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 avid 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	☺	😐	😐

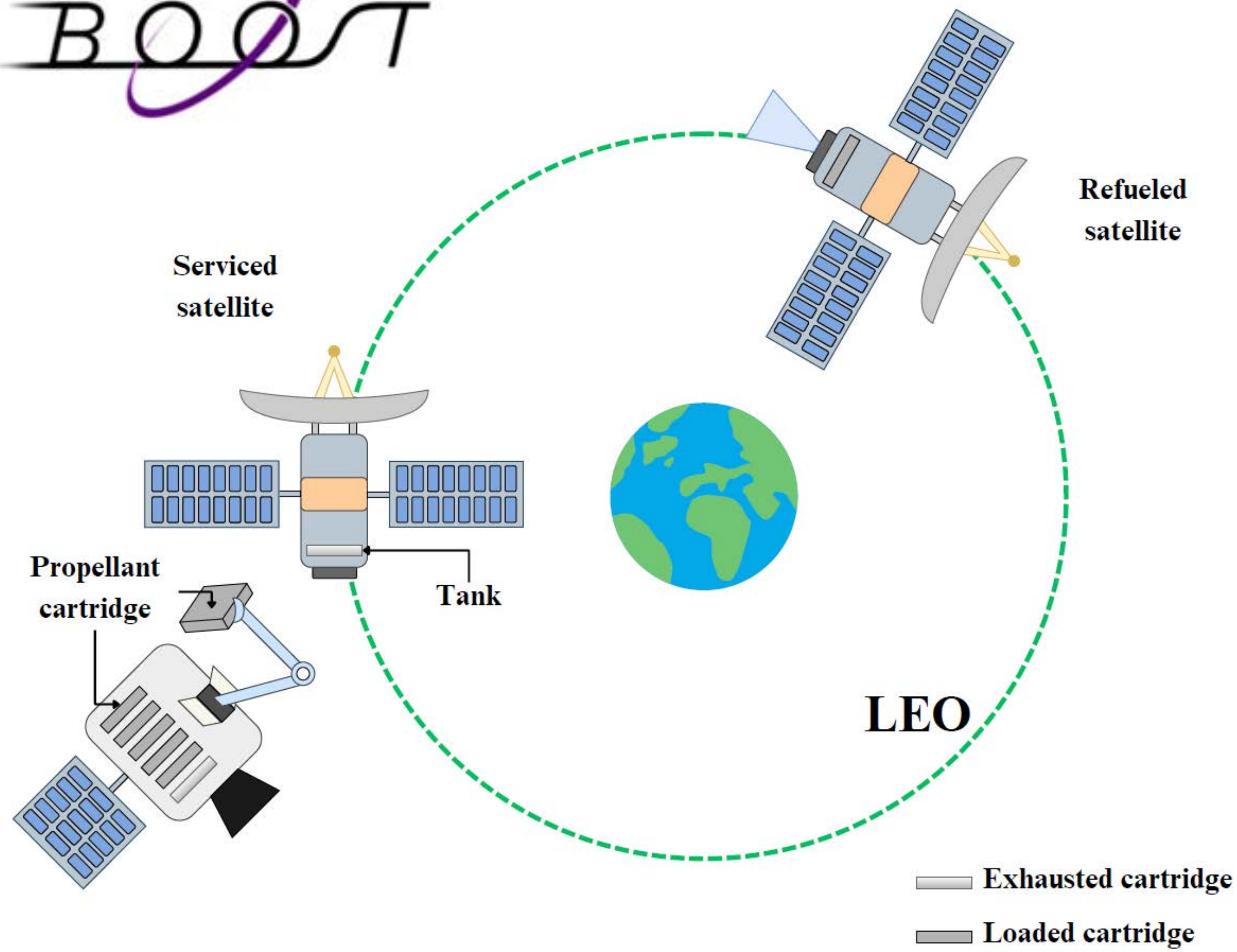
Refuelling mission – Scenarios

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 manouevers 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.

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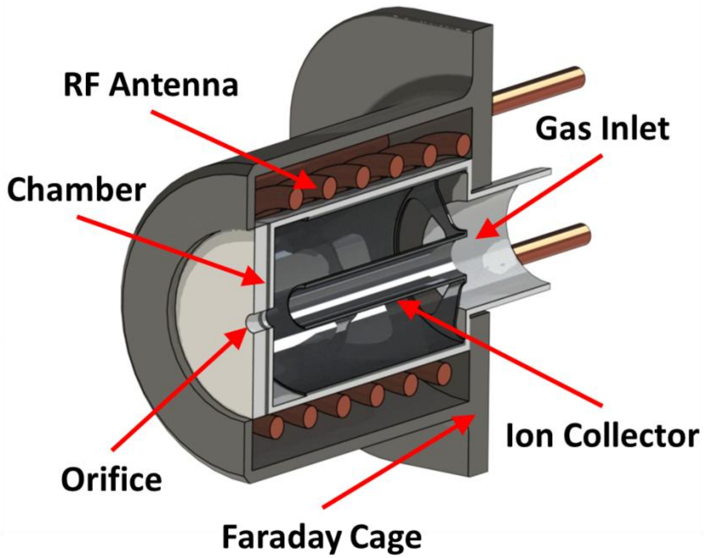
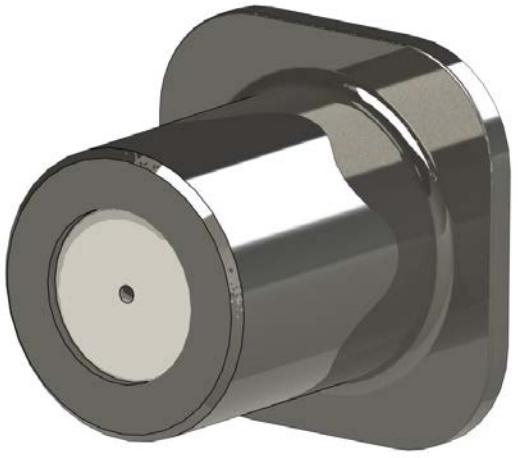
BOOST – Specific Objective 1

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 $\geq$ 100 mA.
- **KPI-2**: Scaled design for increased current applications.

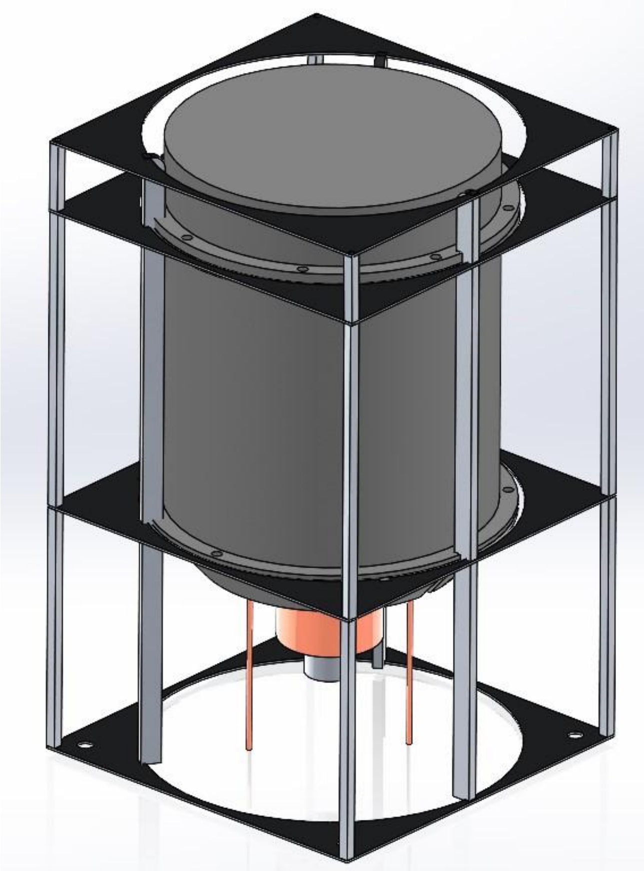
BOOST – Specific Objective 2

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

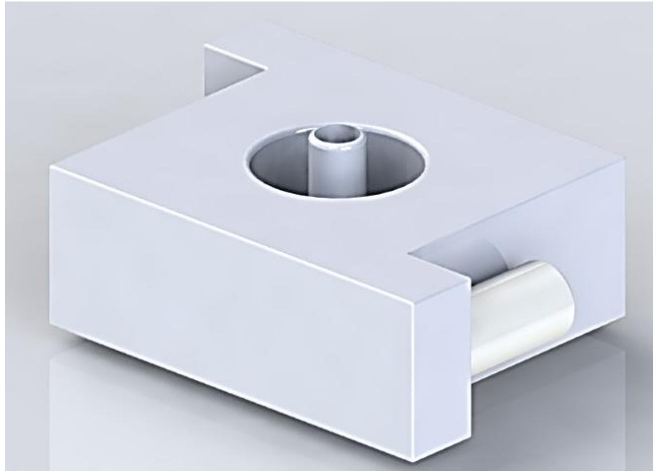
- Improvements targeted:

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 ≥ 10%.
- **KPI-7**: Production of ≥ 2 pieces tested and validated to demonstrate mass production capabilities.

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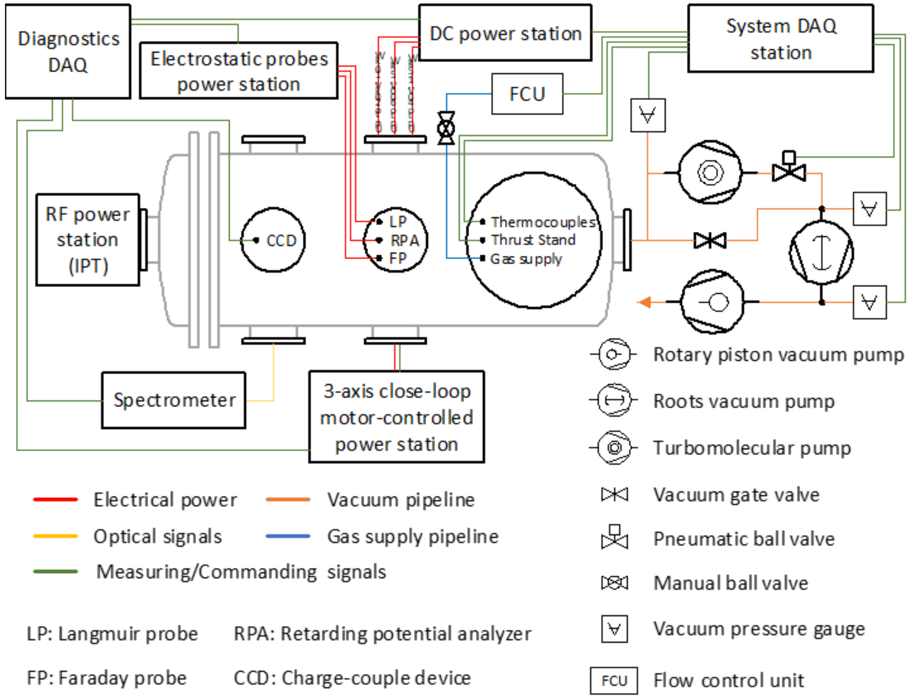
BOOST – Specific Objective 4

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.

BOOST

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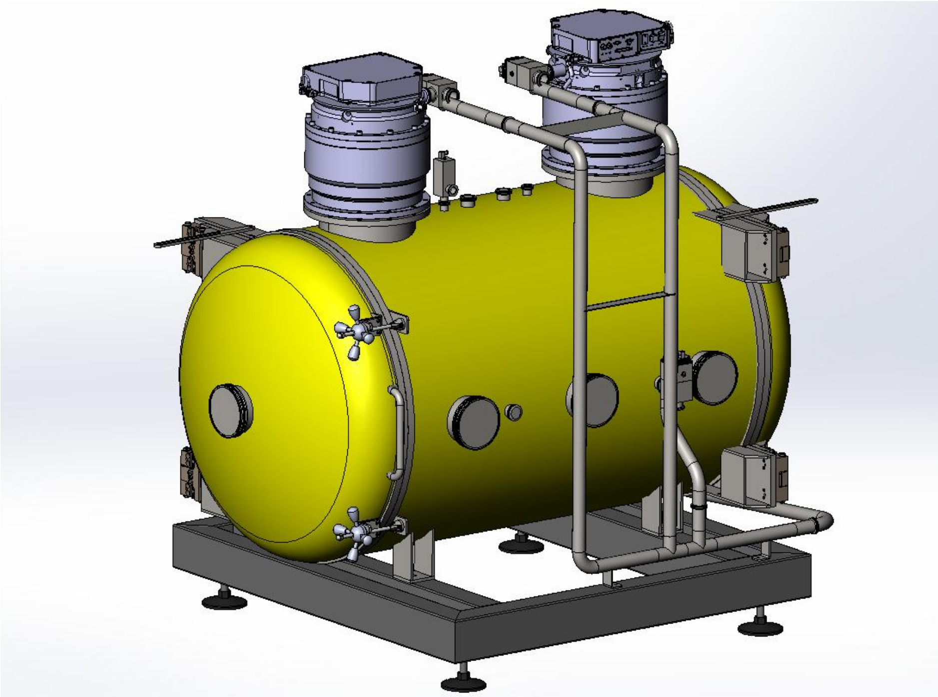
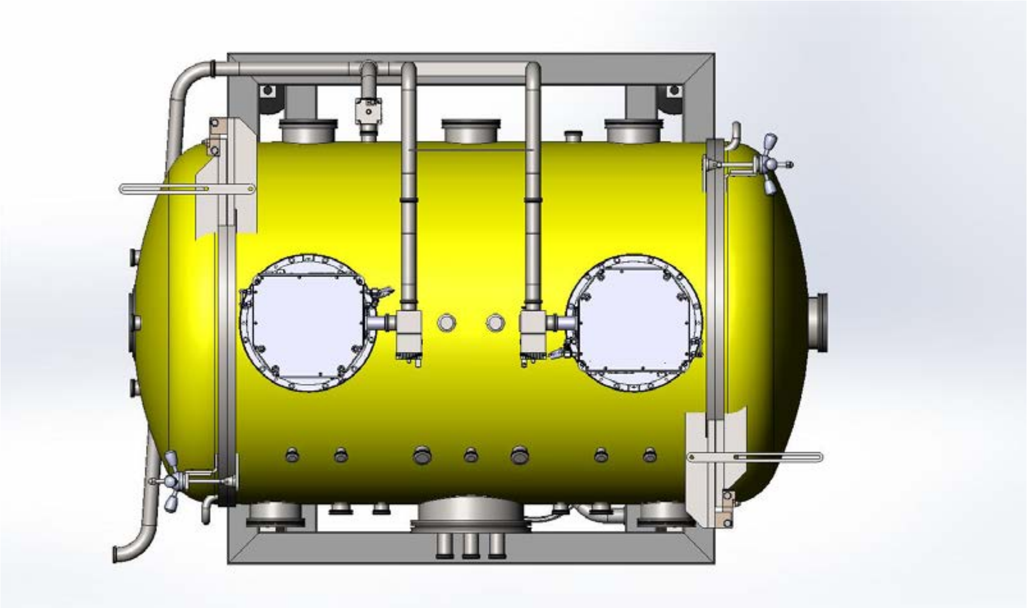
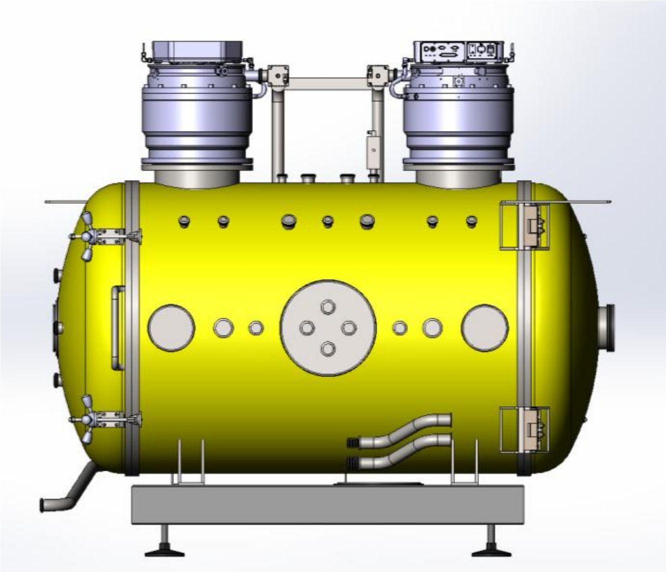
Vacuum chamber

- 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

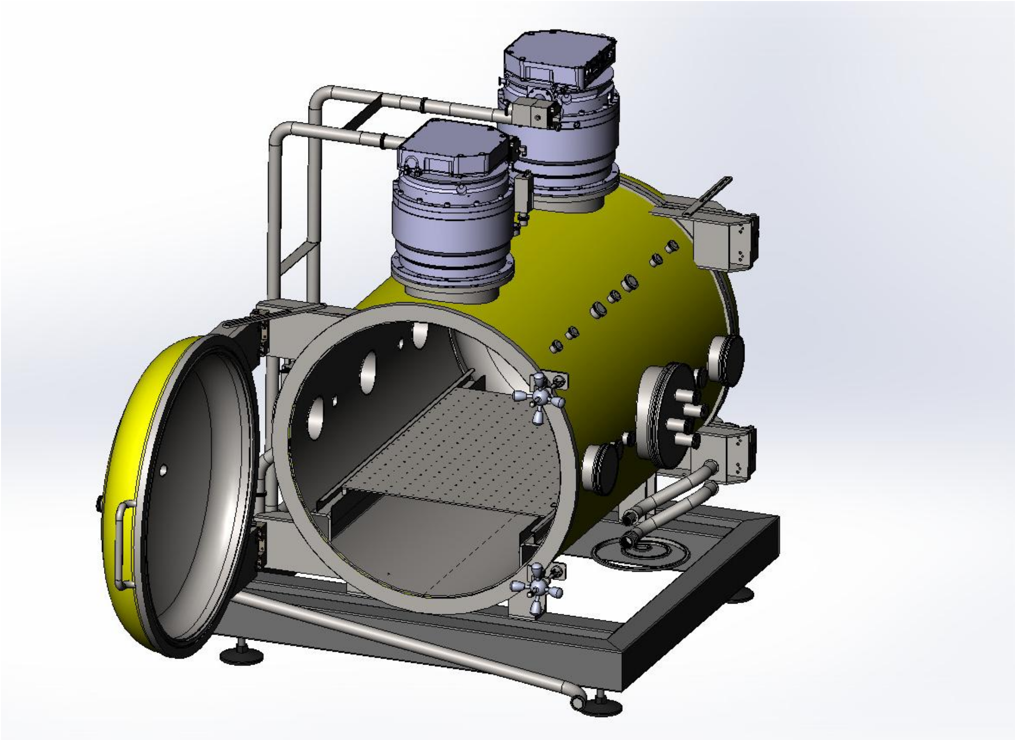


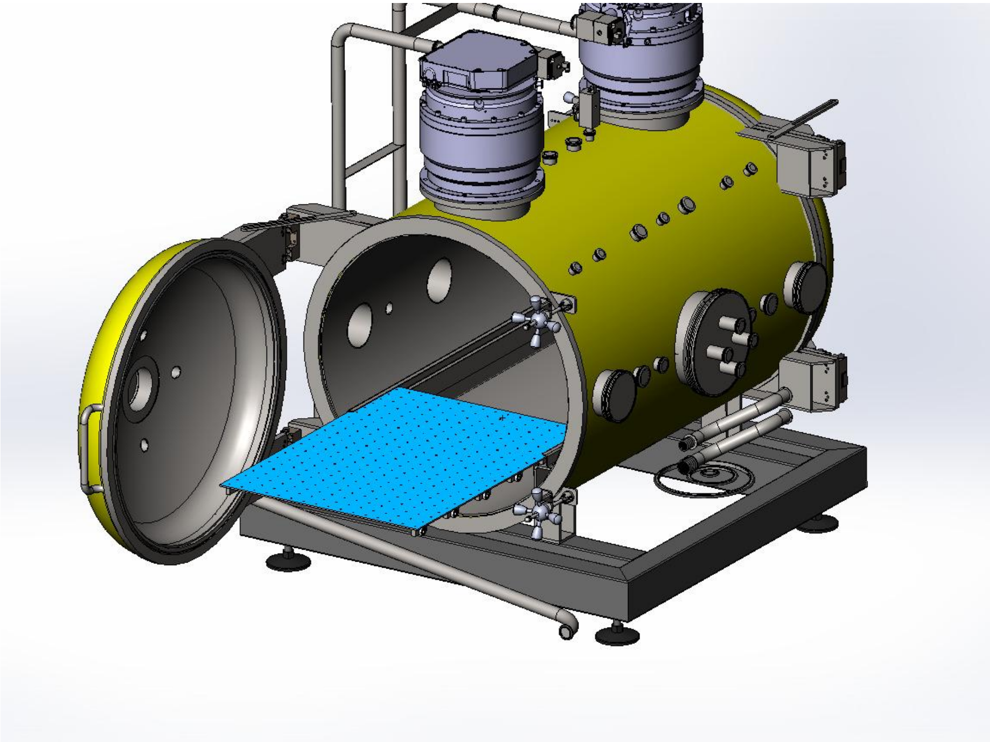




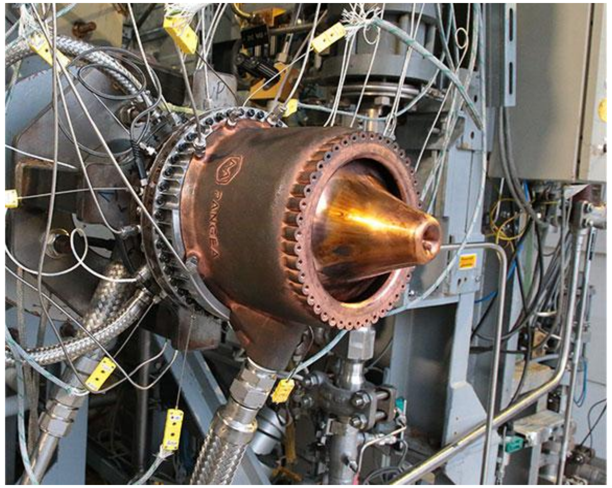
Vacuum chamber

- 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



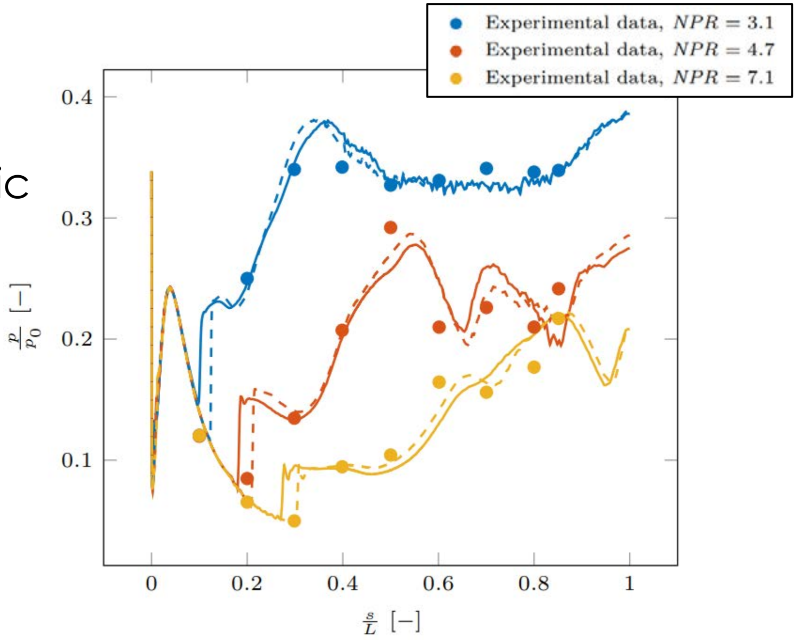
Pangea Aerospace , DemoP1 – aerospike demonstrator additively manufactured

openFOAM solver

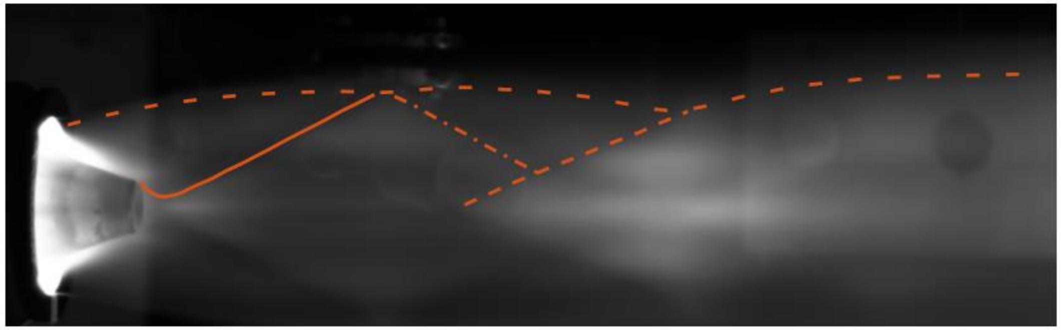
- Compressible viscous flow solver
- HLLC scheme designed for supersonic flow
- k-Ω SST turbulence model
- Open source

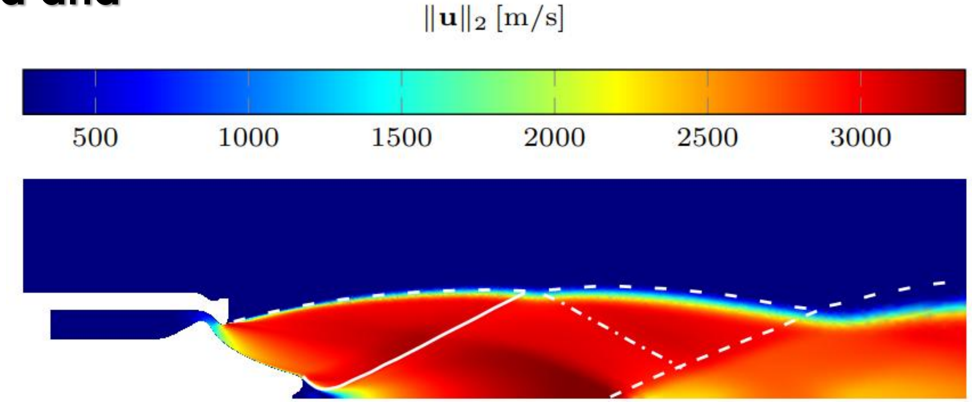
Solver validation

- Experimental data at different NPR
- Solver tested changing the base k-Ω SST parameters



DemoP1 experimental data and simulation





PANGEA™ AEROSPACE

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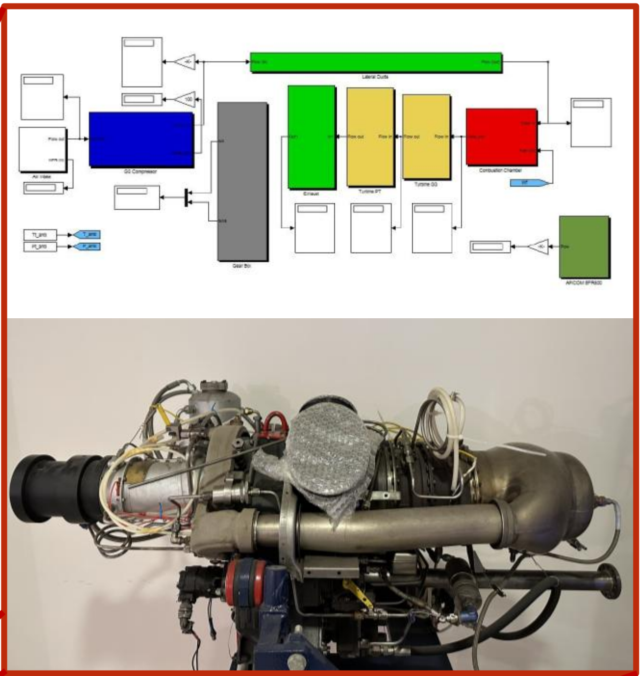
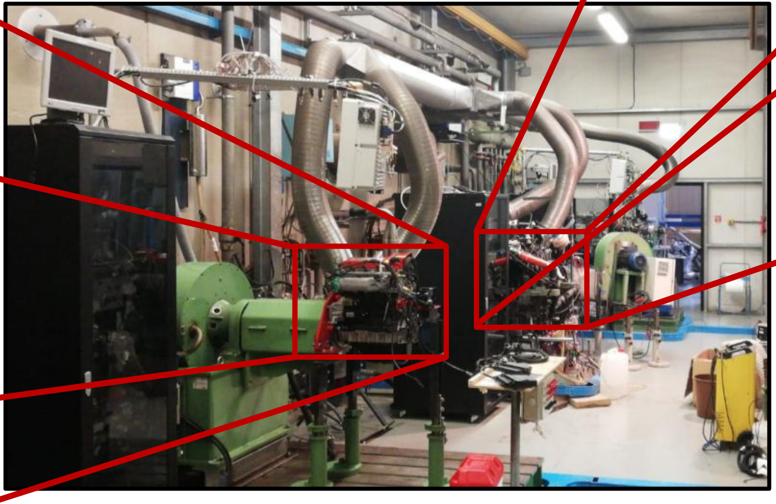
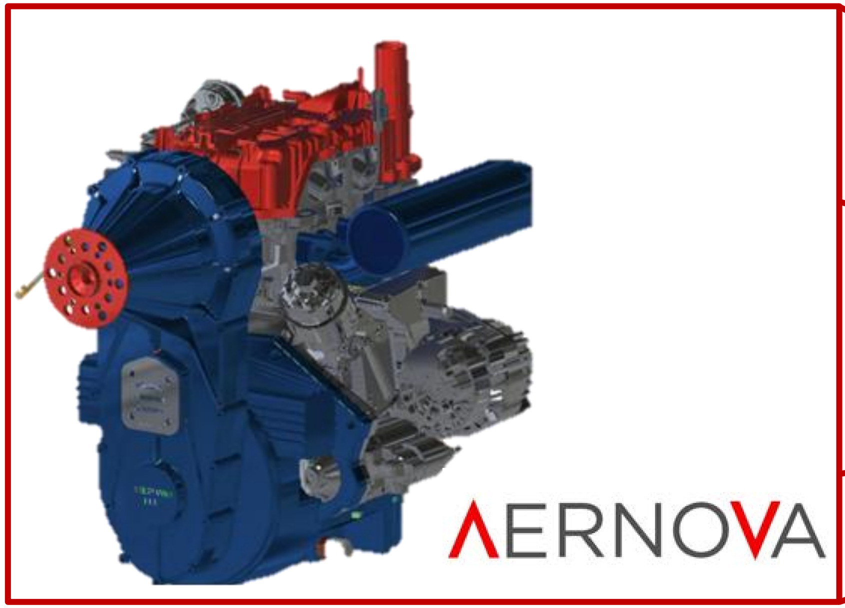
Internal Combustion Engine and Gas Turbine testing facilities

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

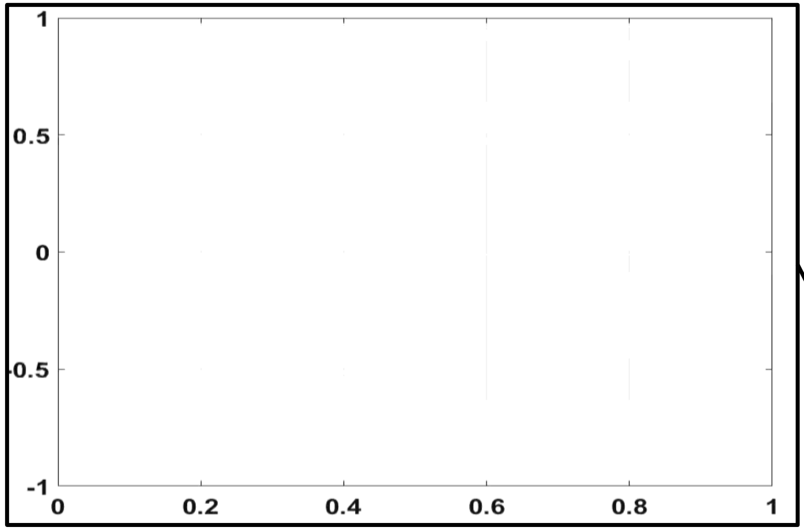




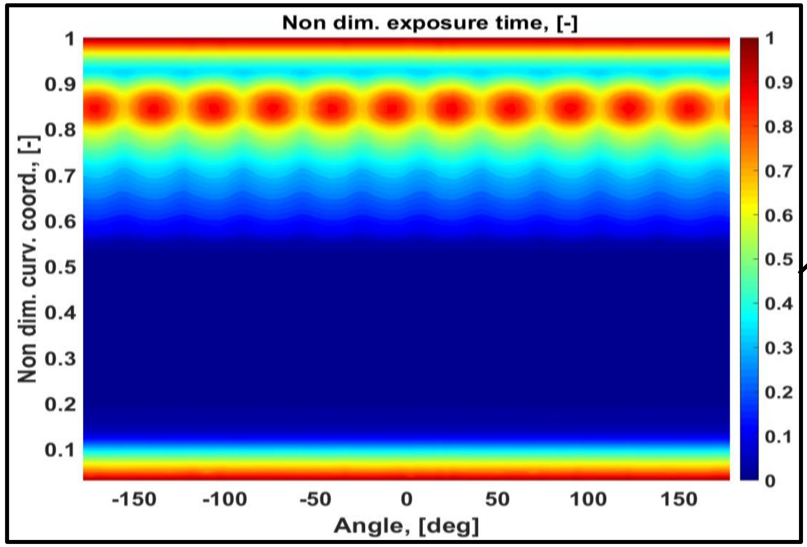


ROcket BOOst Simulation Tool – ROBOOST (1)

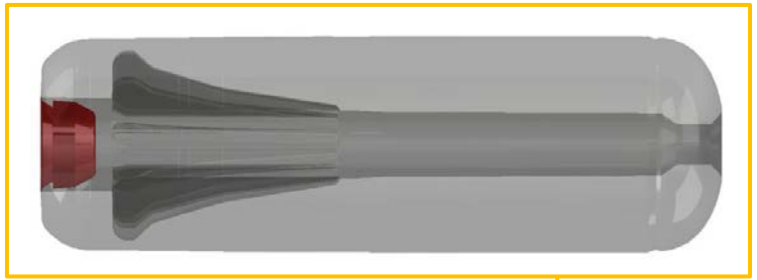
1D Internal ballistics computation

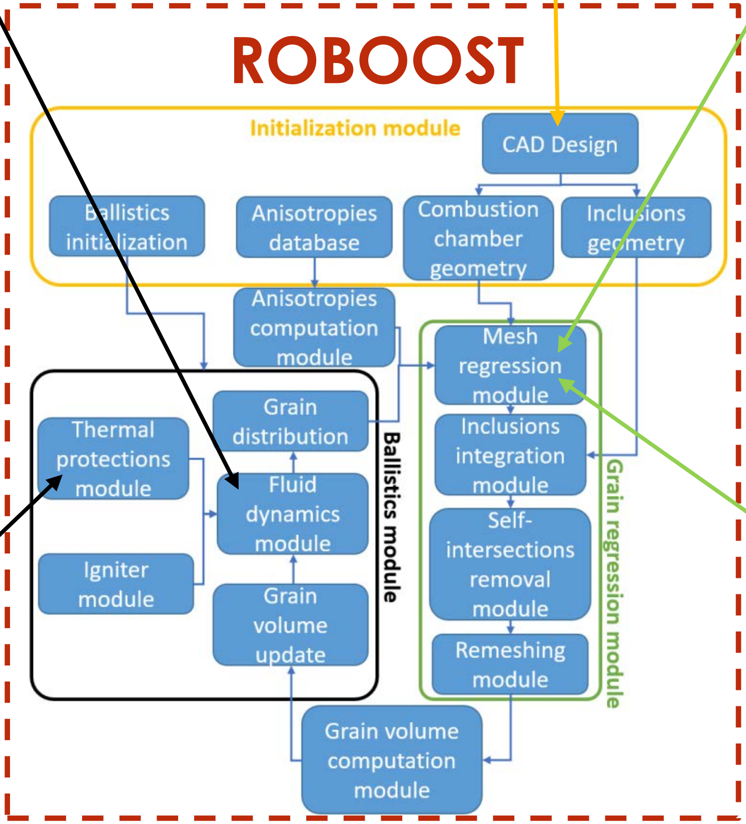


Thermal protection exposure

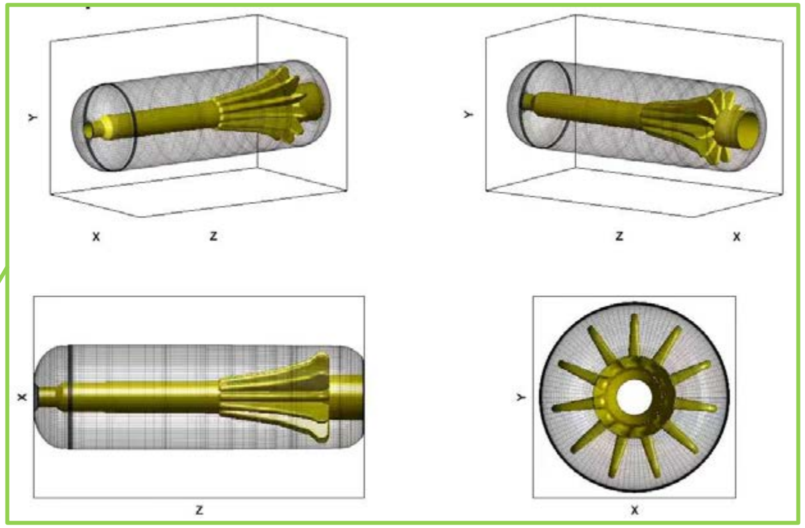


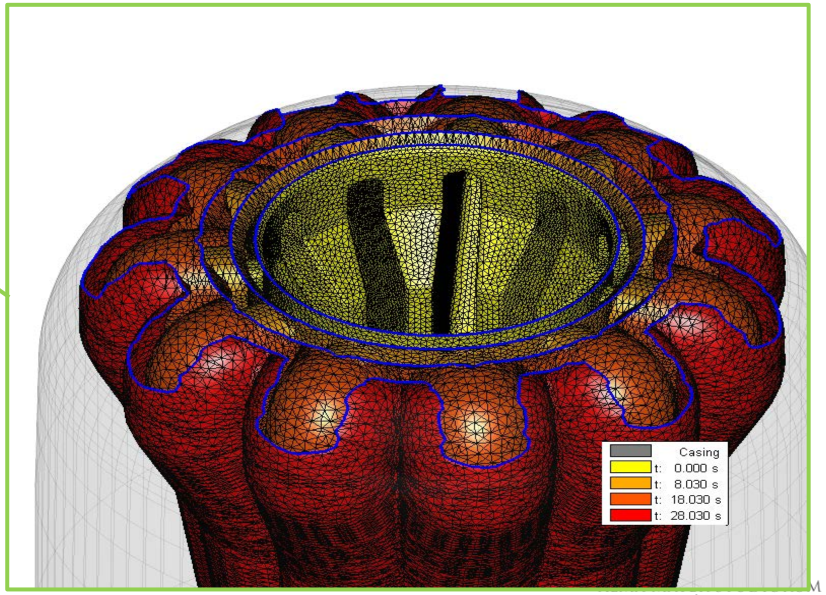
Generic CAD geometry





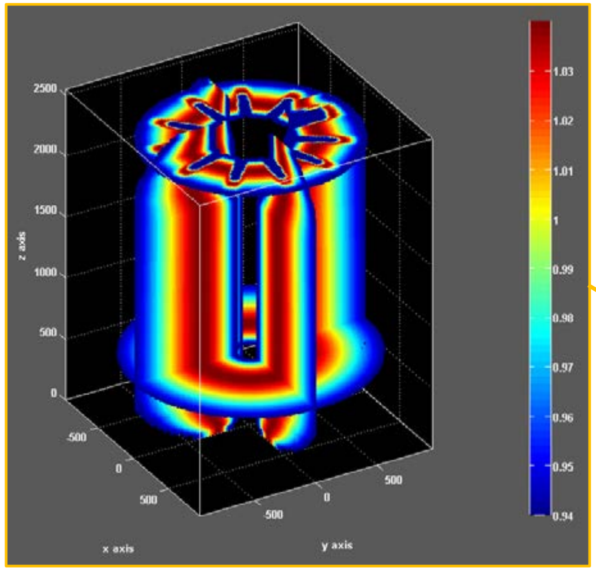
3D Burning surface regression



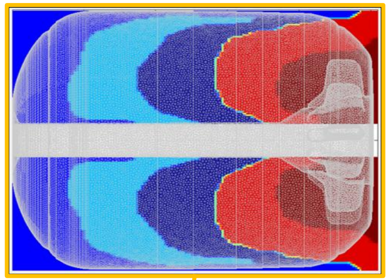


ROcket BOOst Simulation Tool – ROBOOST (2)

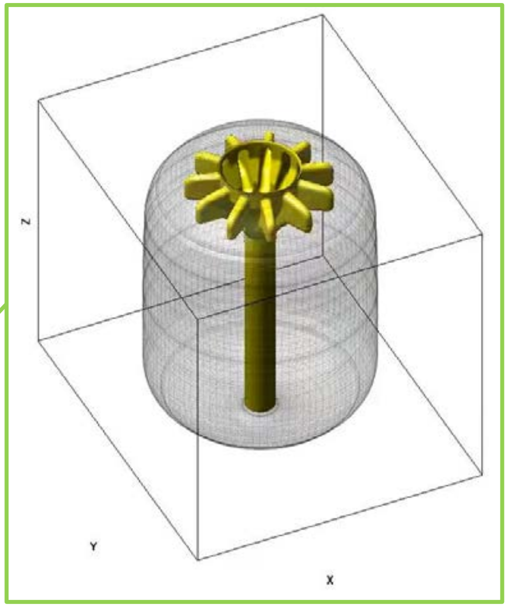
Burn rate anisotropy tables

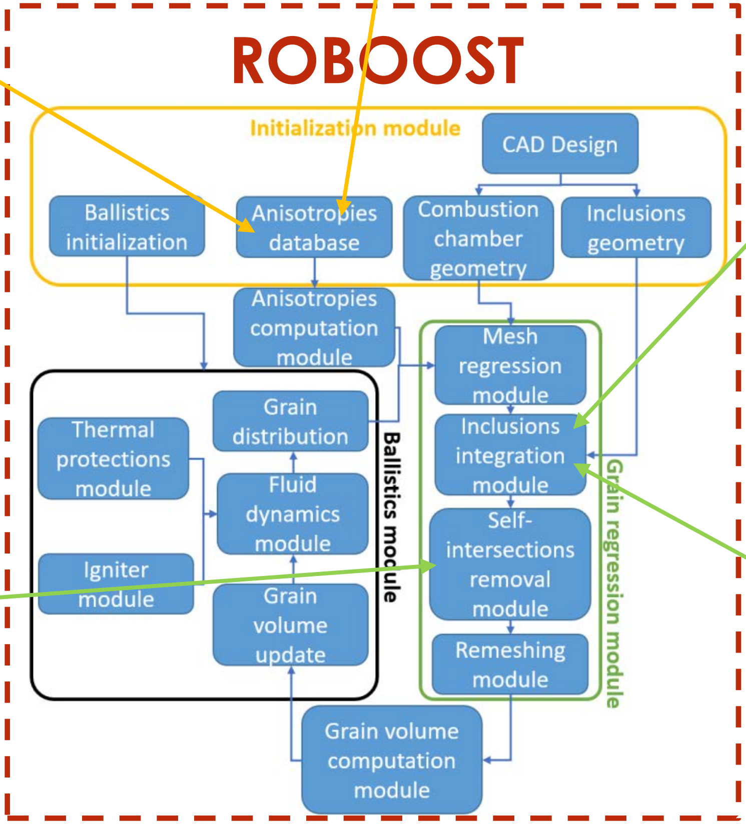


Burn rate anisotropy-multibatch

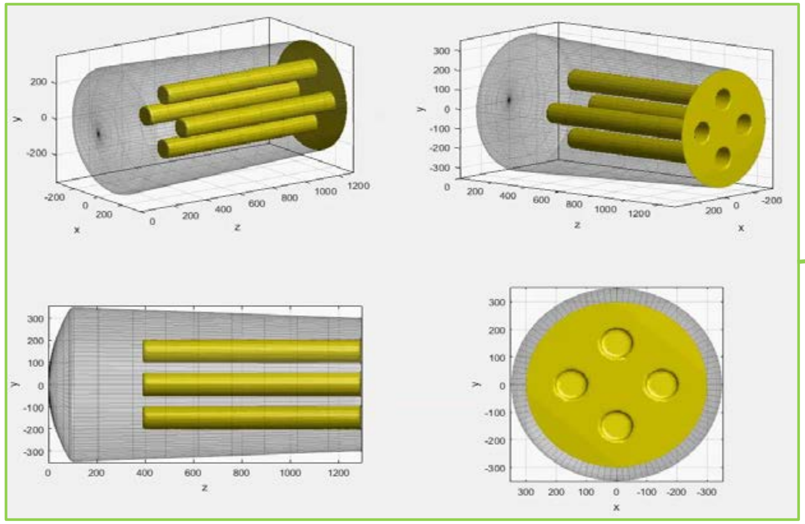


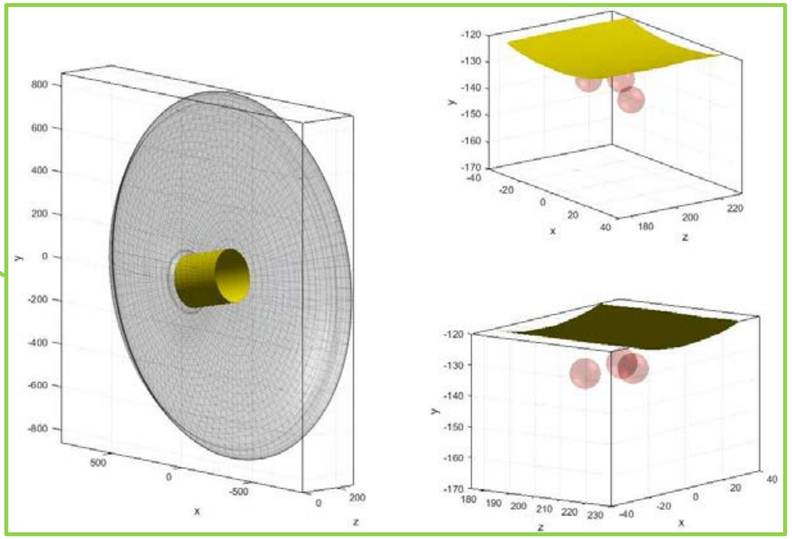
Inclusions-debondings





Self-intersections handling





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