Optimization of the magnetic nozzle of a 50 W helicon plasma thruster

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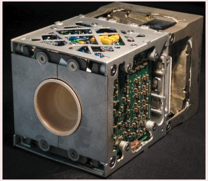
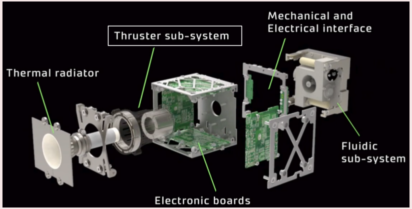
&
Techonology for propulsion and innovation T4I

Outline

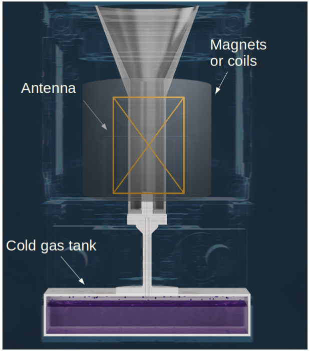
Observations at system level

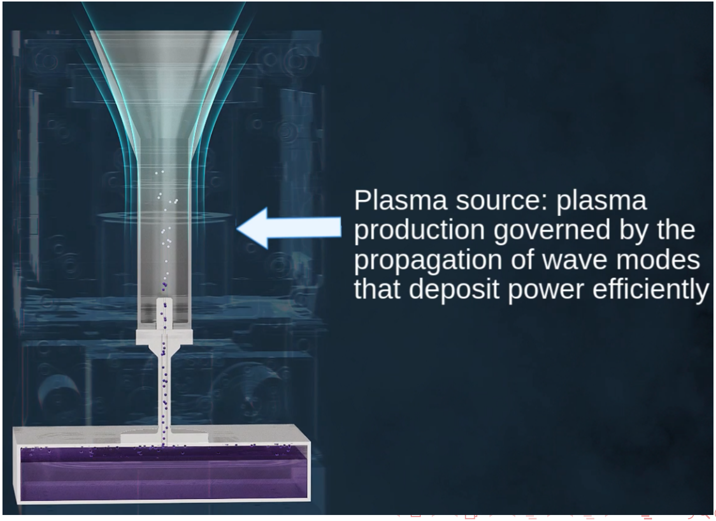
- HPTs do not require electrodes or grids, so they are expected to have a **very long life**
- HPTs do not require a hollow cathode, so their **cost is much lower** than Ion and Hall effect thrusters
- REGULUS currently in orbit, **in-Orbit-Demonstration is in progress**.



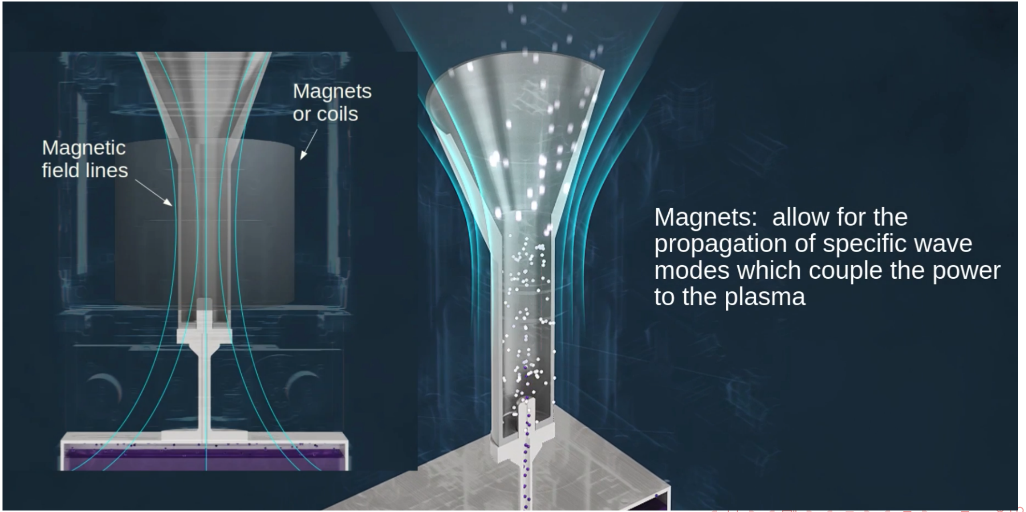


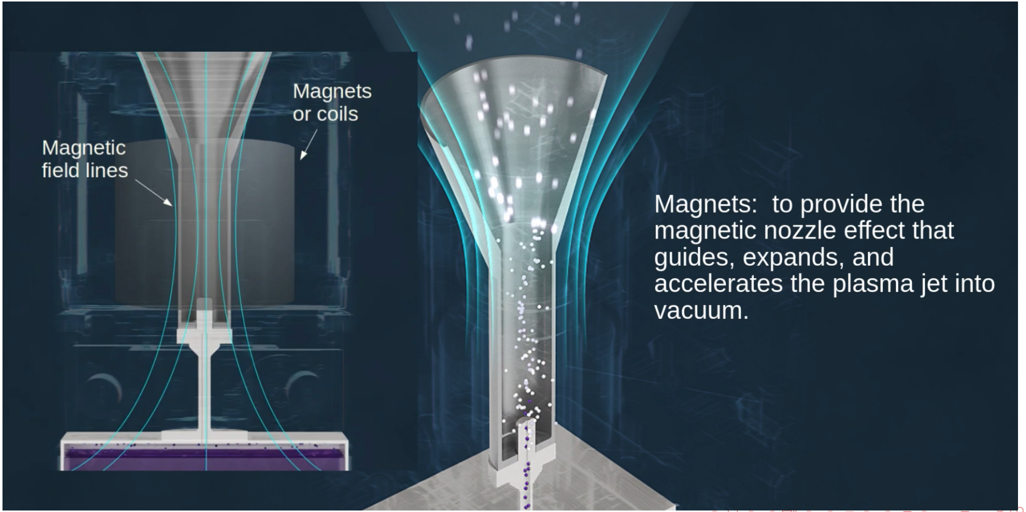
HPT: plasma source





HPT: plasma source



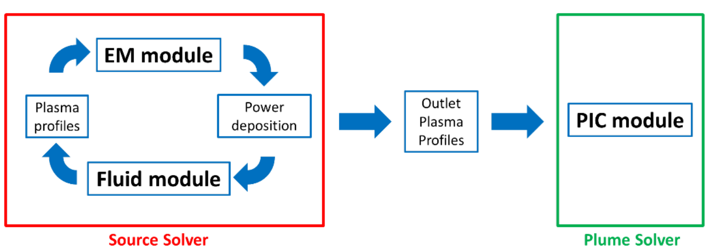

Magnets or coils
Magnetic field lines
Magnets: to provide the magnetic nozzle effect that guides, expands, and accelerates the plasma jet into vacuum.

HPT: Optimization

Numerical-experimental approach

- numerical approach: different numerical strategies to study the different components of the thruster
- experimental approach: experimental setups to evaluate the propulsive performances and plasma properties

Numerical strategy

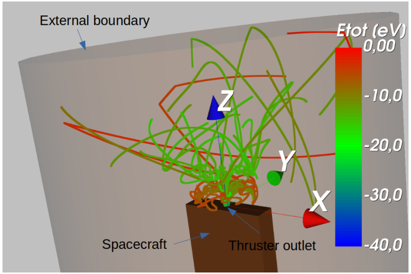


PROPIC: a 3D full kinetic PIC

PROPIC development

PROPIC, a three-dimensional fully kinetic Particle-In-Cell (PIC) software has been developed to simulate the acceleration stage. The tool permits:

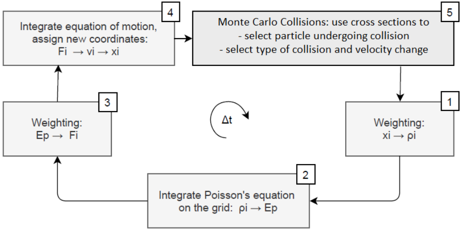
- to simulate in a non-axisymmetric domain the dynamics of a magnetized plasma plume
- to estimate the propulsive performace
- to evaluate the mutual interactions between the plasma plume, the spacecraft surfaces and the environmental plasma including spacecraft charging.



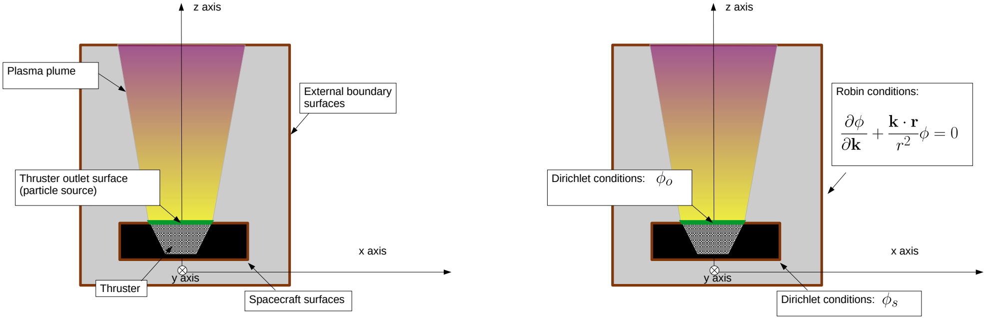
PROPIC loops

The PIC gives a consistent description of the plasma dynamics by means of:

- Integration of particles trajectories, which are determined by **Newton's law** (Lagrangian approach)
- Monte Carlo Collisions evaluation
- Evaluation of **EM fields** on a grid (Eulerian approach)



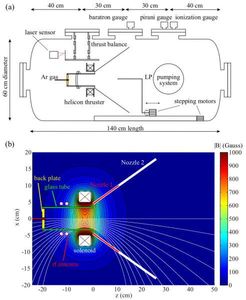
Methodology



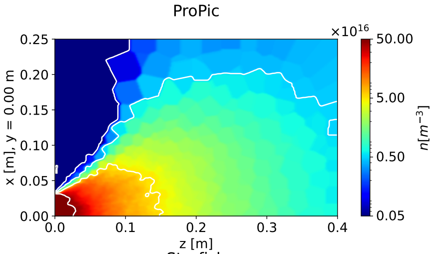
To simulate properly the dynamics of a HPT:

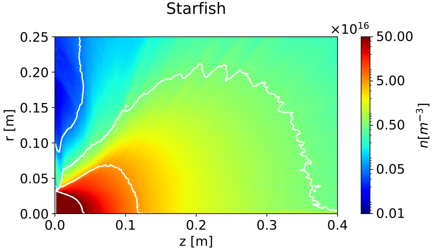
- the addition of a **control loop** to maintain the quasi-neutrality and the current free conditions and compute the spacecraft charging
- the definition of an electron energy boundary condition.

Numerical-experimental validation of ProPic

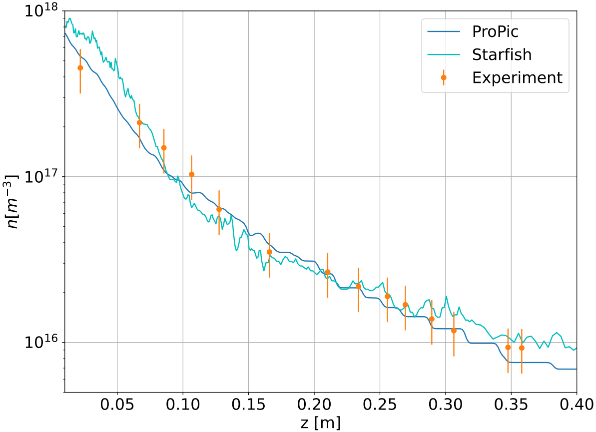


Takahashi, Kazunori, et al. "Effect of magnetic and physical nozzles on plasma thruster performance." Plasma Sources Science and Technology 23.4 (2014): 044004.



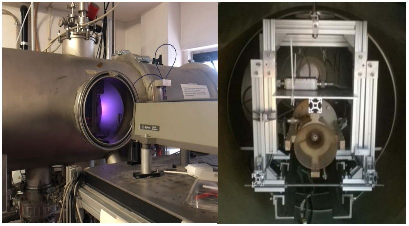


Numerical-experimental validation of ProPic

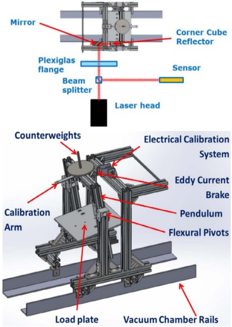


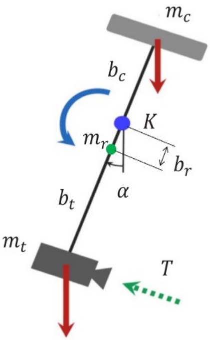
	Thrust [mN]
Experimental	4.54
Starfish	4.9
Propic	4.5

Experimental validation at Cisas facility



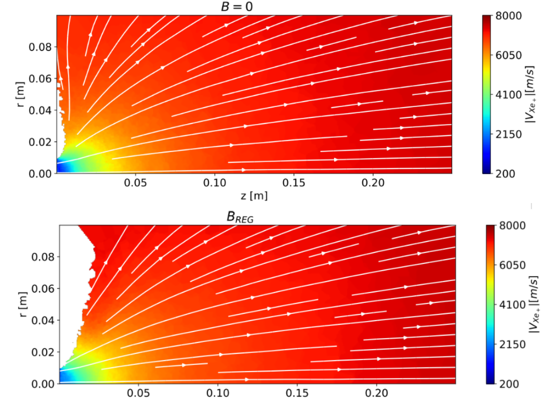
	I_{sp} [s]
Experimental	630
Propic	610





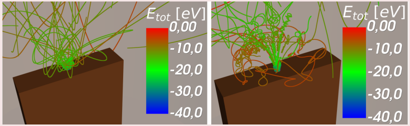
Magnetic nozzle effect

If $B = 0$ $I_{sp} = \mathbf{370}$ s, if $B \neq 0$ $I_{sp} = \mathbf{610}$ s

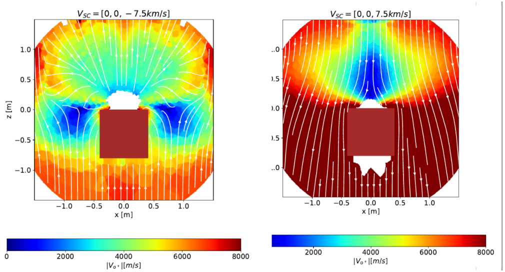


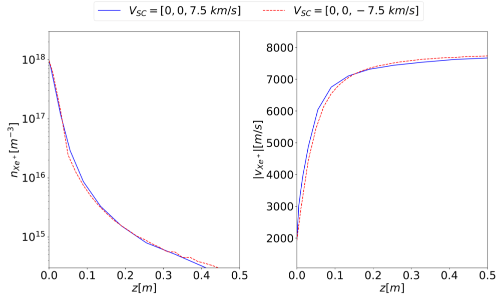
SC charging

If if $B \neq 0$ only **1.6 %** of the emitted particles impinges on the SC surface; this value increases up to **17 %** if $B = 0$.

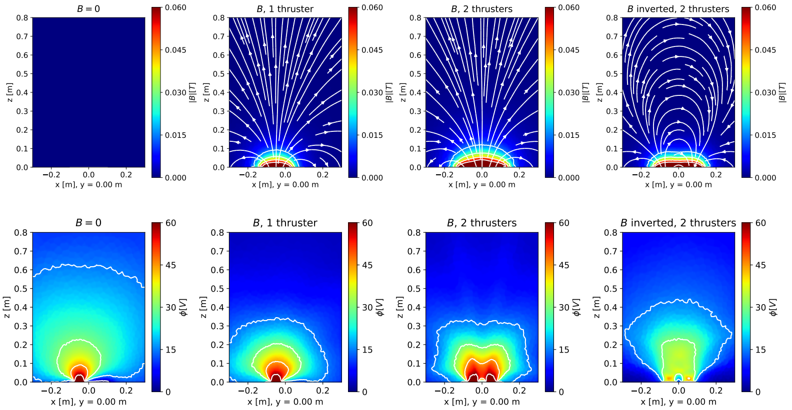


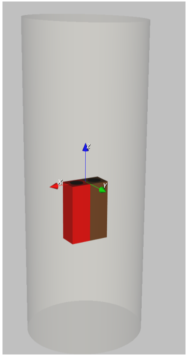
Orbital altitude 600 km, environmental plasma composed by electrons and O^+, $V_{SC} = 6.5\ km/s$.



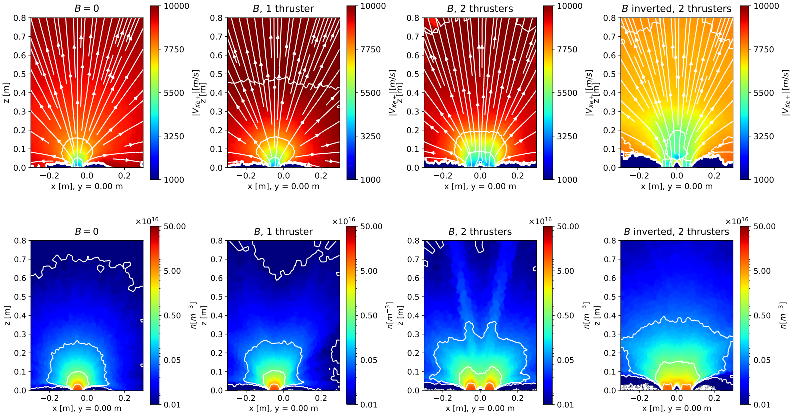


Cluster performance





Cluster performance



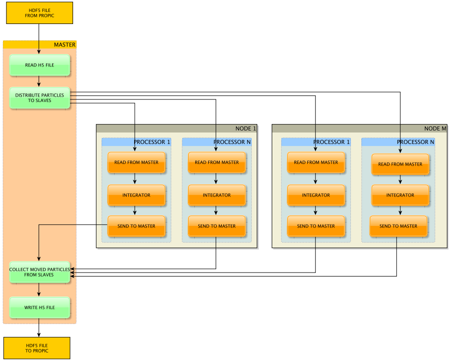
	I_{sp} [s]
$B = 0$	450
B, 1 thruster	611
B, 2 thruster	561
B inverted, 2 thruster	400

Final remarks and conclusions

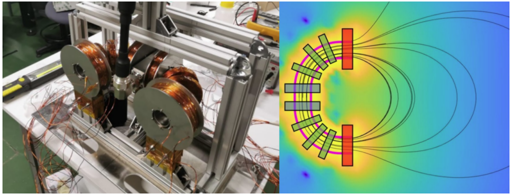
- ProPic, a three-dimensional full kinetic Particle-In-Cell (PIC) software has been developed and experimental-numerical validated to simulate the plasma dynamics of a magnetized plasma plume
- ProPic, coupled with the fluid code 3D-VIRTUS, gives a numerical suite that permits the physical investigation and identification of the driving parameters for the plasma source and magnetic nozzle design
- ProPic permits to evaluate the mutual interactions between the plasma plume, the spacecraft surfaces and the environmental plasma including spacecraft charging.

Final remarks and conclusions

The IRIS - hIgh peRformance computIng plaSma project, a collaboration with CINECA and T4I, has given the first step to parallize ProPic with Mpi libraries.



Interesting mutual influence of cathdoless thrusters in a cluster. This behaviour could be used to improve the thrust and specific impulse with a proper design.



Merino, Mario, et al. "Preliminary model of the plasma expansion in a magnetic arch thruster (and overview of the first prototype)." (2022).

Scientific production

Paper title	Journal	Date
Fully kinetic model of plasma expansion in a magnetic nozzle	PLASMA SOURCES SCIENCE & TECHNOLOGY	2022
Simulation of the plume of a Magnetically Enhanced Plasma Thruster with SPIS	JOURNAL OF PLASMA PHYSICS	2021
Numerical suite for cathodeless plasma thrusters	ACTA ASTRONAUTICA	2022
Design and In-orbit Demonstration of REGULUS, an Iodine electric propulsion system	CEAS SPACE JOURNAL	2021
Multiscale Modeling of the REGULUS Helicon Plasma Thrusters Operating on Xenon, Iodine and Krypton	ACTA ASTRONAUTICA	2023
Magnetic Noozle performance on cluster thrusters	PLASMA SOURCES SCIENCE & TECHNOLOGY	2023

Paper title	Conference	Date
Numerical Suite for Magnetically Enhanced Plasma Thrusters.	72nd International Astronautical Congress (IAC)	2021
REGULUS: INTEGRATION AND TESTING OF AN IODINE ELECTRIC PROPULSION SYSTEM	7th Space Propulsion Conference	2020
NUMERICAL SIMULATION OF THE PLUME OF A MAGNETICALLY ENHANCED PLASMA THRUSTER	7th Space Propulsion Conference	2020
Multiscale Modelling of Alternative Propellants in Helicon Plasma Thrusters	73rd International Astronautical Congress	2022
3D Full PIC Simulation of a Magnetized Plasma Plume	7th Space Propulsion Conference	2022
Simulation of a magnetized plasma plume with a 3D fully kinetic PIC approach	37th International Electric Propulsion Conference	2022