Electric propulsion technologies and computer simulations

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F. Cichocki, F. Taccogna, P. Minelli

Institute for Plasma Science and Technology (CNR-ISTP), Bari, Italy

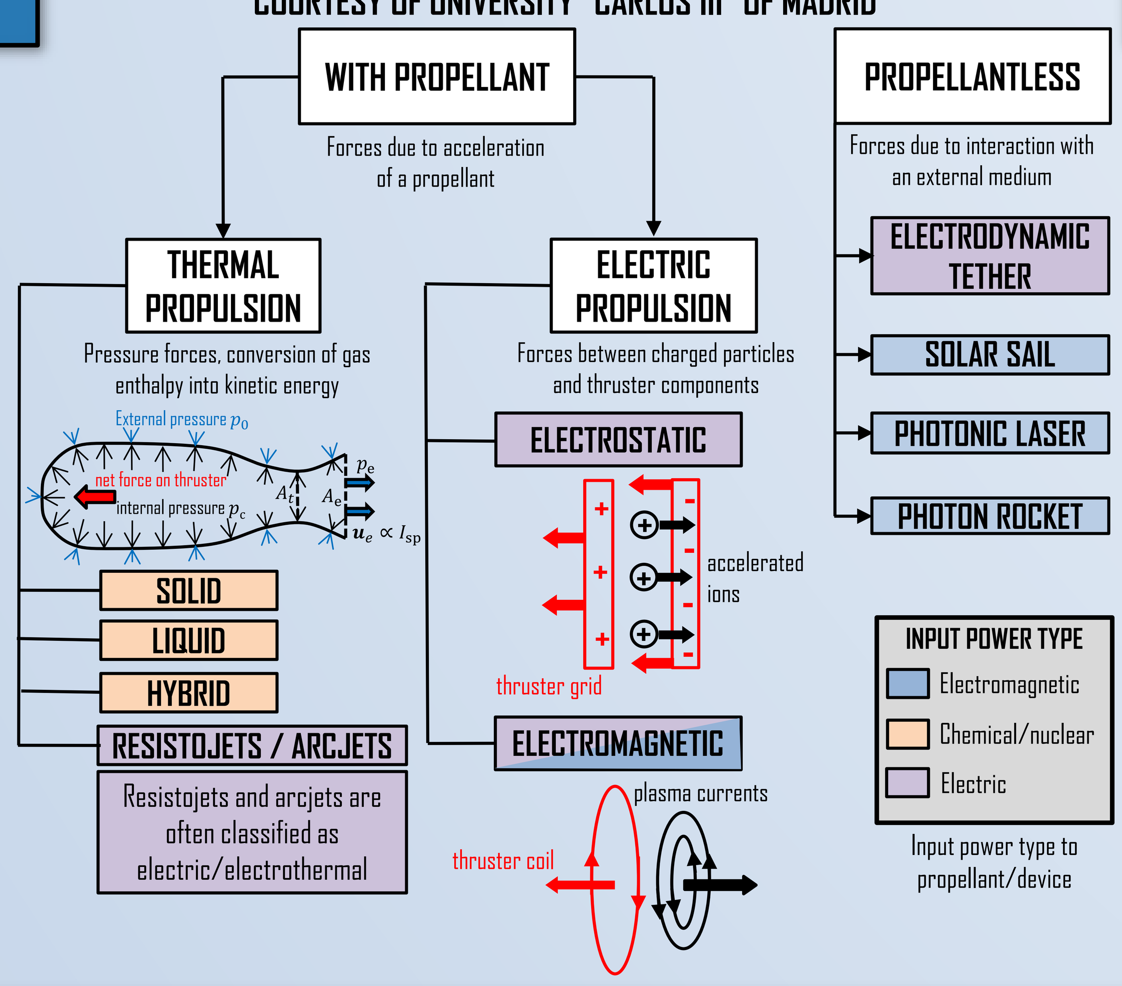
Onboard spacecraft propulsion

- Onboard propulsion is what produces a net thrust force on a spacecraft, thus enabling in-space maneuvers and trajectory control
- Thrust generation principle:
  - Thermal propulsion → gas pressure acting on thruster walls
  - Electric propulsion → electric/magnetic forces on a plasma
  - Propellantless → other force types
- Input power to the thruster/propellant can be electric, chemical/nuclear, or electromagnetic
- In propellant-based propulsion, an essential figure of merit is the required propellant mass for a given mission:

PROPELLANT MASS; INITIAL S/C MASS; MISSION DELTA-V; SPECIFIC IMPULSE ∝ EXHAUST VELOCITY

$$m_{prop} = m_0[1 - \exp(-\Delta V / I_{sp}[m/s])]$$

CLASSIFICATION OF ONBOARD S/C PROPULSION. COURTESY OF UNIVERSITY "CARLOS III" OF MADRID



Electric propulsion

- Electric propulsion is a technology, firstly demonstrated in 1960s, that enables large propellant mass savings compared to the traditional chemical propulsion
  - Accelerated propellant is mainly a **plasma** (i.e. an ionized gas with positive ions and free electrons) → need to first ionize the propellant
  - Ions can be accelerated to **unlimited** exhaust velocities (by applying an appropriate voltage drop)→ specific impulses 10 times as large as those of chemical thrusters are easily achievable: **10s of km/s VS** a **few km/s**
  - Limitation is rather on the available onboard electric power → thrust forces much smaller than those of chemical thrusters: 0.1 mN → 100 mN

THRUST FORCE ⟶ $T = (2\, \eta_T\, P)/I_{sp}[m/s]$

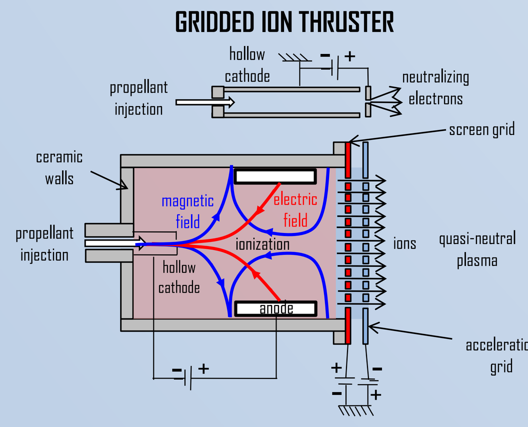
THRUSTER EFFICIENCY ($\simeq$ 50%); INPUT POWER

- **Electrostatic thrusters** → Coulomb force on non-neutral plasma
- **Electromagnetic thrusters** → Lorentz force on plasma electric current

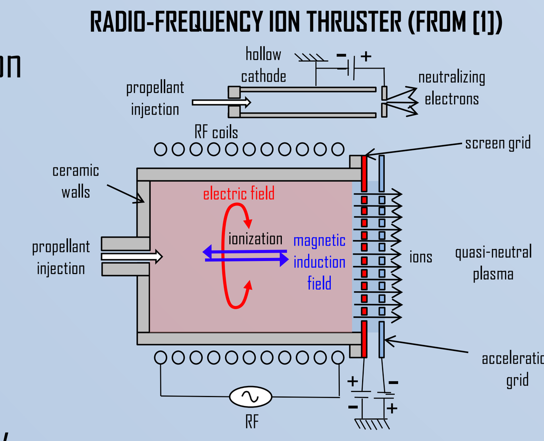
Ion thrusters and Hall thrusters

- The electric thrusters with the highest flight heritage are the **ion thruster** and the **Hall thruster**
- Ion thrusters are electrostatic thrusters
  - Thrust force generated by direct acceleration of ions through a system of grids (with holes) at different electric potentials
  - Plasma inside discharge chamber created by different means:
    - **Capacitive discharge** (gridded ion thruster)
    - **Inductive discharge** (radio-frequency ion thruster)
  - Need of an external neutralizer to avoid beam stalling
  - I_{sp} up to 100 km/s, low thrust density

GRIDDED ION THRUSTER

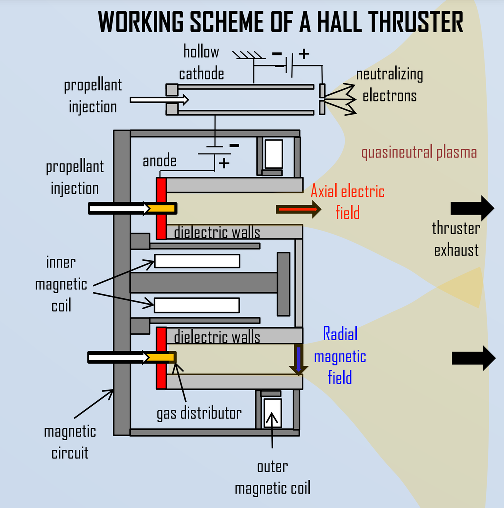


RADIO-FREQUENCY ION THRUSTER (FROM [1])

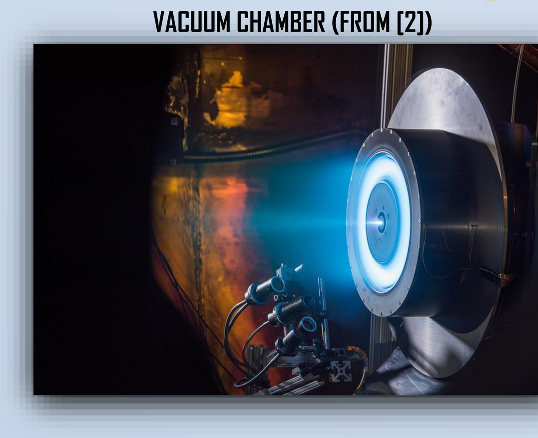


- Hall thrusters (HTs) are electromagnetic thrusters
  - Radial magnetic field applied at annular channel exit → electrons from the cathode are forced to move in the azimuthal direction due to the **ExB** drift and ionize efficiently the propellant
  - Ions are accelerated downstream by the applied potential (anode-cathode) and form a quasineutral plume
  - Thrust due to interaction of azimuthal currents and applied B field
  - $I_{sp} \simeq$ 10-30 km/s, high thrust density

WORKING SCHEME OF A HALL THRUSTER



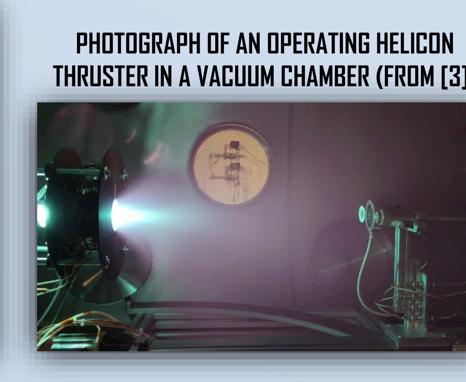
PHOTOGRAPH OF AN OPERATING HALL THRUSTER IN A VACUUM CHAMBER (FROM [2])



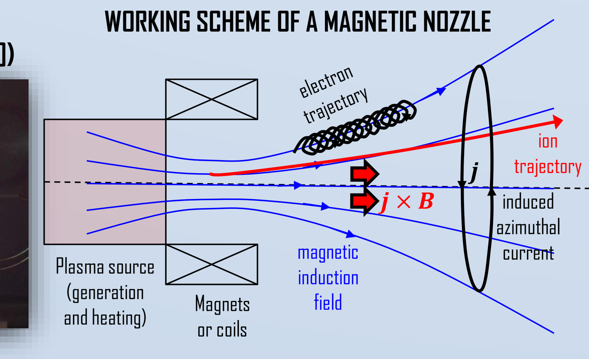
Other electric propulsion concepts

- **Field Emission Electric Propulsion** (FEEP) → electrostatic acceleration of ions from liquid metals
- **Pulsed Plasma thrusters** (PPT) → Electromagnetic (Lorentz force) acceleration of a plasma created through a capacitive discharge between capacitor plates
- Electromagnetic thrusters with a **magnetic nozzle** (MN):
  - **Electron Cyclotron Resonance** (ECR) thrusters
  - **Helicon** thrusters
  - **VASIMR** thruster (ion resonance heating)

PHOTOGRAPH OF AN OPERATING HELICON THRUSTER IN A VACUUM CHAMBER (FROM [3])



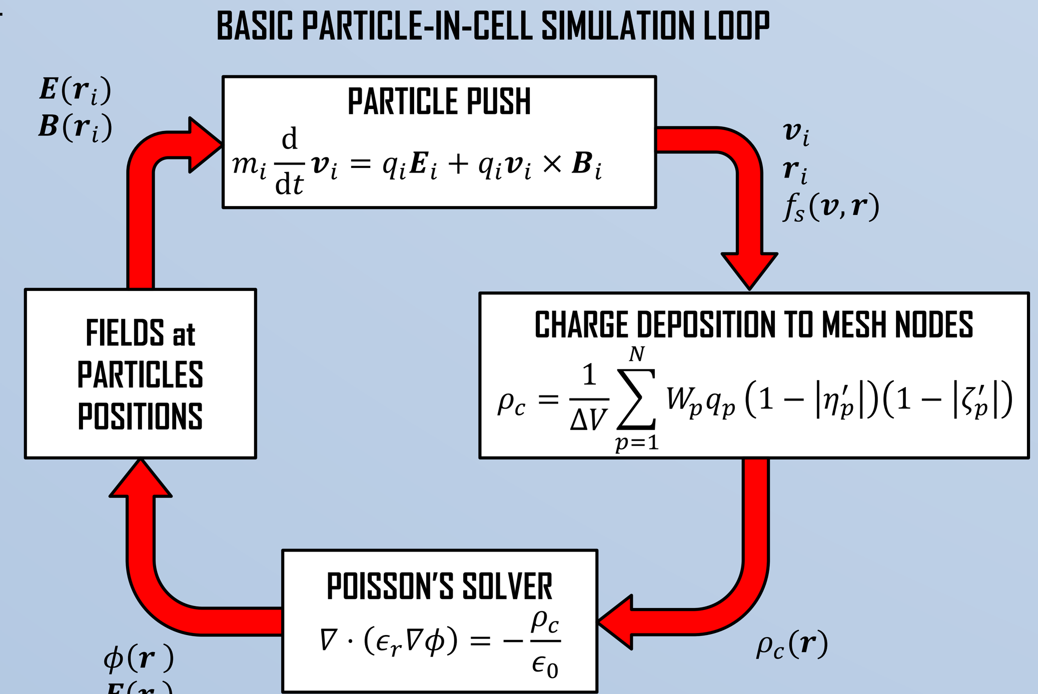
WORKING SCHEME OF A MAGNETIC NOZZLE



Importance of simulations and available models

- Testing electric thrusters require very costly experiments inside high-vacuum chambers (<10^-5 mbar) → simulations are a key element to understand the underlying physics and advance in the design quickly, without having to build expensive protoypes
- Main numerical models for simulations:
  - **Multi-fluid models** → solution of conservation equations for various fluids (ions, neutrals, electrons)
  - **Electrostatic Particle-In-Cell** (PIC) models → particle representation of all species, with a mesh-based Poisson's solver
  - Direct solution of **Boltzmann/Vlasov equations** → particle distribution functions f_s in multi-dimensional phase spaces
  - **Hybrid models**: fluid electrons, PIC for ions/neutrals

BASIC PARTICLE-IN-CELL SIMULATION LOOP



Active research lines at ISTP

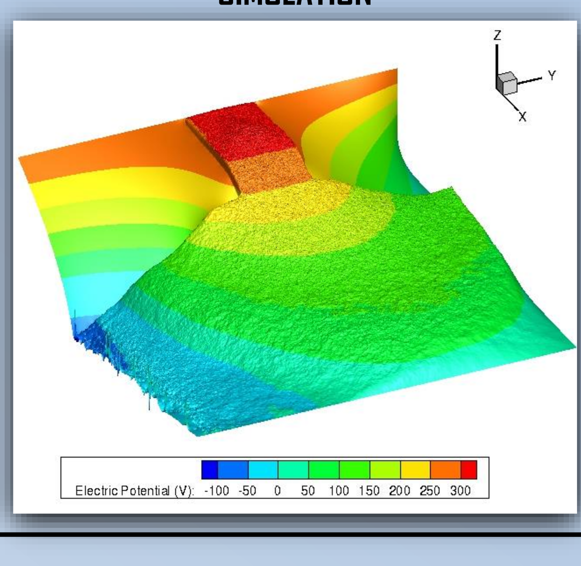
- The ISTP-Bari research group is active in the following research lines:
  - **Air-breathing Hall thrusters** (PON "CLOSE to the Earth" No. ARS ARS01-00141): 2D PIC model accounting for complex propellant chemistry and wall-interaction (associative recombination, secondary electron emission, etc…)
  - **Hall thruster anomalous transport fundamental study**: 3D PIC model applied to a HT to study azimuthal fluctuations in plasma properties, which are thought to be at the origin of the enhanced axial electron mobility inside the channel
  - **Plumes from Hall thruster clusters**: hybrid 3D models
  - **Plasma plume interaction with spacecraft**: hybrid 2D/3D PIC models
  - Microwave **micro-thruster manufacturing and simulation** (RIPARTI, Puglia)
  - **ExB device benchmark simulations**: Penning device

Simulation Results

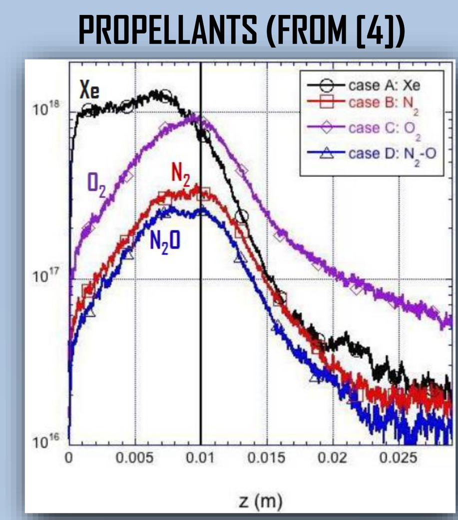
2D HALL THRUSTER MODELING

- Assessment of the thruster performance using alternative propellants like O_2, N_2 and an N_2/O mixture→ feasibility of air-breathing propulsion

ELECTRIC POTENTIAL MAP IN A 2D HET PIC SIMULATION



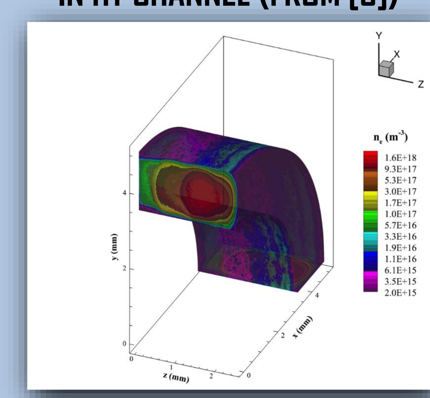
PLASMA DENSITY [m^-3] ALONG CHANNEL CENTERLINE FOR VARIOUS PROPELLANTS (FROM [4])



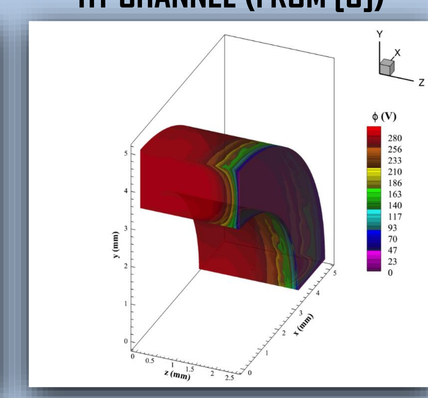
3D HALL THRUSTER MODELING

- Anomalous axial transport of electrons in HTs is thought to be provoked by azimuthal plasma properties fluctuations in time and space
- 3D PIC simulations of a HT seem to confirm the formation of such azimuthal structures

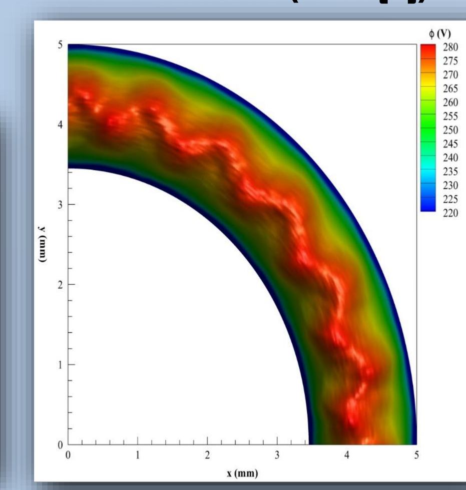
3D PLASMA DENSITY CONTOURS IN HT CHANNEL (FROM [6])



3D POTENTIAL CONTOURS IN HT CHANNEL (FROM [6])



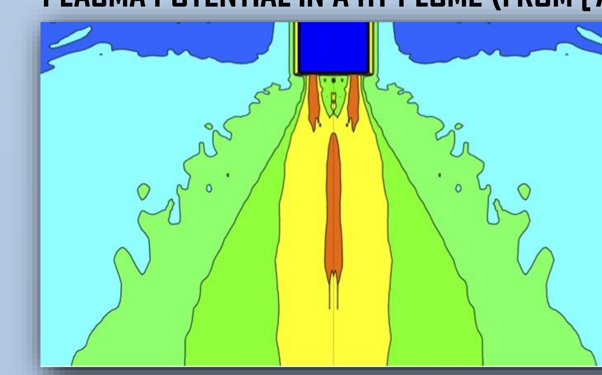
AZIMUTHAL PLASMA POTENTIAL FLUCTUATIONS (FROM [6])



HT PLUMES MODELING

- HT plasma plume expansion and divergence due to charge-exchange ion-neutral collisions
- Plasma-spacecraft interaction
- Cluster plumes interference and self-organized electrostatic structures

PLASMA POTENTIAL IN A HT PLUME (FROM [7])



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[1] F. Cichocki et al, *Electric Propulsion Subsystem Optimization for "Ion Beam Shepherd" Missions*, Journal of Propulsion and Power, 33(2), 370-378.

[2] Photograph by Charly W. Karl license at: https://creativecommons.org/licenses/by-nd/2.0/

[3] F. Cichocki et al. *Magnetic Nozzle and RPA Simulations vs. Experiments for a Helicon Plasma Thruster Plume*, Frontiers in Physics, Vol. 10, 2022

[4] F. Taccogna, F. Cichocki, P. Minelli, *PIC model of an air-breathing low power Hall thruster*, 8th Space Propulsion Conference, N. 324, Estoril, Portugal, May 9-13, 2022

[5] F. Taccogna, L. Garrigues, *Latest progress in Hall thrusters plasma modelling*. Reviews of Modern Plasma Physics, 3(1), 1-63, 2019

[6] F. Taccogna, P. Minelli, *Three-dimensional particle-in-cell model of Hall thruster: The discharge channel*, Physics of Plasmas, 25(6), 061208, 2018.

[7] F. Taccogna et al, *Three-dimensional plume simulation of multi-channel thruster configuration*, Plasma Sources Science and Technology 23 (6), 065034, 2014

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CONTACT

filippo.cichocki@istp.cnr.it

francesco.taccogna@cnr.it

pierpaolo.minelli@cnr.it

web: https://www.istp.cnr.it/