Overview of CIRA development in Plasma Electric Propulsion

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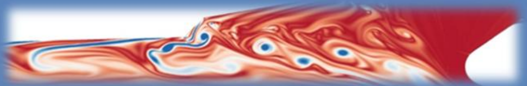
CiP 2026
1° Conferenza Italiana Plasmi

- Technical competencies that covers **different phases of projects** related to propulsion systems development from requirement definition, advanced analysis (CFD,PIC,FEM), design of systems and subcomponents, manufacturing process development and testing
- Experience gained since 2011 thanks to the participation at national and international **cutting-edge projects**
- **Manage Electric Propulsion Laboratory**

Research Fields

Supersonic Propulsion

Solid Rocket Motors



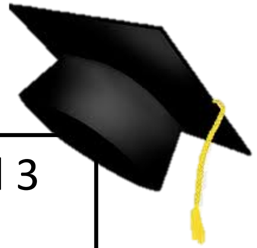
Cryogenic rocket propulsion (LOX/LCH4)

Hybrid rocket propulsion

Electric propulsion

Main Partnerships and Cooperations

SITAEL, AVIO, Consiglio Nazionale delle Ricerche, JAXA, ONERA, Università degli Studi della Campania Luigi Vanvitelli, MAI, COMOTI, DLR, TU Delft, ISAE ENSMA, Politecnico di Torino, Purdue Propulsion, Universität der Bundeswehr München, FISMET SERVICE, VII, Marotta, OKOS, CECOM, POLITECNICO MILANO 1863

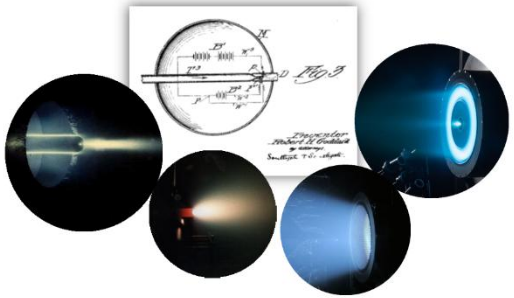


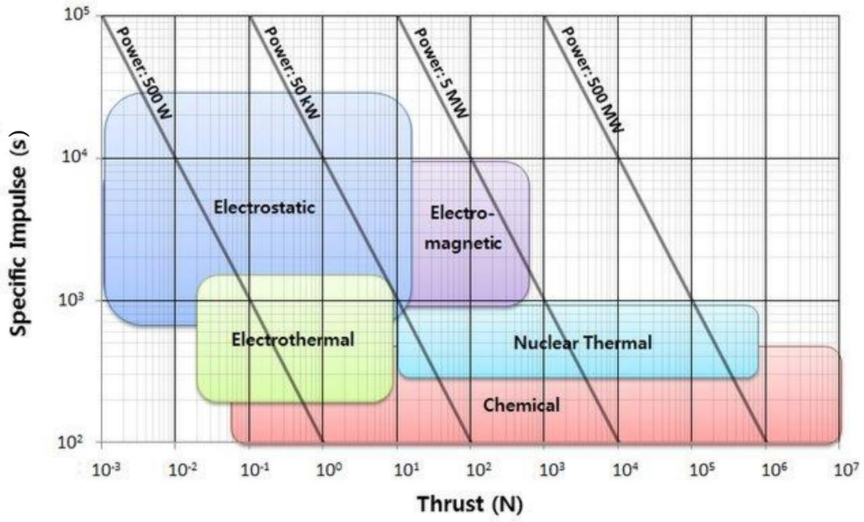
Hosted about 12 Master students and 3 PhD students per year

Background: Electric Propulsion

- Operates by using **electrical energy to accelerate particles**, which in turn generates thrust. It reaches very high levels of specific impulse and low thrust
- Commonly used for missions requiring high efficiency over long durations, such as satellite station-keeping and attitude control, deorbiting or space exploration.

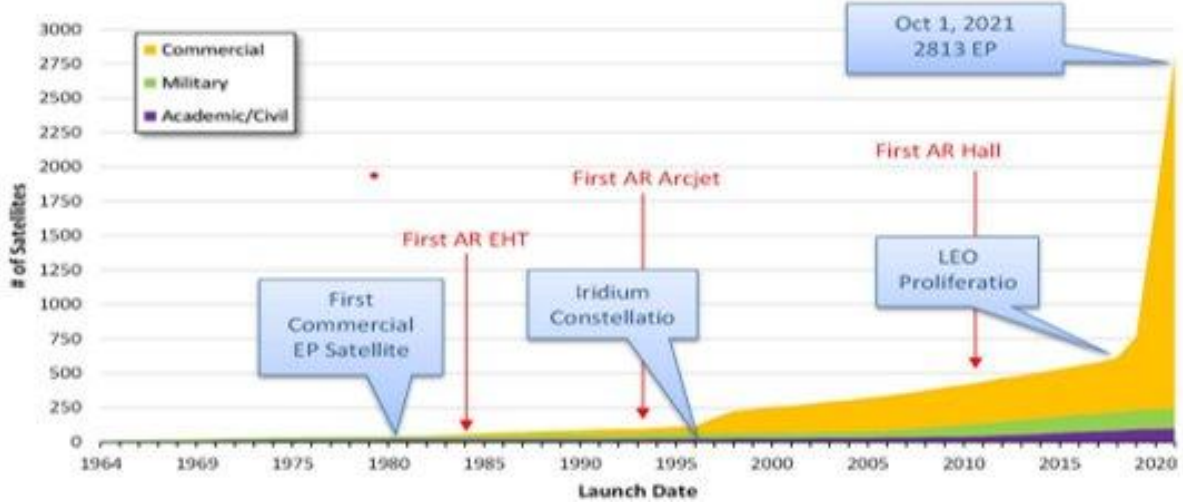
Electric Propulsion
- ElectroThermal
- ElectroStatic
- ElectroMagnetic





Accelerating Process		Form of Energy Supplied to the Thruster: Electric			Chemical	Nuclear
Gasdyn.	$v_e \sim \sqrt{\frac{T}{m}}$	Electro thermal		Resistojets Arcjets	Solid and Liquid Propellant Rockets	Nuclear Rockets
Electrostatic	$v_e \sim \sqrt{\frac{2qV}{M}}$	Electro static	Ion Thrusters	Gridded Ion Thrusters FEEP, Colloid Thrusters		
			Plasma Thrusters	Hall Effect Thrusters		
Electromag.	$v_e \sim \frac{I^2}{\dot{m}}$	Electro magnetic		MPD Thrusters		

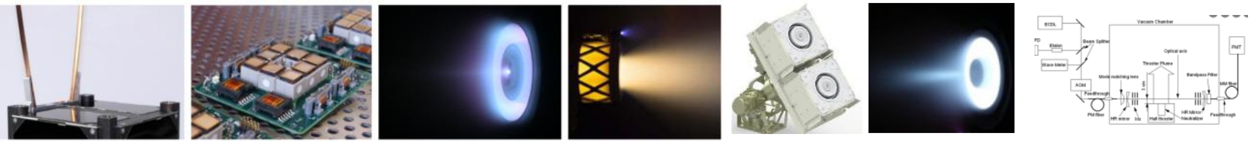
(Jhan, R.G., *Physics of Electric Propulsion*, McGraw-Hill, New York, 1968)



(Frongello, B.R. et al. *Spacecraft Electric Propulsion at an Inflection Point*, AIAA 2021-4151)

Programma Nazionale di Ricerche Aerospaziali
Investments in Electric Propulsion

Low Power Electric propulsion (LPEP)



images from open literature

Facility upgrades

Upgrade of current facility (MSVC) capabilities and availability
Small vacuum chamber (SSVC) for subsystem development
New closed clean area for integration

Diagnostics

Cavity Ring Down Spectroscopy
DLIF system
New Thrust stands
New Probes

Design & Analysis

Consolidation of thruster testing activities
New experimental thrusters
Advanced numerical code

The X2, X3, and N30 nested Hall thrusters
(Jorns, B. *Future Directions for Electric Propulsion Research*, Aerospace 2020, 7, 120)

Design and realization of a brand new simulator devoted to high power thrusters (>10 kW)

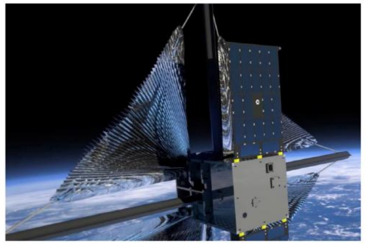
Development of experimental thrusters and diagnostic for research purposes

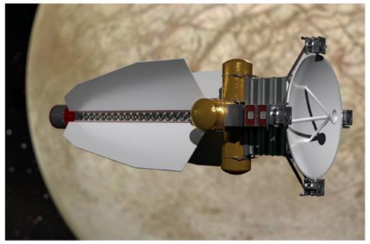
High Power Electric propulsion (HPEP)

Innovative Technologies (MATI)

To improve TRL of innovative solutions

To explore Disruptive technologies in Electric Propulsion





Electric Propulsion Laboratory
Main features

Medium Scale Vacuum Chamber (MSVC)

AIMS

- Enabling the start of planned **R&D activities** on engines up to **5** kW (to improve experimental, design and analysis capabilities; to test advanced diagnostics; to research on innovative materials, propellants, technologies; to evaluate performance, to characterize plume, to perform lifetime tests)
- Integrating test infrastructures, currently available in Italy and commercially oriented, with an advanced facility
- Promoting the **Cooperation** with other National and International actors

MAIN FEATURES

- **Dimension**: 2 m-diameter x 4.5 m-long
- **Pumping speed:** up to about 80,000 l/s (Xe) and fully cooled
- **Vacuum Performance**: 5e^{-8} mbar (ultimate pressure); < 4.0e^{-5} mbar (working)

SSVC (Small Scale Vacuum Chamber)

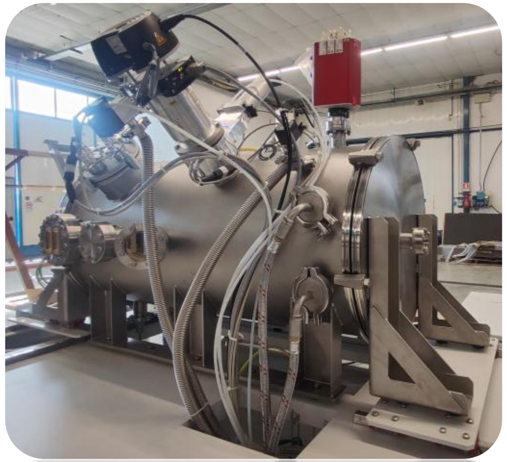
AIMS

- Conceived for **R&D activities** on **cathodes** and **micro-propulsion**

Installation: end of 2025

MAIN FEATURES

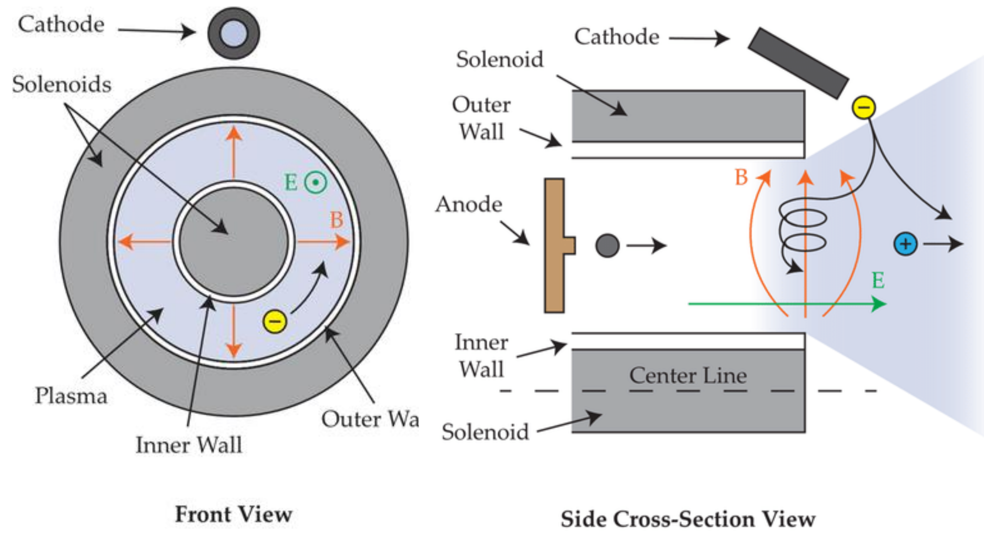
- **Dimensions:** 0.5 m- diameter x 1.0 m-long
- **Pumping speed:** 8000 l/s (Xe), one cryopanel
- **Vacuum Performance**: 1 e^{-7} mbar (ultimate pressure)

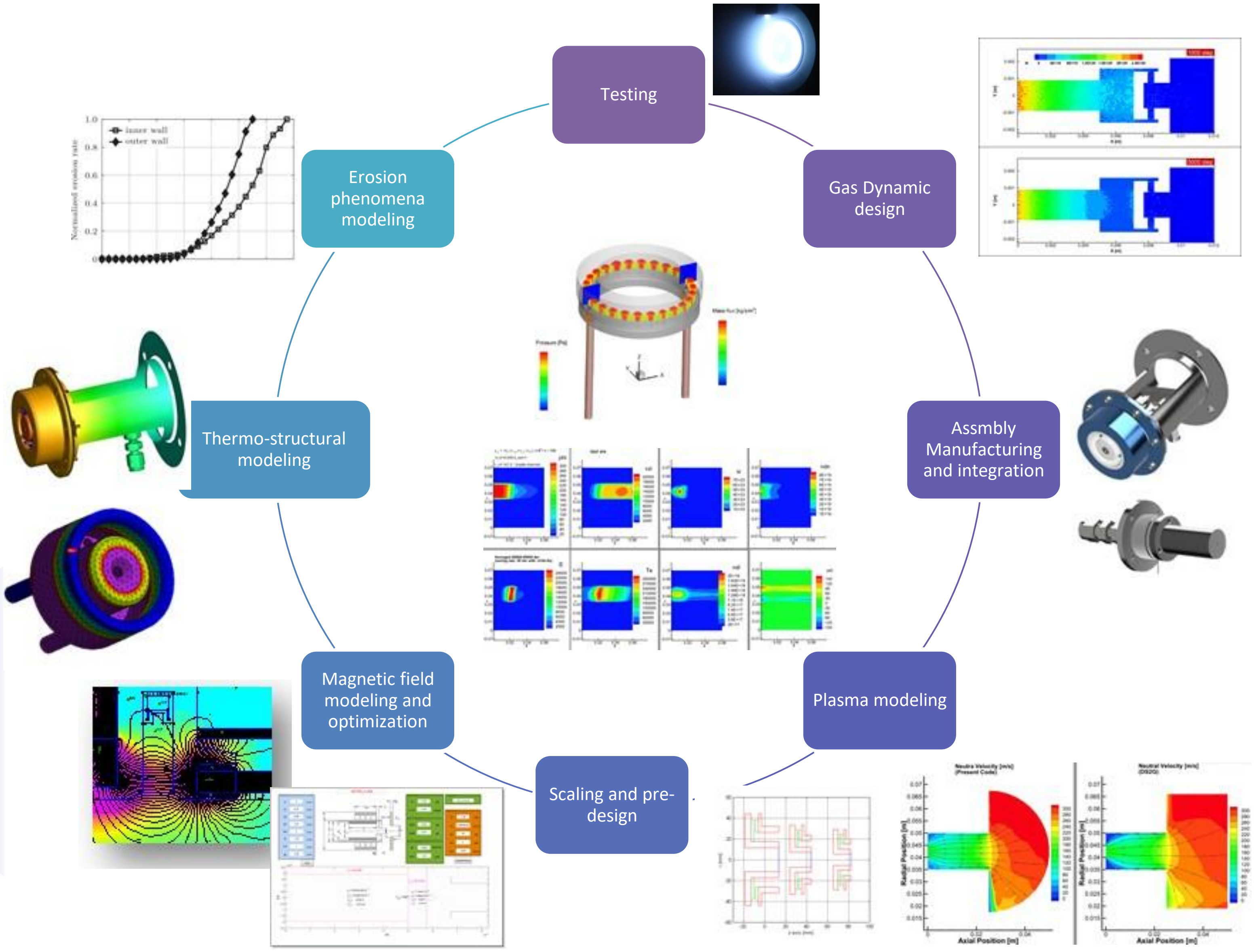


Development of Laboratory Hardwares
Hall Effect Thruster (HET)

The **Experimental Thrusters** line has been established to improve knowledge on design and modeling aspect of electric propulsion
Competences cover the activities from design to AIT and post-test investigations

- Some **HARDWARE** has been designed and manufactured to verify design and manufacturing processes (thrusters and cathodes)
- Proprietary design **NUMERICAL TOOLS** have been developed

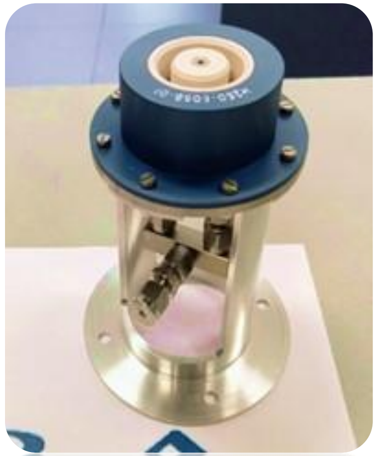




Development of Laboratory Hardwares
CRHET-250

CRHET-250 is a 250W Hall Effect Thruster (HET), designed and manufactured by CIRA. Three Units, namely MarK (**MK**) are currently available and further two ones will be shortly ready after configuration optimization analyses.

CRHET-250	
Discharge Power	250 W
Thrust	11 mN
Specific Impulse	1250 s
Propellant	Xe/Kr
Cathode Location	External
Thruster Mass	0.45 kg



MK3

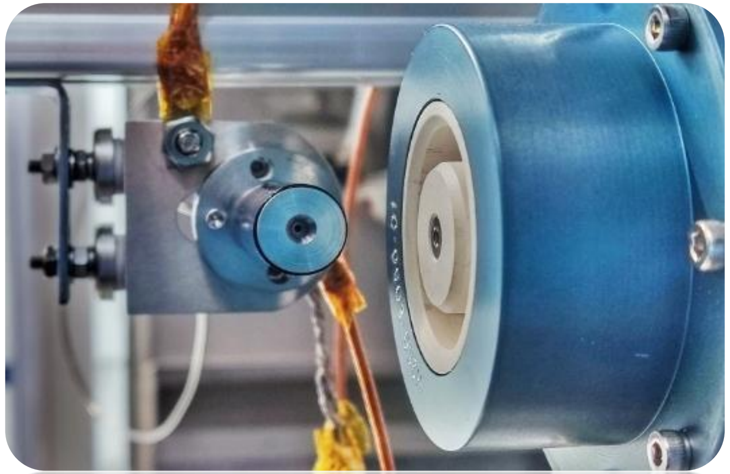
MK1 [1] Experimental Results @ 0.6 mg/s	
Discharge Power	150W-300W
Thrust	7.5 -10 mN
Specific Impulse	1300-1550 s
Propellant	Xenon

- **MK1**
  - About **100 ignitions**
  - > **100h of cumulated firing time**
  - At least **50h of continuous firing**
- **MK2**
  - currently under test

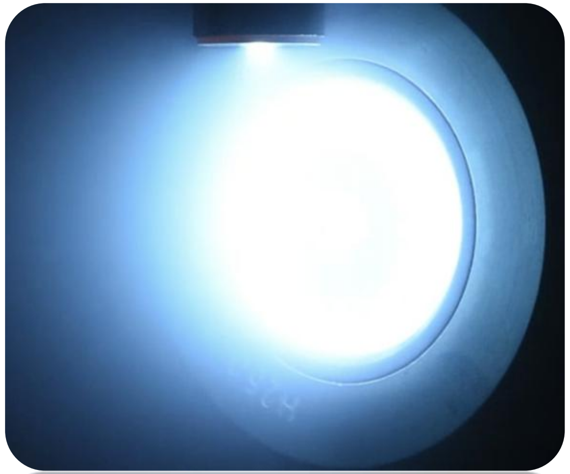
Experimental Campaigns goals

- ✓ Ignition strategy
- ✓ Optimization of cathode position
- ✓ Electrical Characteristics Study
- ○ Performance Tests
- ○ Improvement of thrust balance arrangement
- ○ Endurance tests
- ○ Performance optimization through diagnostics

○ On going
✓ Completed



MK1: experimental set-up



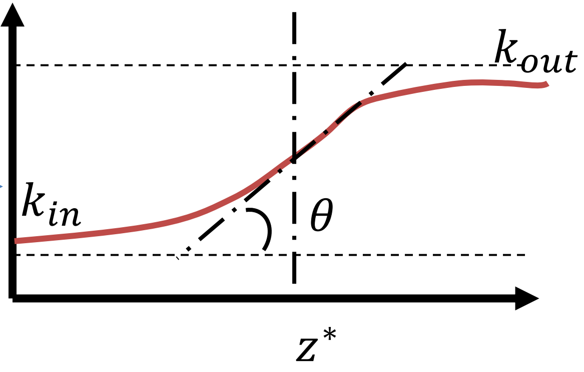
MK2: High ionization regime

NUMERICAL ACTIVITIES
HYPICFLU2 (HYbrid Particle-In-Cell + FLUid) [4]

- 2D axis-symmetric (radial-axial)
- Unsteady
- Domain: channel + near plume (semicircular)
- PIC: neutrals and ions (only primary ionization)
  - Wall BC: neutrals diffuse-reflect; ions recombined
- Fluid approach: electrons – thermalized potential
  - Dirichlet: (Te, V) @ cathode & Anode (Te)
- Wall Sheath: Charge Saturation Regime included
- Bohm Forcing Condition at domain boundary
- Neglected collisions: neutral-neutral, ion-neutral, ion-ion, elettron-electron.
- Semi-empirical Electron Mobility model:

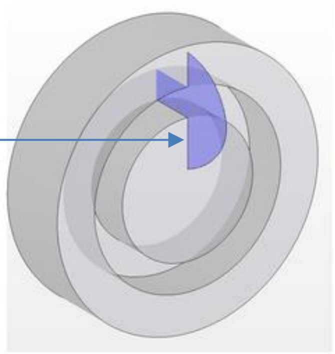
$$\mu_e = \frac{m_e(\nu_{en} + \nu_{ei} + \nu_w)}{e\,B^2} + \frac{k}{16\,B}$$

$$k = f(k_{in}, k_{out}, \theta, z^*)$$



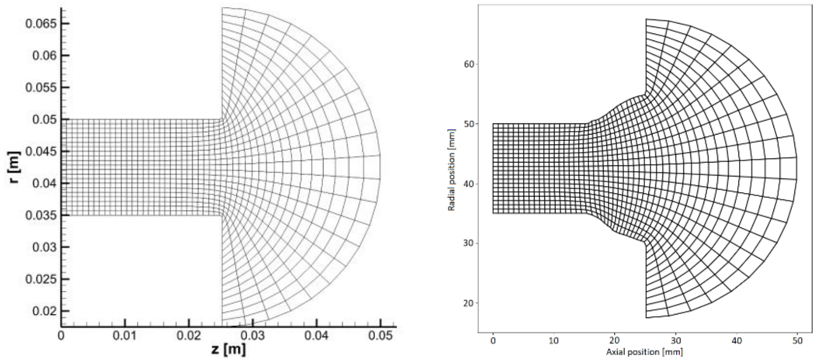
- python Parallelized (mpi4py)

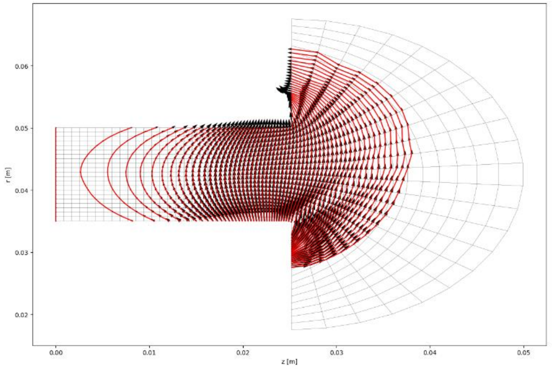
Domain



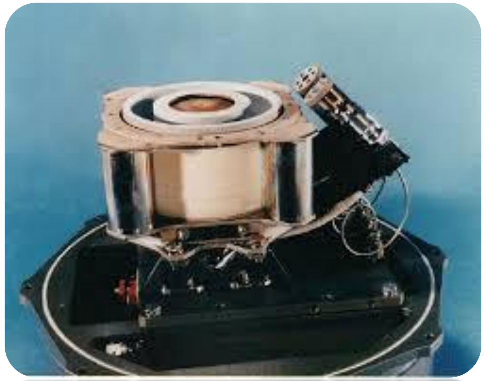
Automatic Elliptic PIC Mesh Generator

Possibility to mesh domains with eroded channel wall's profile





NUMERICAL ACTIVITIES
HYPICFLU2 [4] - Validation: SPT100



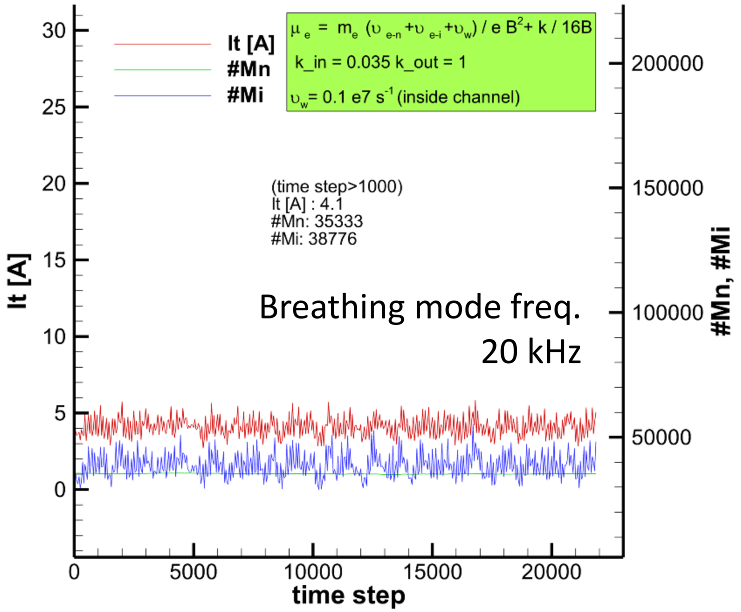
Nominal Operating Point [2]

Outer radius [mm]	50
Inner radius [mm]	35
Channel length [mm]	25
Max magnetic field value [G] (coils)	180
Mass flow rate (Xe) [mg/s]	5.3
Discharge Voltage [V]	300 V
Discharge Current [A]	4.5
Discharge Power [W]	1350
Specific impulse [s]	1600
Efficiency [%]	50

Computational Time

<u>22000 timesteps completed in 5h</u>

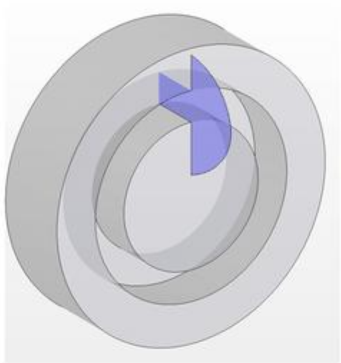
Using 1 node (36cpus) of CIRA cluster (Turing): dual socket Xeon E5-2697 v4 @ 2.30GHz tot: 1440 core



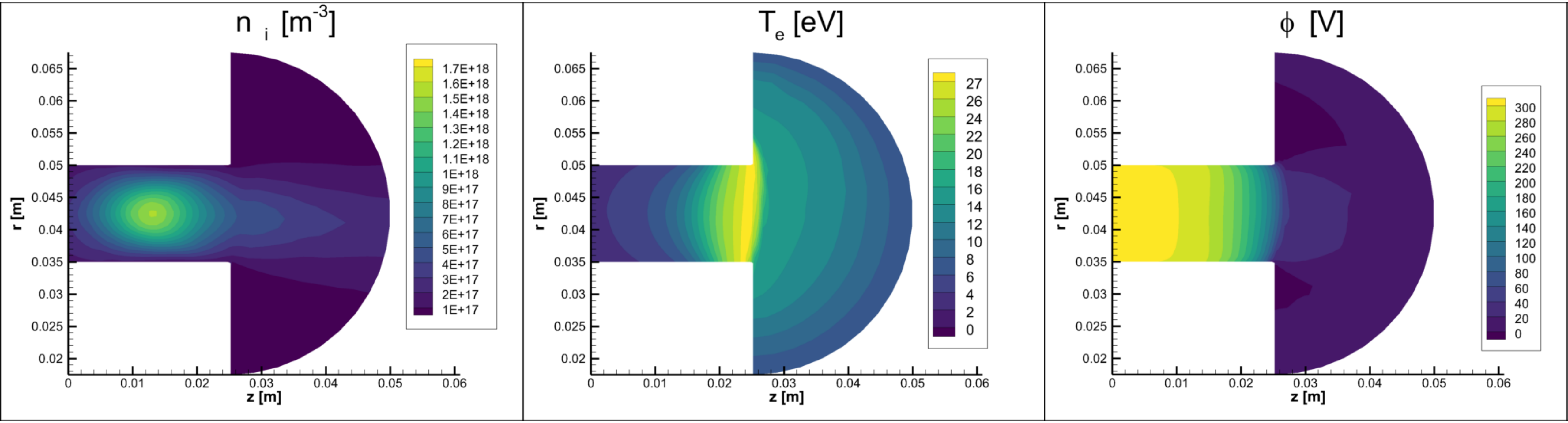
	EXP. [2]	NUM. [3]	HYPICFLU2 [4]
Discharge Current [A]	4.5	4.5	**4.1**
Power [W]	1350	1350	**1207**
Ion exhaust velocity [km/s]	15.7	17	**16.2**
Mass flow rate [mg/s]	5.29	5	**4.67**
Specific Impulse [s]	1600	1733	**1646**
Thrust [mN]	83	85	**75**
Efficiency [%]	50	55	**50**

- Low current (i.e. power) due to low mobility with respect the reference; (improvement cab be achieved by modifying the <u>mobility function empirical parameters</u>)
- Low Thrust due to lower ion flow rate at the cathode line

Time averaged [time window 1ms] contour plots of:



- ✓ plasma density (n_i): peak within the channel
- ✓ electron temperature (Te): peak toward channel exit
- ✓ potential (ϕ): sharp decreasing at the channel exit

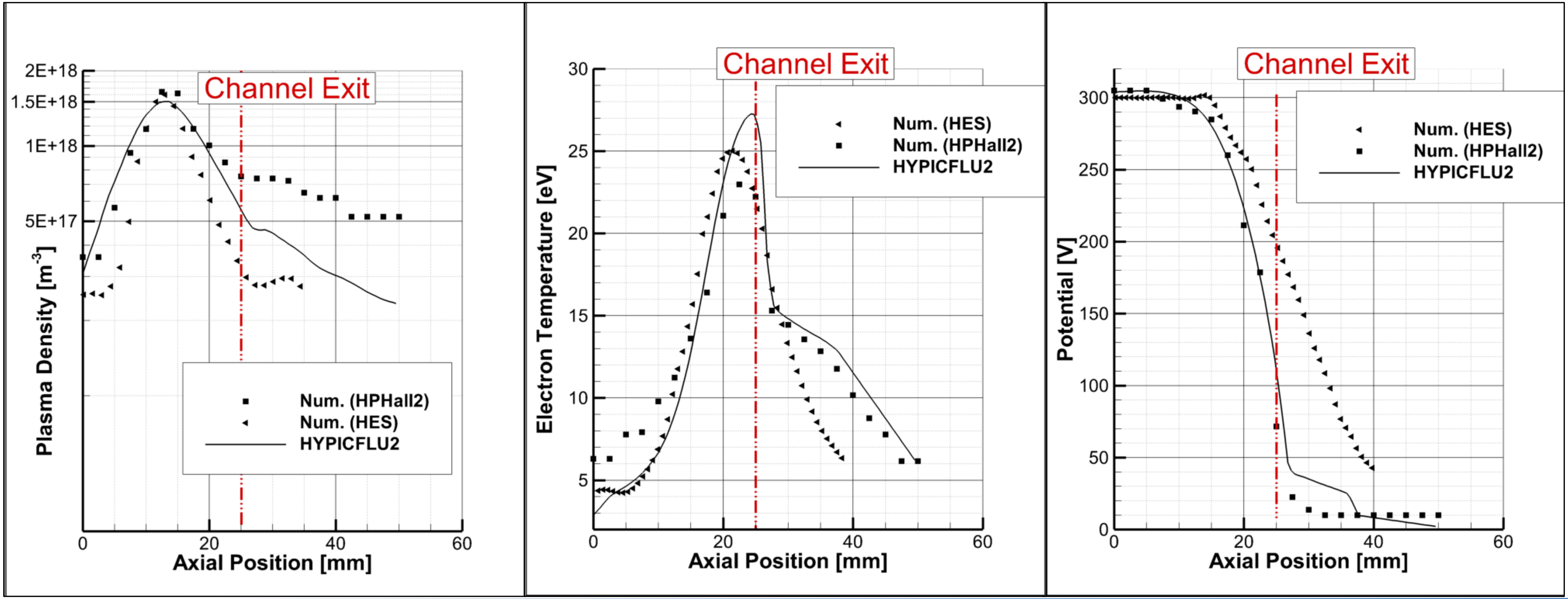


Profiles extracted along the mean centerline

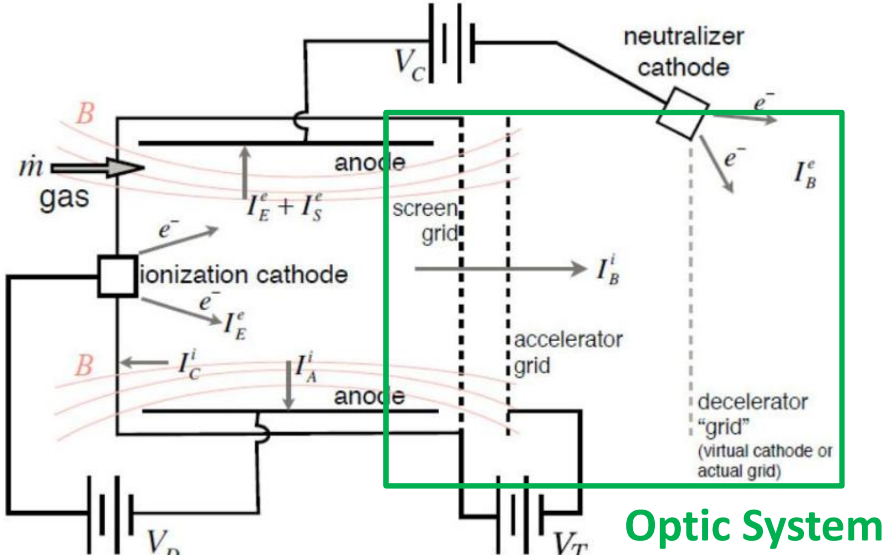
- Peak similar to HPHall2 [3]/HES [5]
- Lower density in the plume (HPHall2)

- Peak higher than HPHall2/HES

- Trend similar to HPHall2



NUMERICAL ACTIVITIES
Gridded Ion Thruster (GIT) Optic System



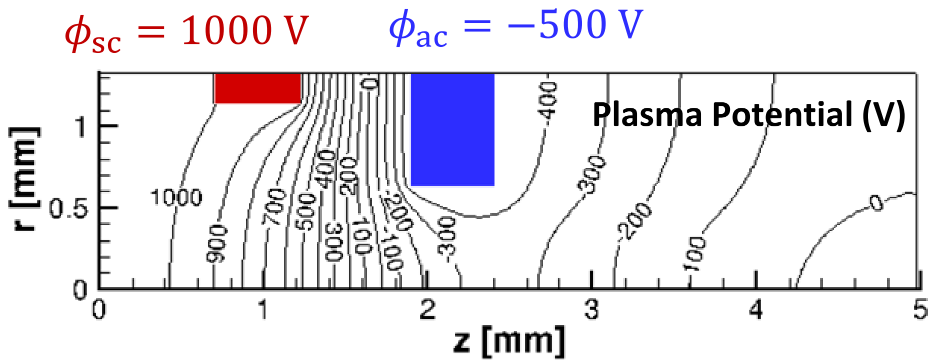
GosPIC: Hybrid Particle-In-Cell approach [6]

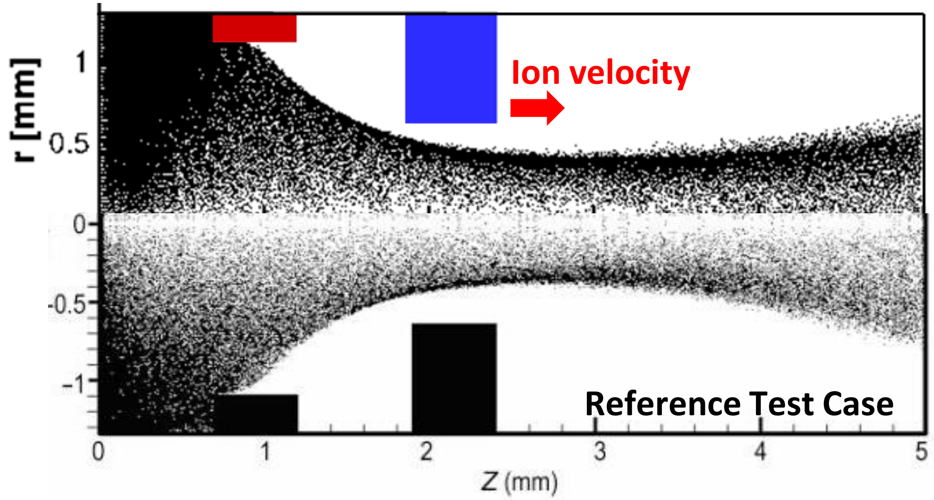
- Representation of ions by macroparticles
- Modeling of electrons as an isothermal fluid

Assumptions

- Xenon ions
- 2D axisymmetric domain with a uniform mesh, representing half of a single aperture of a grid set
- Complete ionization of plasma
- No charge-exchange ions (CEX)
- Metallic grids

$\phi_{sc} = 1000\text{ V}$ $\phi_{ac} = -500\text{ V}$

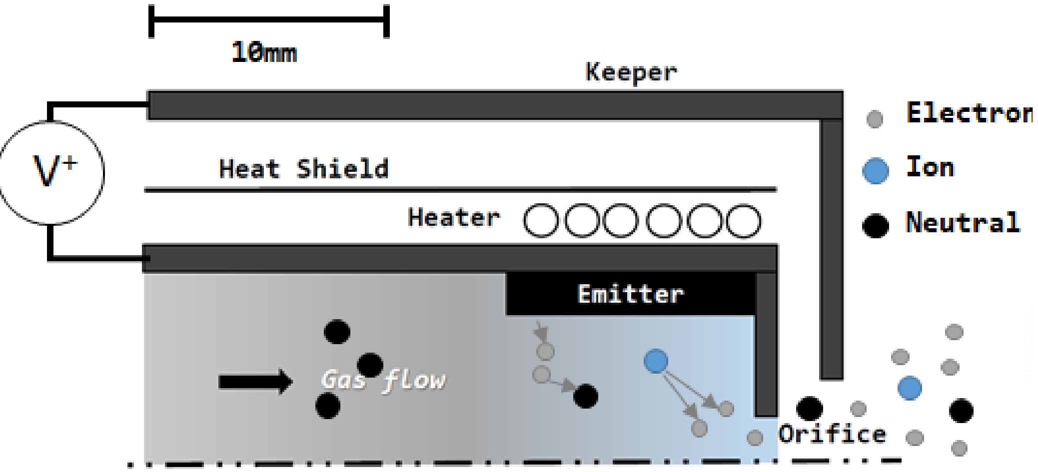


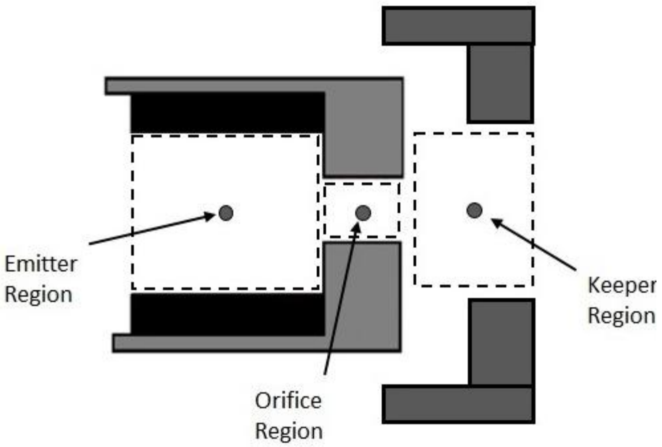


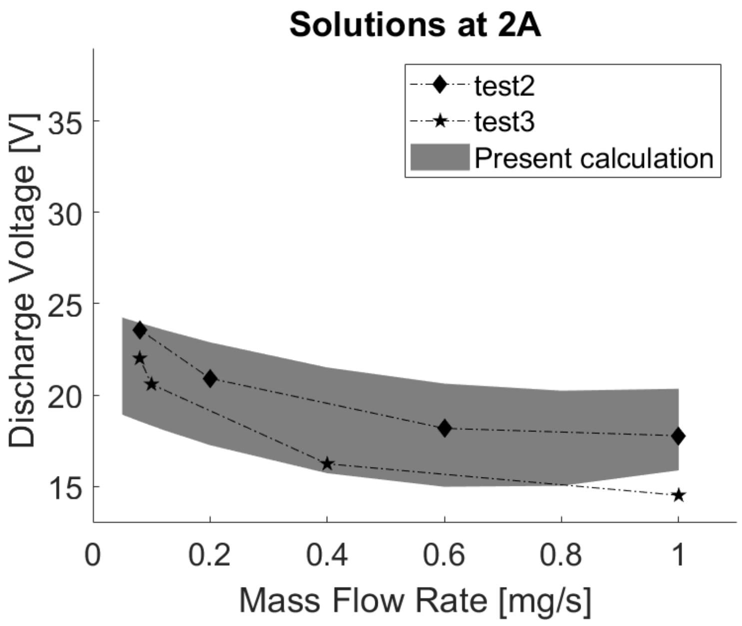
(Zhong et al., *Numerical Simulation of Ion Extraction Through Ion Thruster Optics*, Plasma Science and Technology. 2010)

NUMERICAL ACTIVITIES
Orificed Hollow Cathode Reduced Plasma Model (0D)

Particle Swarm Optimizator (PSO) used to solve non linear system of equations for plasma







CR-CAT Orificed Hollow Catode [7]

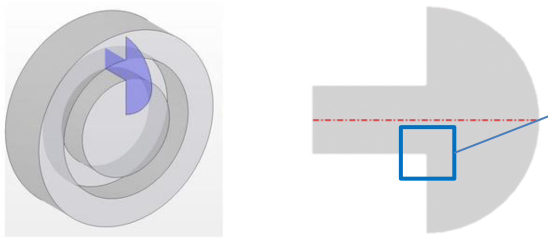
CR-CAT	
Discharge Current	1 A
Discharge Voltage	14.2 V
Mass Flow Rate	0.097 mg/s
Propellant	Xenon

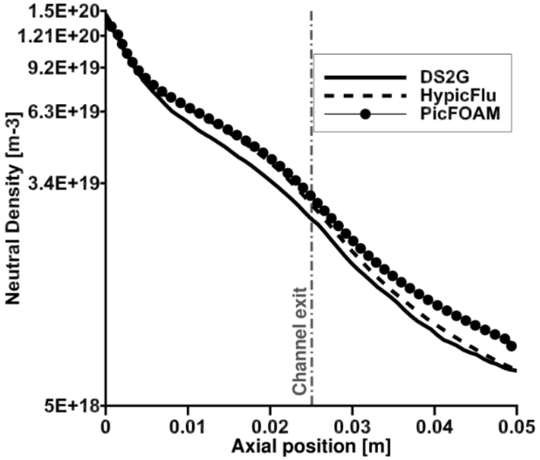
Preliminary Orificed Hollow Cathode (OHC) design tool [8]

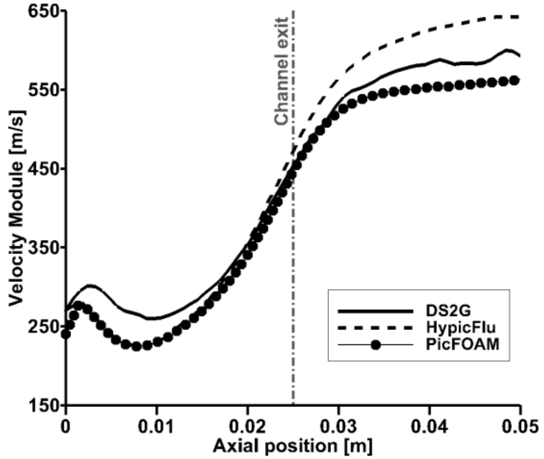
AB - HET: Plasma-OFF simulations

Air-Breathing thrusters **captures air in Very Low Earth Orbit (VLEO)** through an intake and conveying it to the accelerator channel.

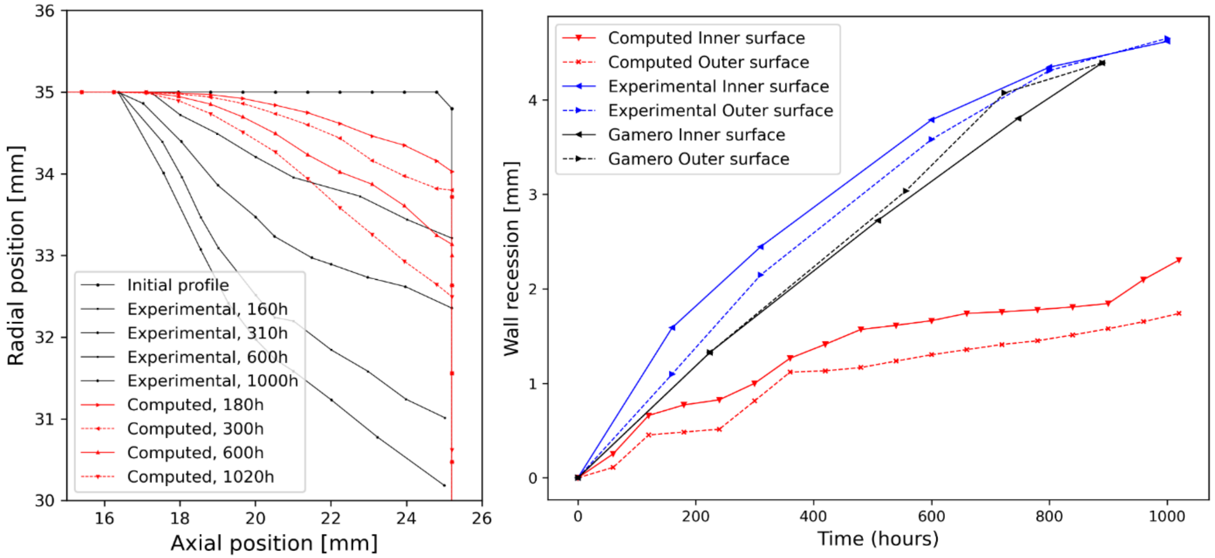
N_2 - O_2 mixture flowing into HET's channel []







HET wall channel Erosion [4]



Sputtering Yield (Xe-BNSiO$_2$)

$$Y_i = f(E,\theta)C_T$$

→ Empirical coeffiecient to include temperature effect

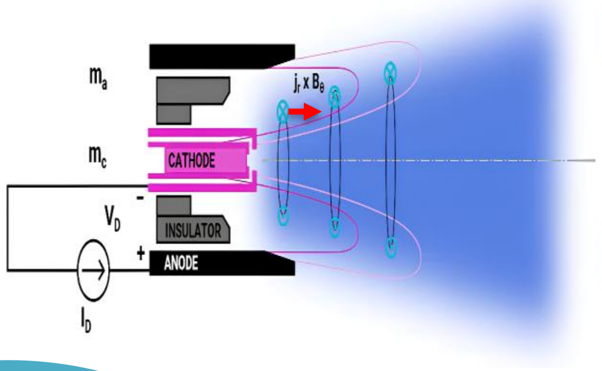
- Underprediction vs. experiments: 50-60 %
- But the erosion rate decreases with time

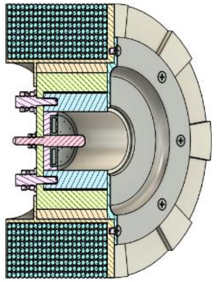
Curve Fitting Approach

Other Models (Thermal, Magnetics)

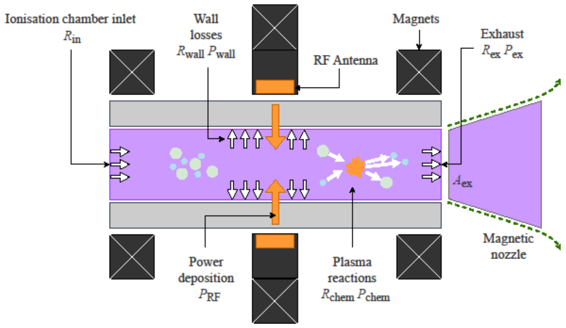
Plasma Model

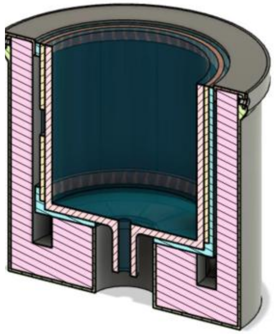
Magneto Plasma Dynamic Thruster (**MPDT**)



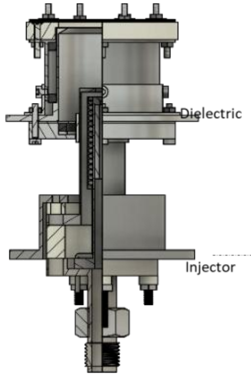


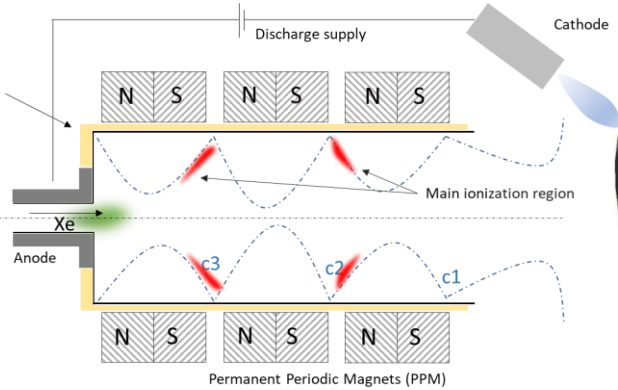
Helicon Plasma Thrusters (**HPT**) [11]

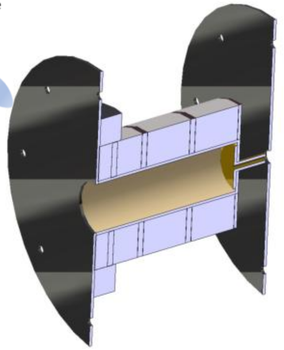




Gridded Ion Thruster (**GIT**) [12]







High-Efficiency Multistage Plasma Thruster (**HEMPT**) [13]

PROTOTYPE DESIGN
HPT – MPDT

We are going to build two laboratory demonstrators to be tested in MSVC

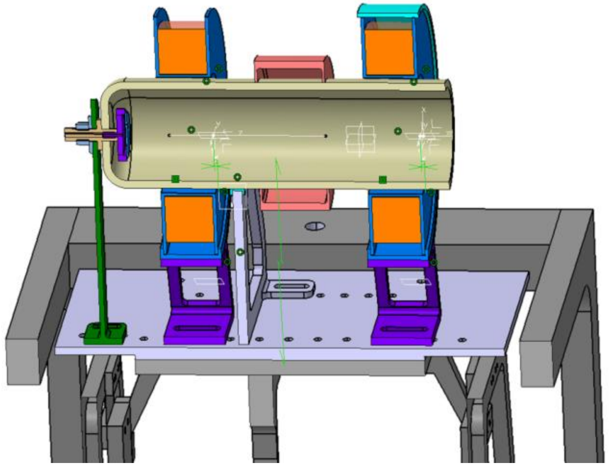
HPT [14]

P_{in} = 1 kW

Propellant mass flow rate: 3-5 mg/s (Argon)

Antenna Configuration: toroidal

Applied Field : 0.06 T



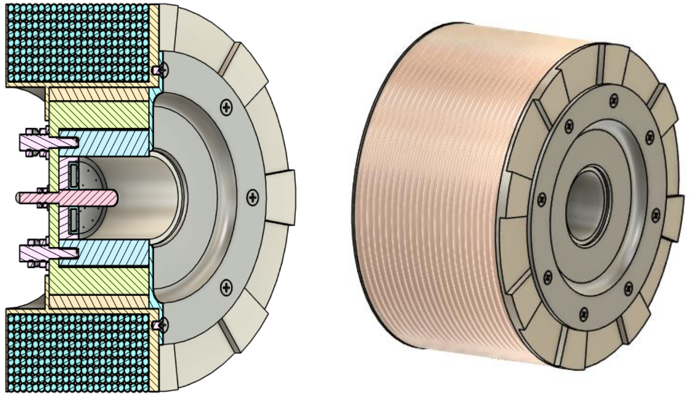
MPD

P_{in} = 4.5 kW

Propellant mass flow rate: 10 mg/s (Argon)

Configuration : AF-MPDT

Applied Field : 0.2 T



Conclusions

- Electric Propulsion Laboratory:
  - Medium Vacuum Scale Chamber (MSVC) – 5kW Plasma Thrusters
  - Small Scale Vacuum Chamber (SSVC) – Cathodes and micro plasma propulsion
- Hardware Design:
  - Hall Effect Thruster (CR-HET250) – Designed/Tested
  - Helicon Plasma Thruster (HPT) – Design on going
  - Magneto Plasma Dynamic (MPD) - Design on going
- Numerical Activities:
  - Hall Effect Thrusters (HET) – HPYCFLU2 / Wall Erosion by plasma
  - Gridded Ion Thrusters (GIT) - GosPIC
  - GIT, HPT, MPD, High-Efficiency Multistage Plasma Thruster (HEMPT) - Global Models

Workshop

- Plasma simulations (HET, MPD, HPT)
- Code-code comparison
- Air Breathing Electric Propulsion: simulations and experiments
- Sputtering evaluation:

  Xenon-Borisil (BN-SIO2); Temperature: 30 -600°C; Impact angle: 0-85°; Energy: 10-250 eV
- Intrusive or Optical Diagnostics for plasma
- Electron Mobility Modeling

References

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Thank you for listening!

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