HYPICFLU2: Hybrid PIC-Fluid plasma model for Hall Effect Thrusters

EPIC Workshop 2023, Naples, IT

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2002-2007 - MSc in Aerospace Engineering - University of Naples, Federico II.

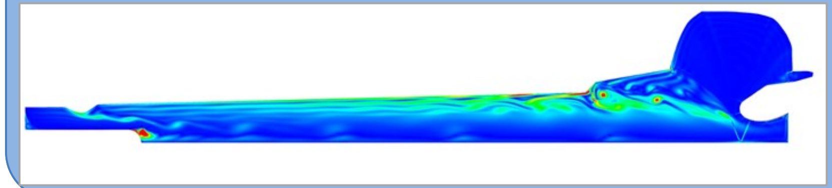
2008-2011 - PhD in Aerospace, Naval and Quality Management Engineering - University of Naples, Federico II.

2011-today - Researcher - Space Propulsion Laboratory - The Italian Aerospace Research Centre (CIRA)

Research Activities at CIRA:

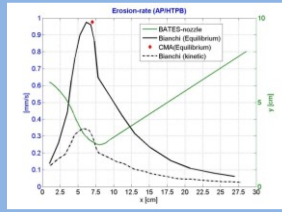
SRM

Pressure oscillation

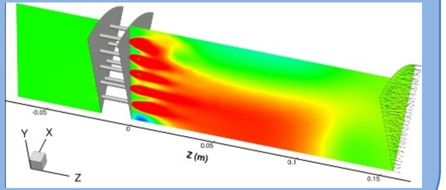


HRE

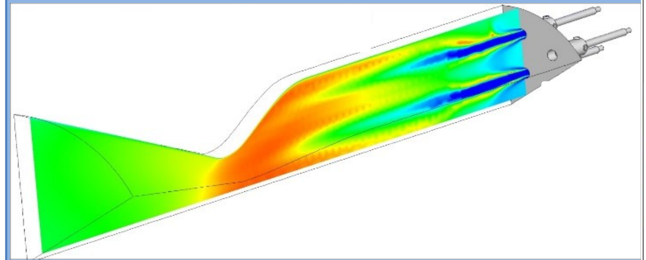
Nozzle ablation



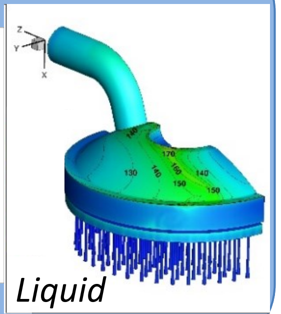
Cavitating Injection



LRE



Combustion – heat transfer

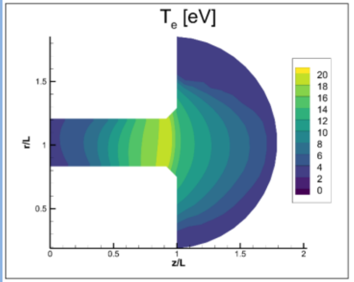


Liquid Distribution

EP

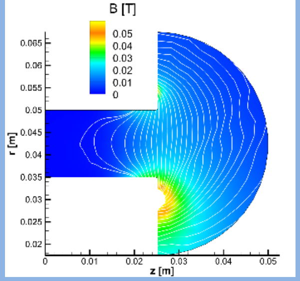
OHCs' plasma

OHCs' design

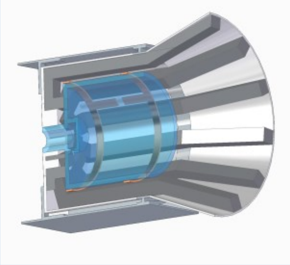


HETs' plasma

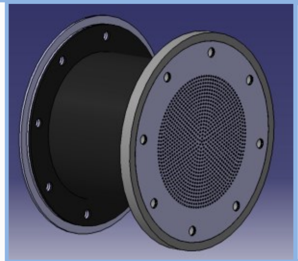
HETs' design



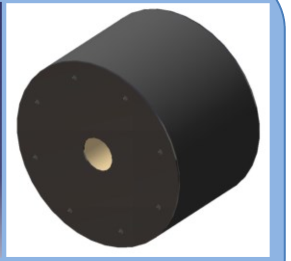
MS-HETs



HPT

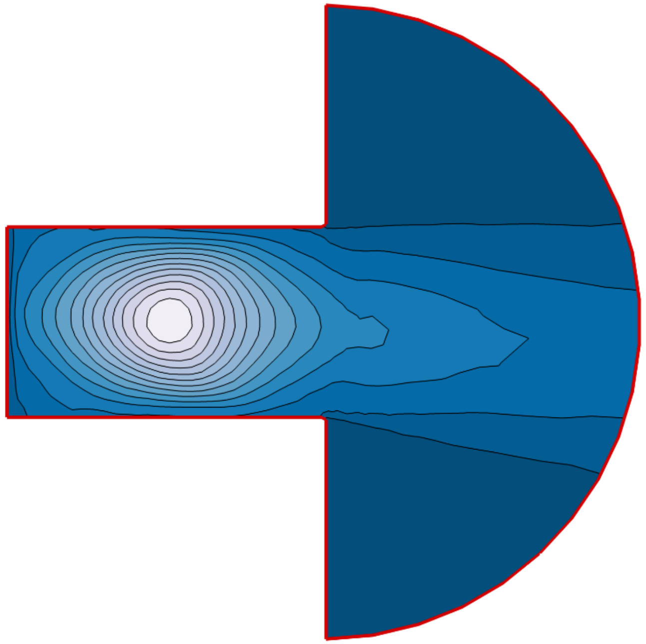


GIT



HEMPT

Outline



HYPICFLU2 logo

- CIRA company overview
- CIRA research activities in EP
- HYPICFLU2
  - ✓ Overview
  - ✓ Validation
- Conclusions
- Future Developments

CIRA IN BRIEF

Not-for-profit shareholding Consortium founded in July 1984.

Main shareholders: CNR (National Research Council ASI (Italian Space Agency), Consorzio ASI/Regione Campania and the main Italian aerospace industries.

CIRA operates according to the guidelines provided by the Ministry of Education, University and Research (**MIUR**).

The Italian government has entrusted CIRA to manage the **PRORA** (Italian Aerospace Research Program).

Mission:

- build, operate, maintain, and upgrade large scale facilities and laboratories;
- develop theoretical and experimental R&TD activities, produce and exchange information, educate and train personnel, participate to European and international programme.

Corporate

- 370 employees and approx. 50 university students and PhD candidates a year

CIRA in Electric Propulsion: a recent story

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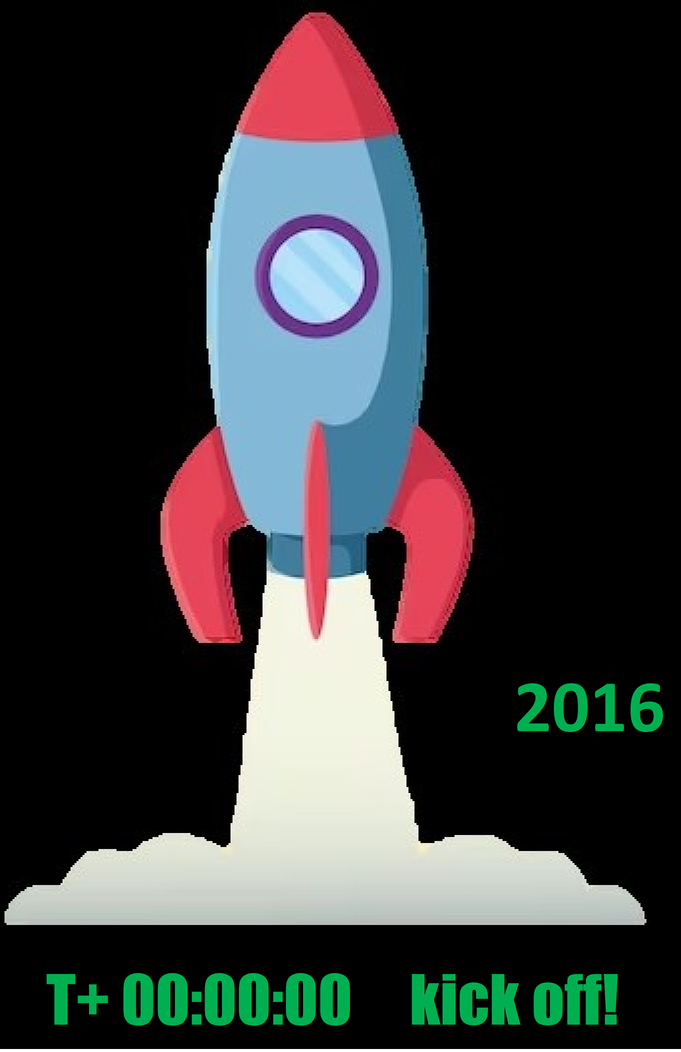


HYPICFLU2

HYPICFLU

Development of 2D plasma model for HETs

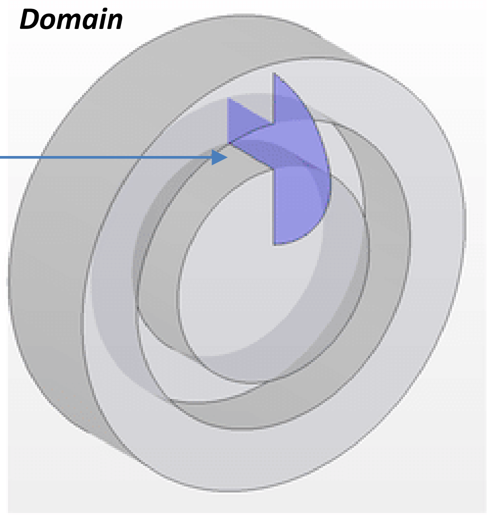
Development of 0D plasma model for OHCs

Electric propulsion research program

- design and installation of test facilities
- development and improvement of basic and advanced diagnostic methodologies
- development of design methodologies and technologies for electrical thrusters:
  - preliminary design tools
  - **numerical modeling**
  - laboratory models

HYPICFLU2 (HYbrid Particle-In-Cell + FLUid)

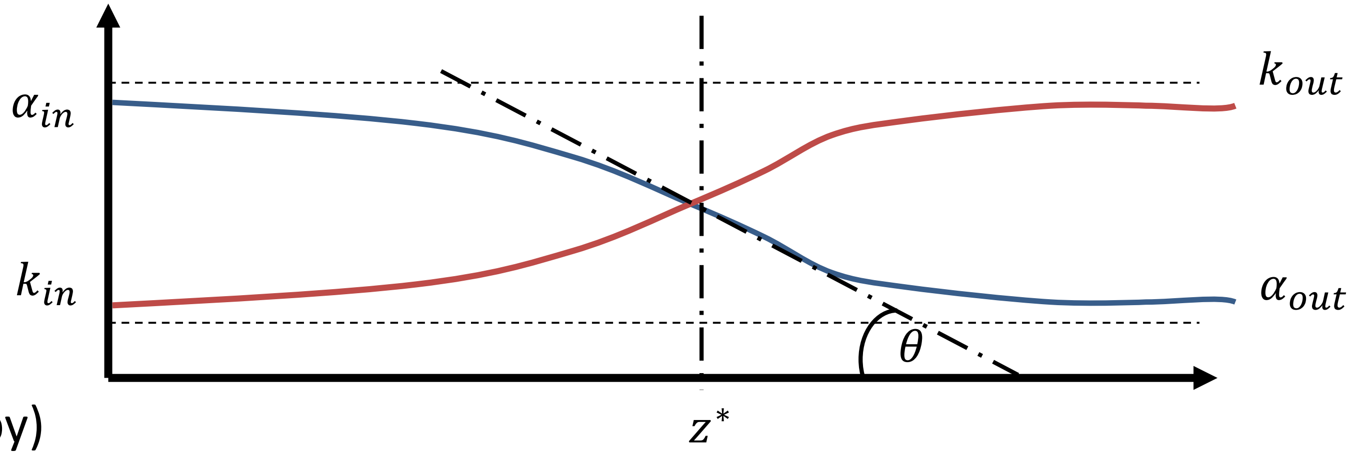
- 2D axis-symmetric
- Unsteady
- Domain: channel + near plume (semicircular)
- Particle in Cell: neutrals and ions (only primary ionization)
- Fluid approach: electrons
- Wall Sheath: Charge Saturation Regime included
- Bohm Forcing Condition at domain boundary
- Neglected collisions: neutral-neutral, ion-neutral, ion-ion, elettron-electron.
- Semi-empirical Electron Mobility model; k, α varies continuously from inside to outside the channel;



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

$$\nu_w = \alpha \cdot 10^7\ s^{-1}, \alpha \in [0.1 \div 1]$$

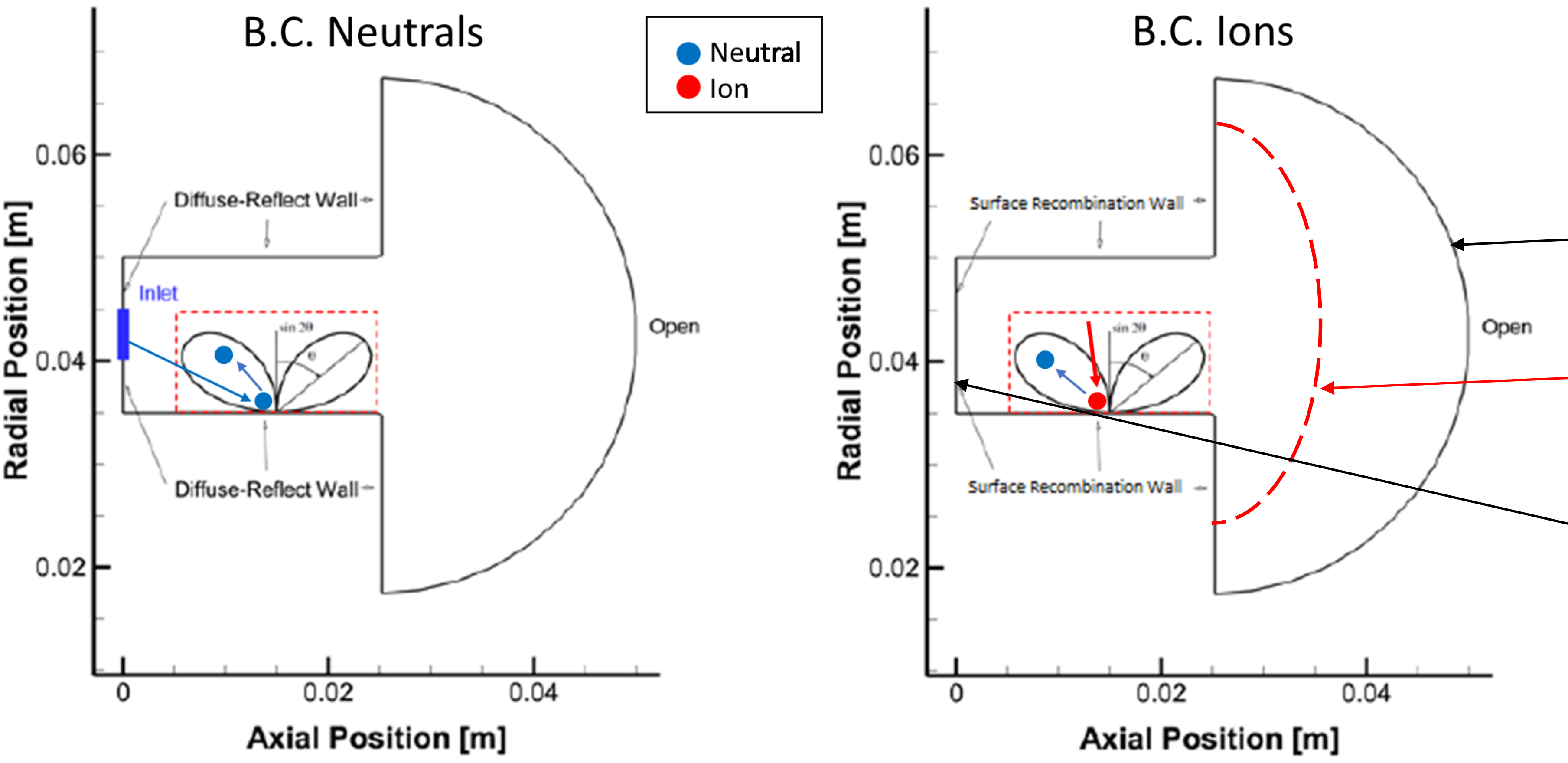
$$\alpha = f(\alpha_{in}, \alpha_{out}, \theta, z^*) \qquad k = f(k_{in}, k_{out}, \theta, z^*)$$



- python: (fast learning) – Parallelized (mpi4py)

Boundary conditions

PIC

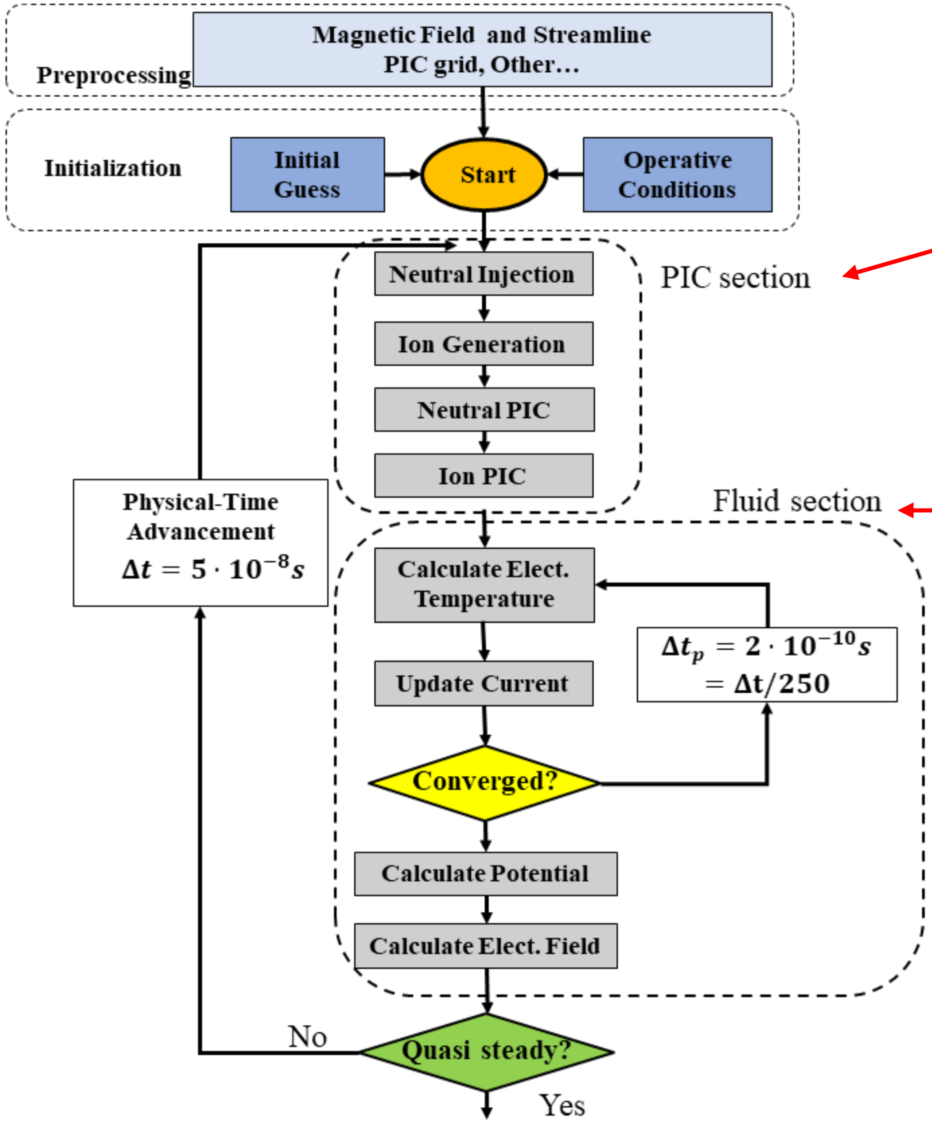


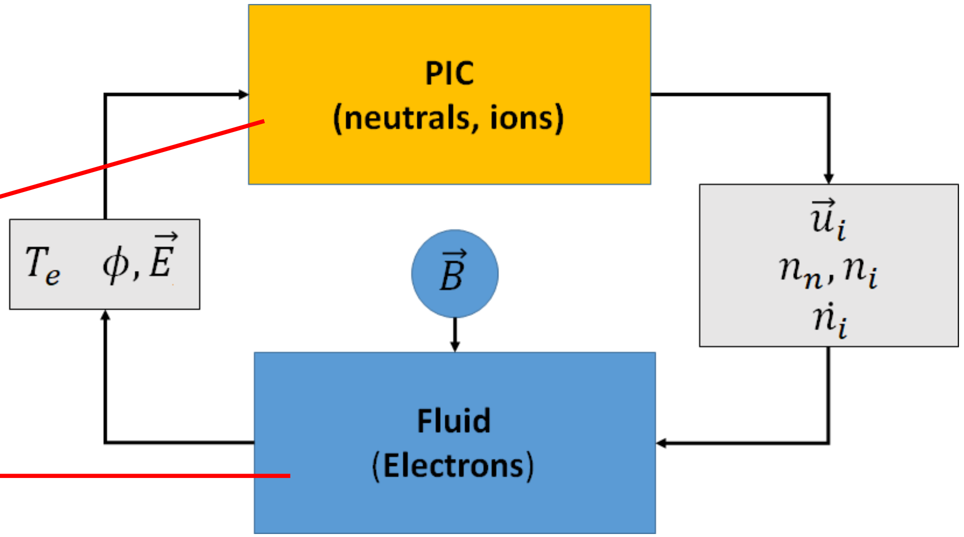
Fluid

	T_e	ϕ
Ground	Dirichlet	Dirichlet
Cathode	Dirichlet	Dirichlet
Anode	Dirichlet/ Neumann	Free

T_e = Electron Temperature
ϕ = Potential

HYPICFLU2 (HYbrid Particle-In-Cell + FLUid)

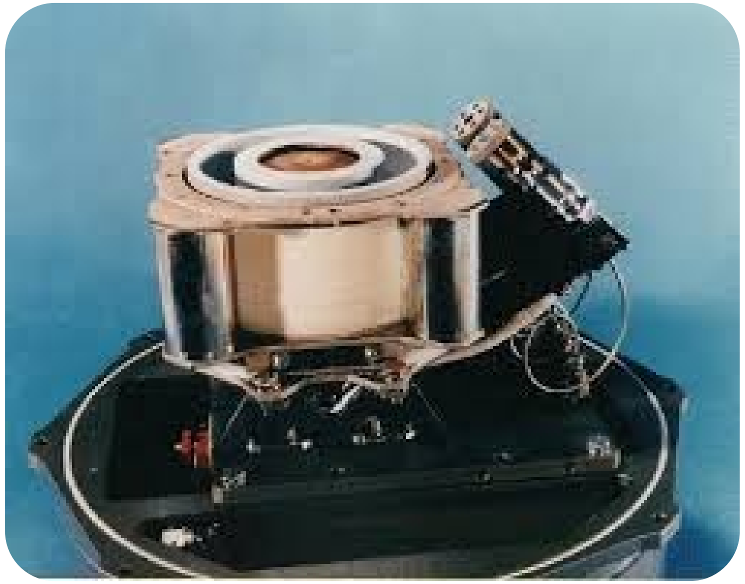




n_n = neutral density $[m^{-3}]$
n_i = ion density $[m^{-3}]$
$\vec{u}_n$ = neutral velocity $[m/s]$
$\vec{u}_i$ = ion velocity $[m/s]$
T_e = Electron Temperature $[eV]$
ϕ *or* $\vec{E}$ = Potential/Electric Field $[V]$, $\left[\frac{V}{m}\right]$

Validation: SPT100

Great availability of Experimental and numerical data



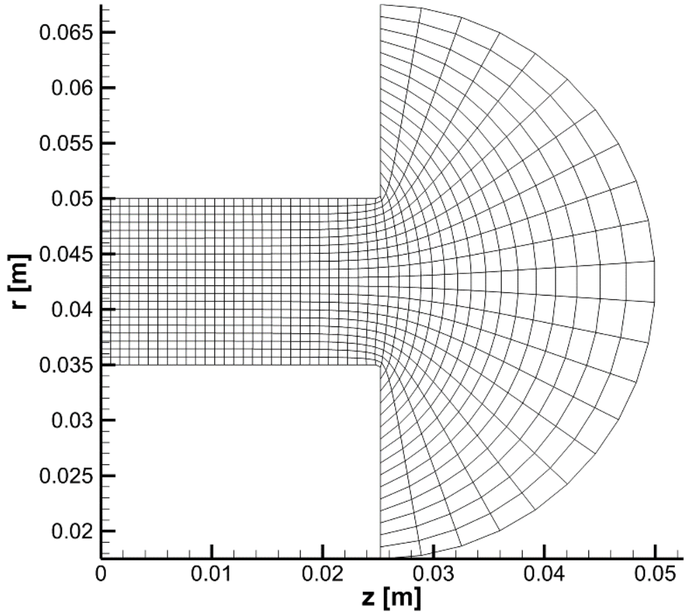
Outer radius [mm]	50
Inner radius [mm]	35
Channel length [mm]	25
Max magnetic field value [G] (coils)	180
Mass flow rate (Xe) [mg/s]	5.3
Discharge Voltage [V]	300 V
Discharge Current [A]	4.5
Discharge Power [W]	1350
Specific impulse [s]	1600
Efficiency [%]	50

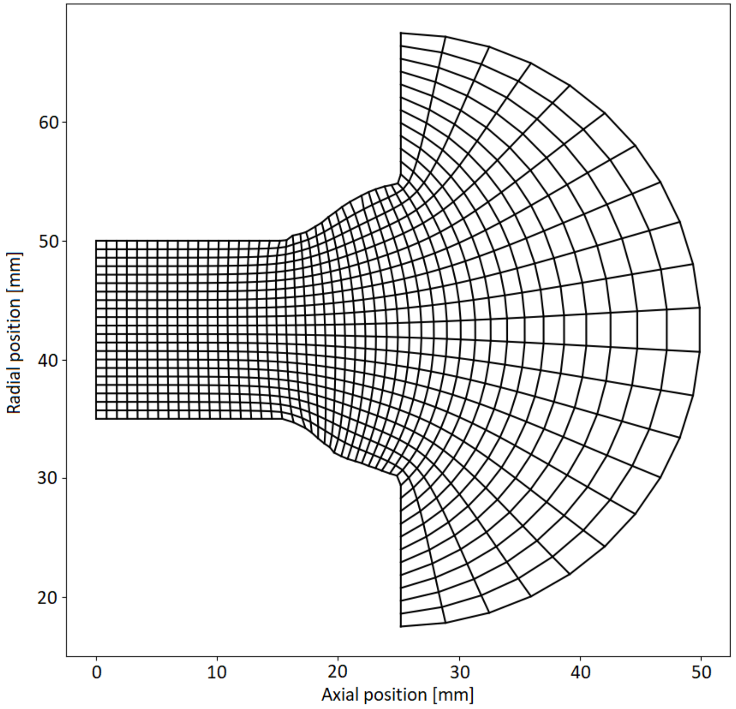
Nominal Operating Point (Mass flow rate through Efficiency)

Test Case Settings	
PIC grid nodes	47x22
Fluid mesh nodes	58x22
Neutral specific weight	2.5e11
Ion specific weight	2.5e9
PIC Time step [s]	5e-8
Fluid Time step [s]	2e-10
Anode Temperature [K]	750
Channel wall temperature [K]	850
k_{out} (Bohm Diffusivity coeff. Outside channel)	1
k_{in} (Bohm Diffusivity coeff. Inside channel)	0.035
a_{in} (Electron-wall collision frequency coeff.)	0.1
Anode Electron Temperature [eV]	2
Cathode Electron Temperature [eV]	13
Ground Electron Temperature [eV]	6
Cathode Potential [V]	10
Ground Potential [V]	2

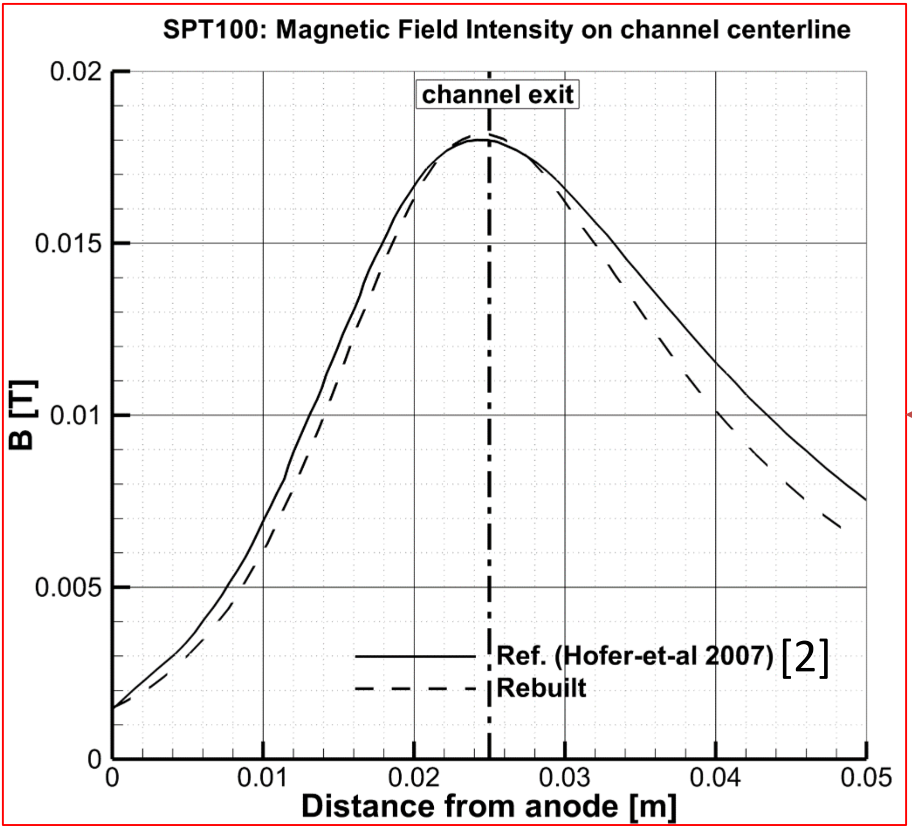
Automatic Elliptic Mesh Generator

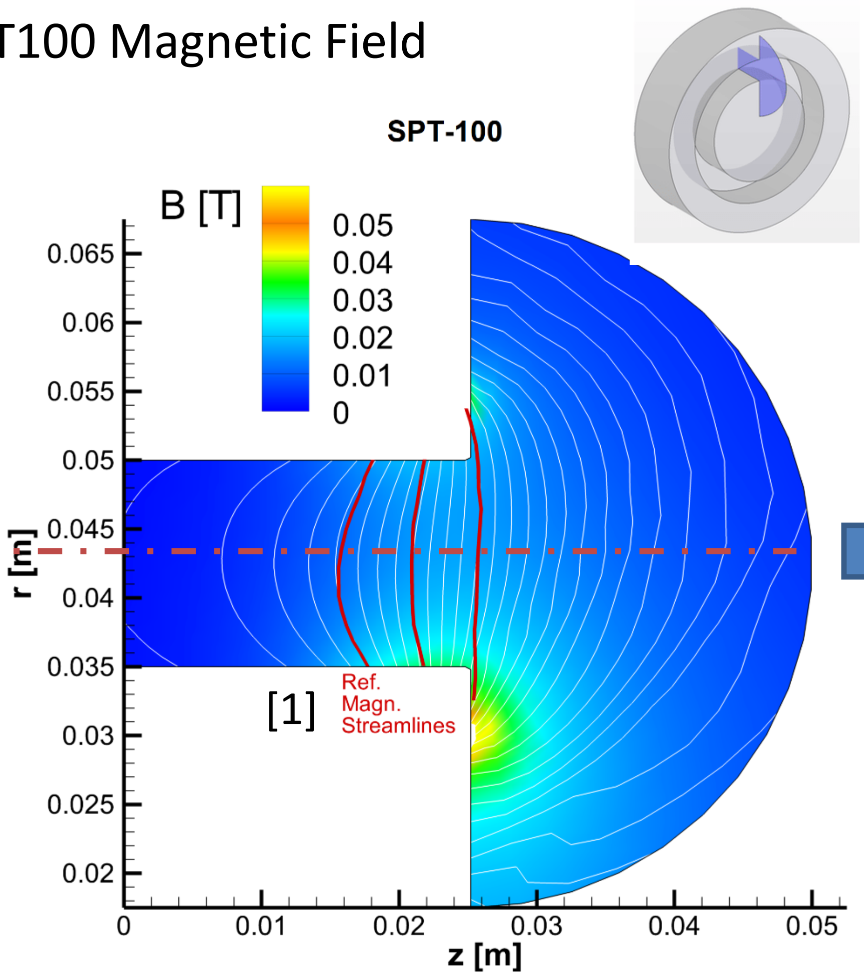
Possibility to mesh domains with eroded channel wall's profile



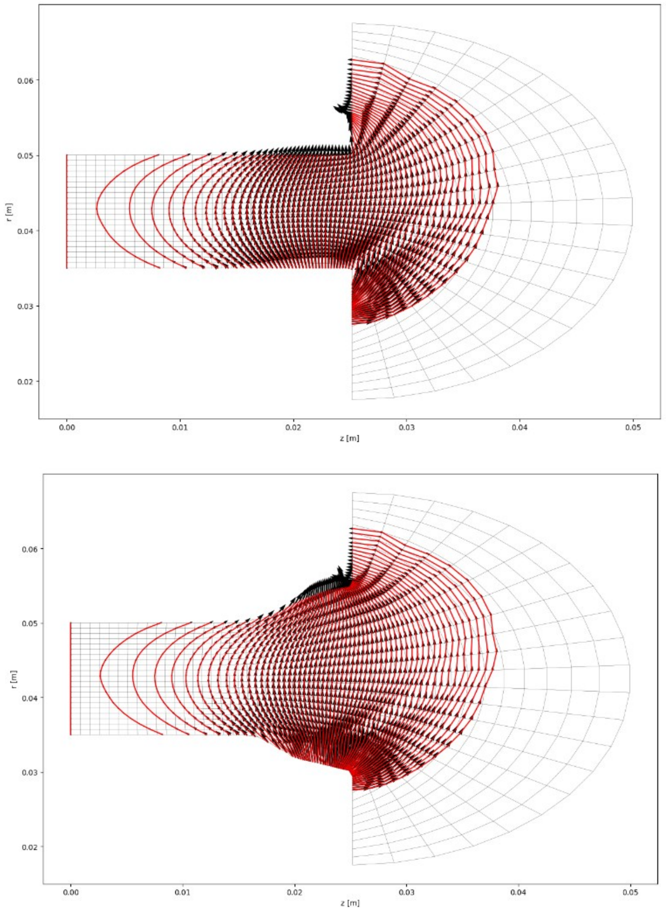


Rebuilt SPT100 Magnetic Field



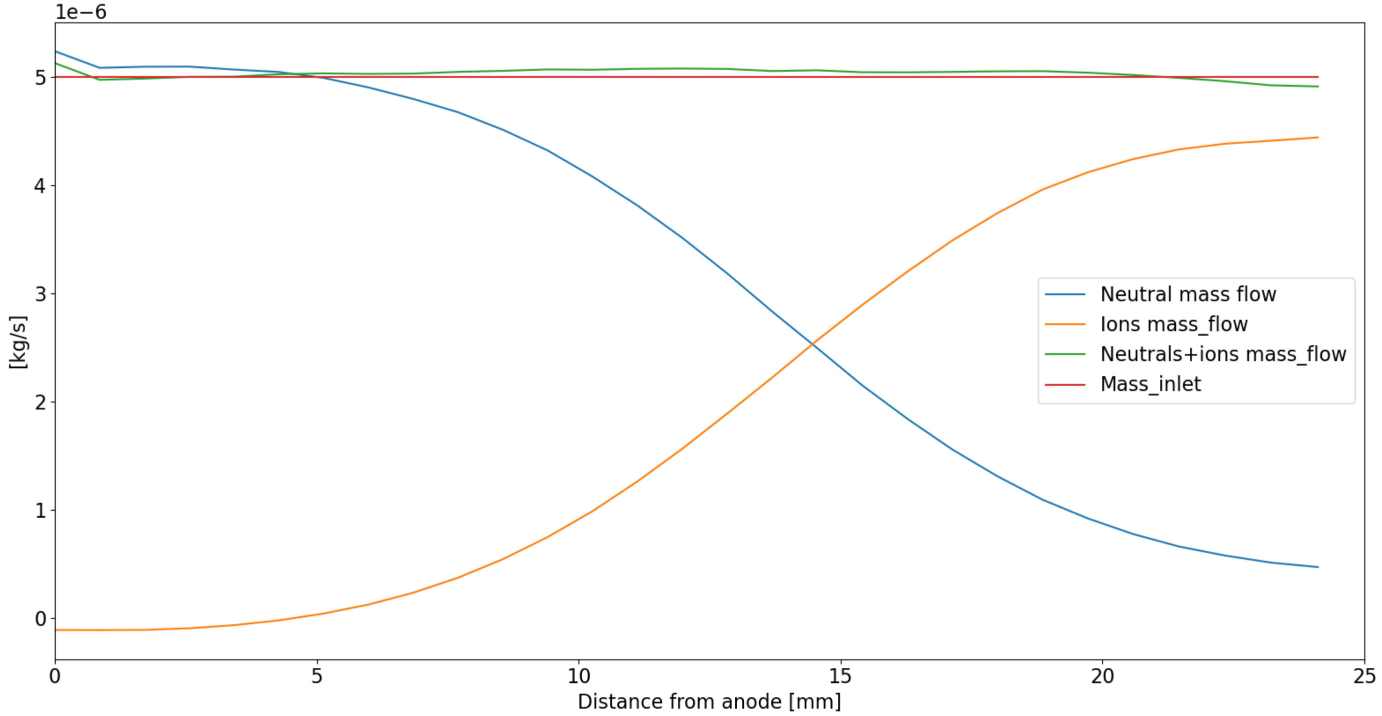


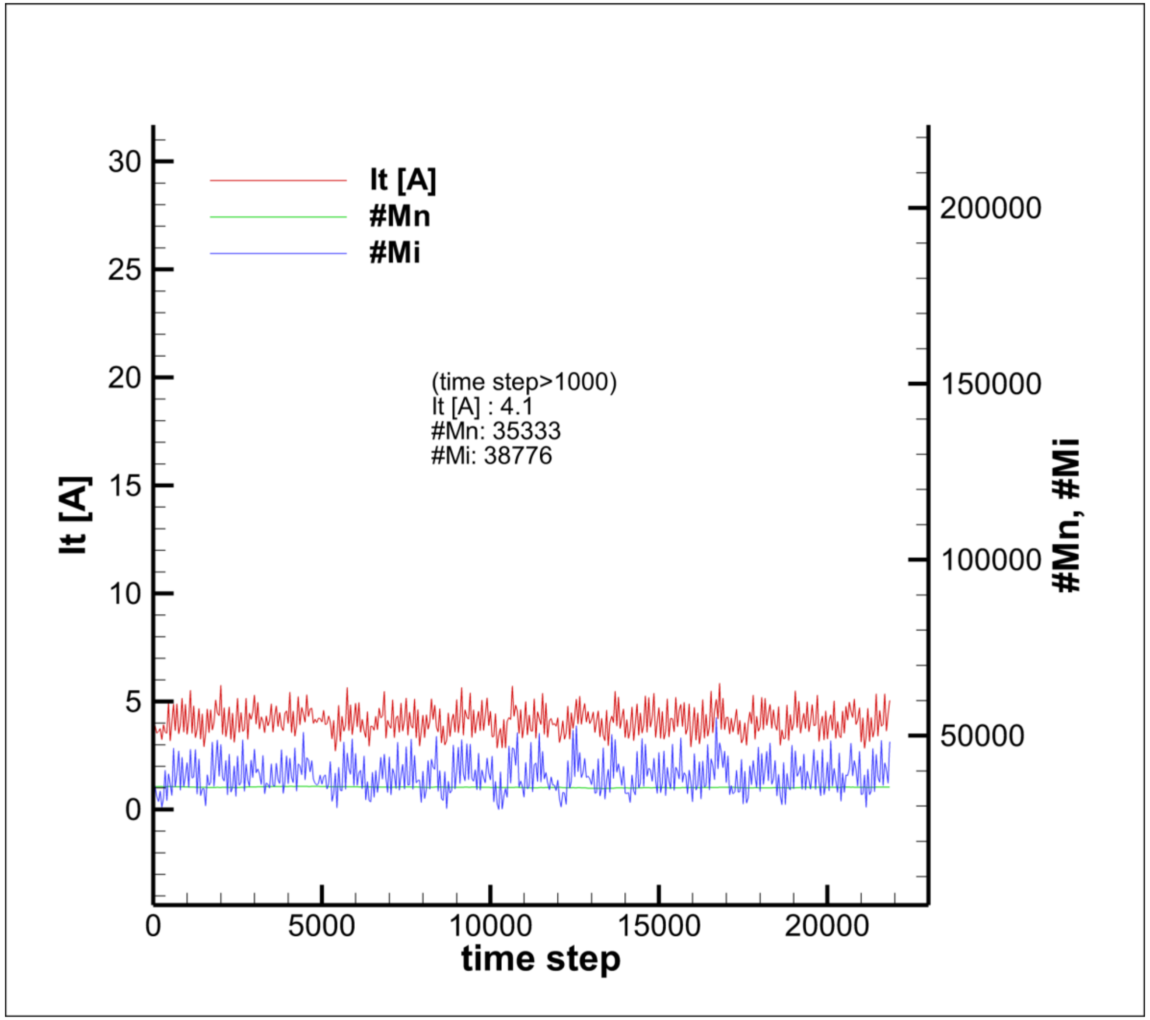
Fluid Mesh



Validation: SPT100

- ✓ Convergence: quasi steady state
- ✓ Breathing mode: 20 kHz
- ✓ Mass-Balance verified

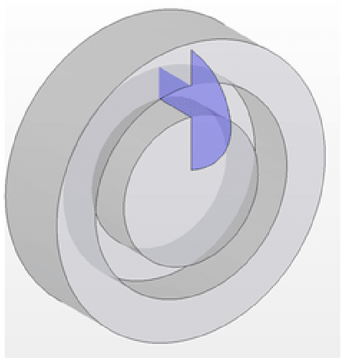


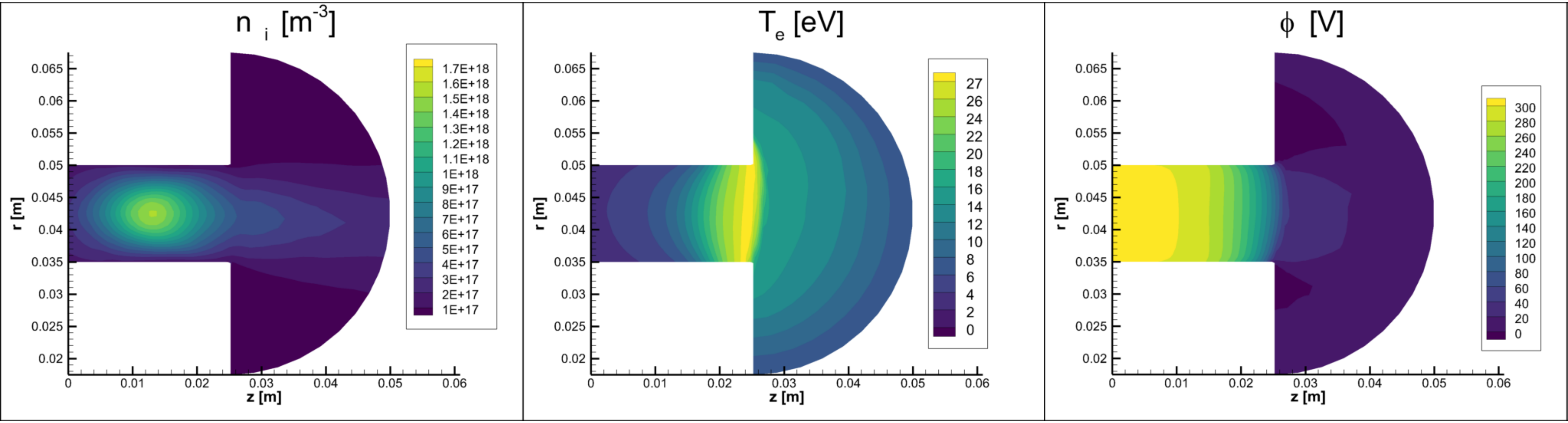


Validation: SPT100

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

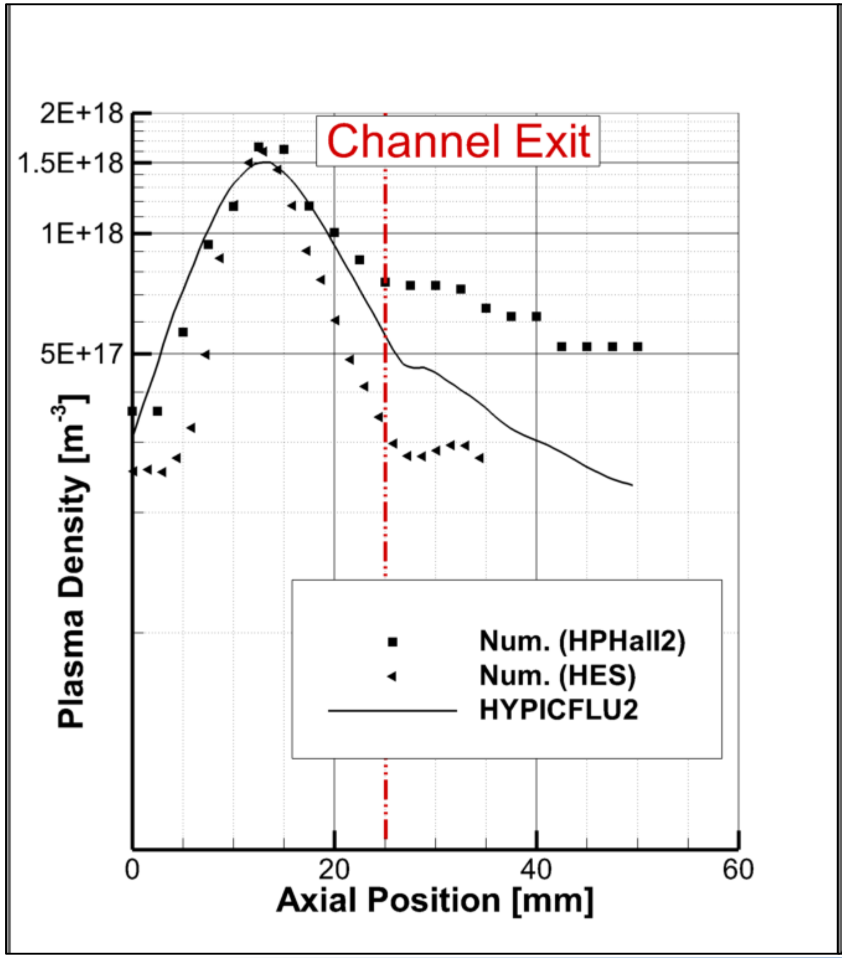




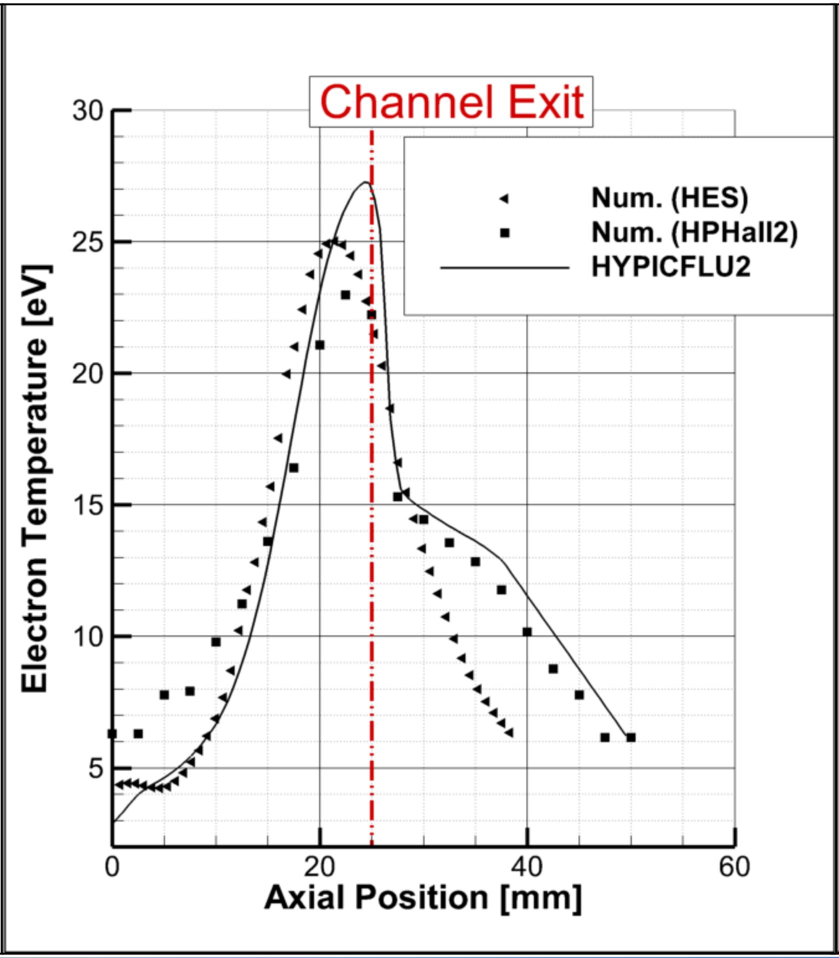
Validation: SPT100

Profiles extracted along the mean centerline

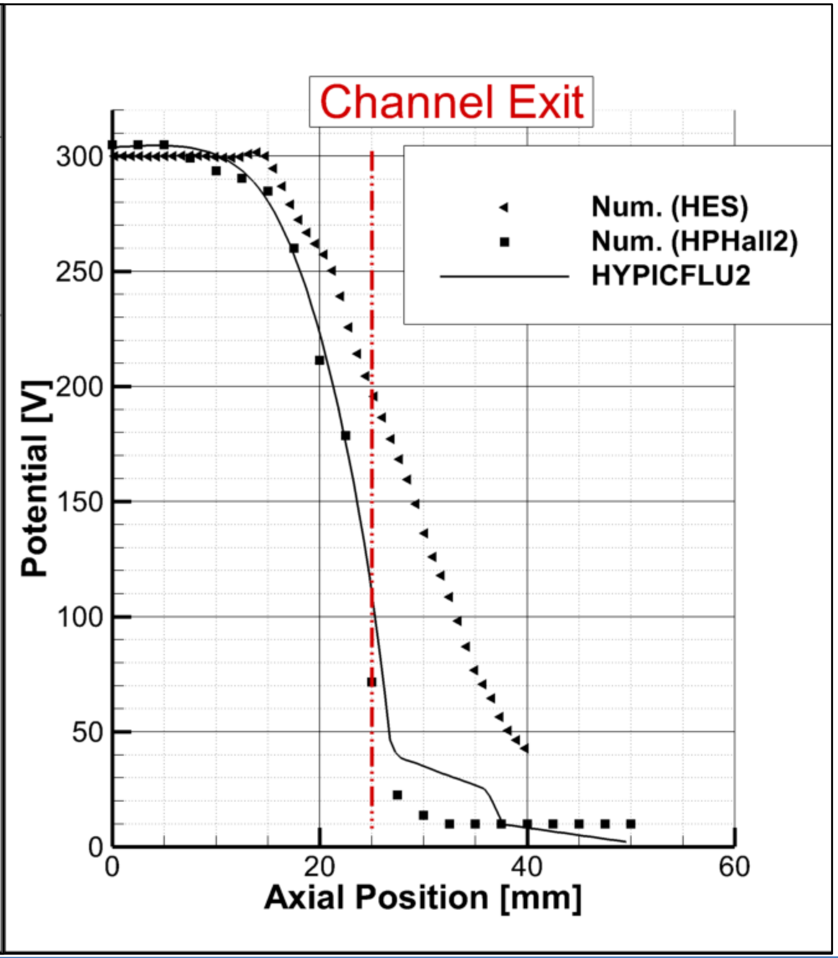
- Peak similar to HPHall2 [2]/HES [3]
- Lower density in the plume (HPHall2)



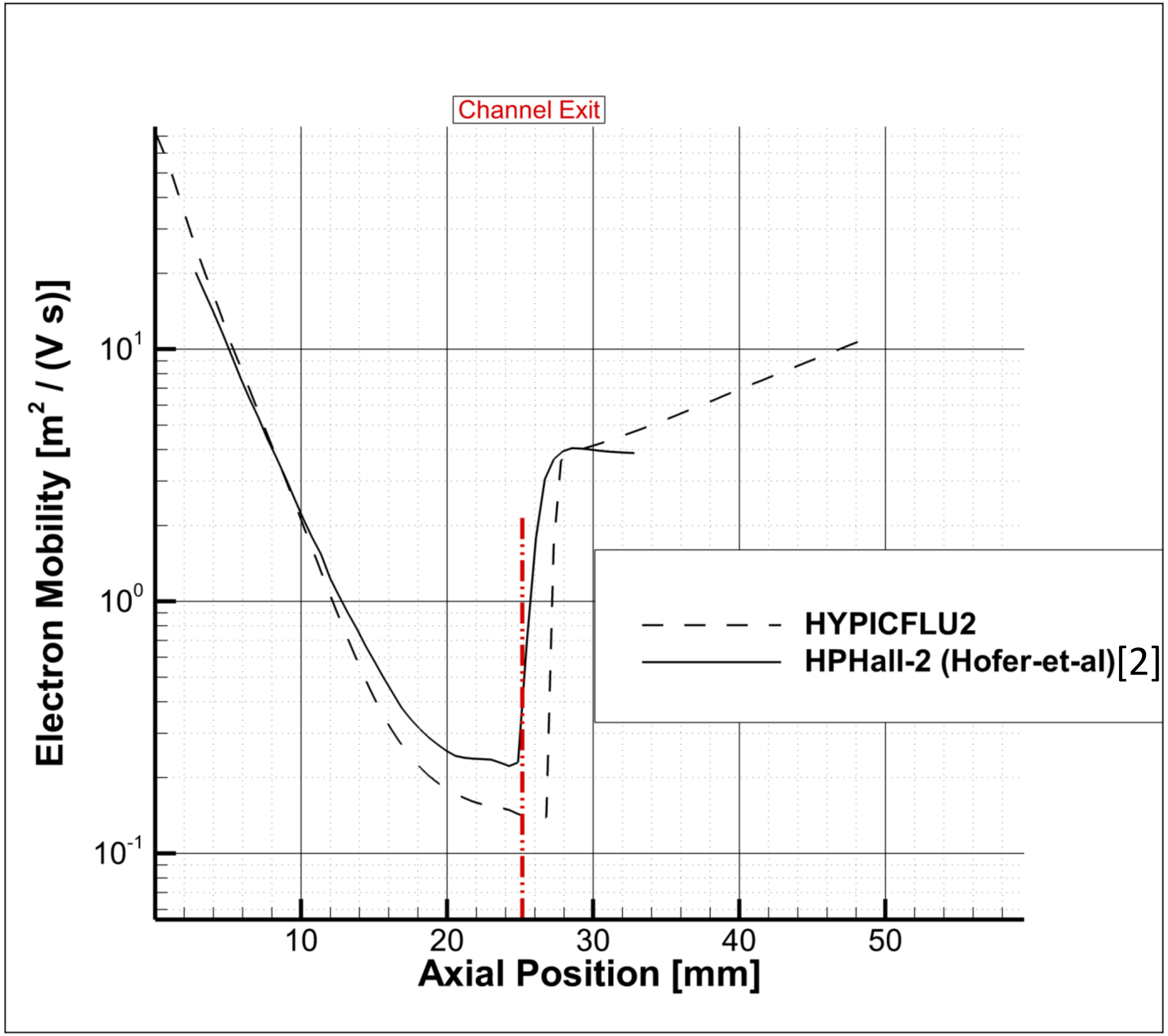
- Peak higher than HPHall2/HES



- Trend similar to HPHall2



Validation: SPT100

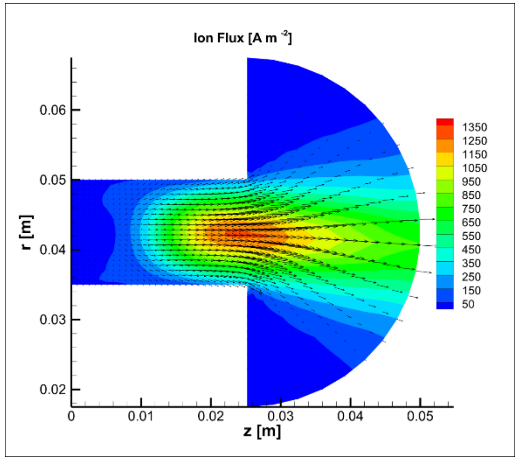


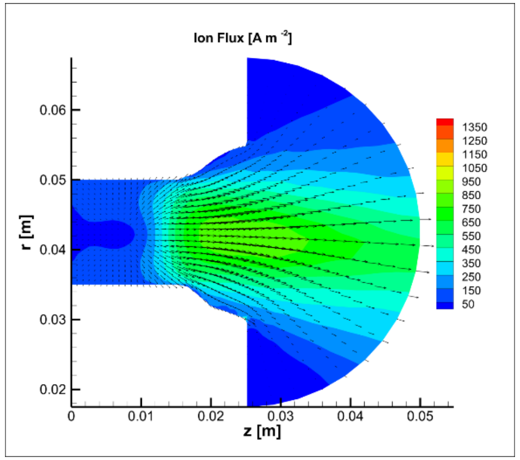
- Low current (i.e. power) due to low mobility with respect the reference; (improvement cab be achieved by modifying the mobility function empirical parameters)
- Low Thrust due to lower ion flow rate at the cathode line

	EXP. [4]	NUM. [2]	HYPICFLU2
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

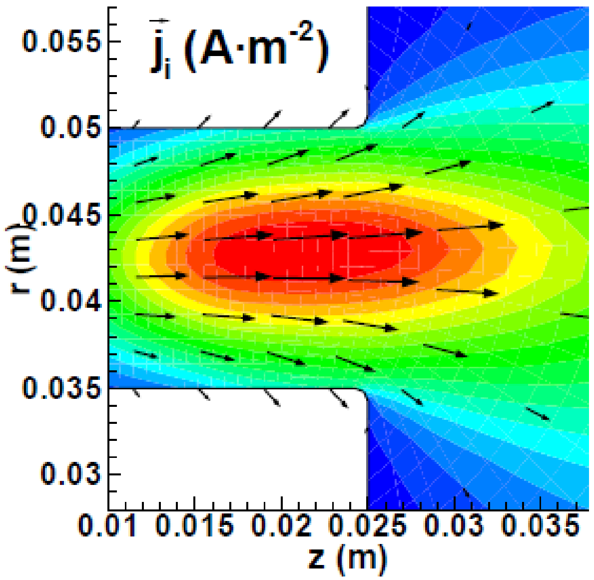
Application to eroded domain: Reduction of ion flux due to eroded domain

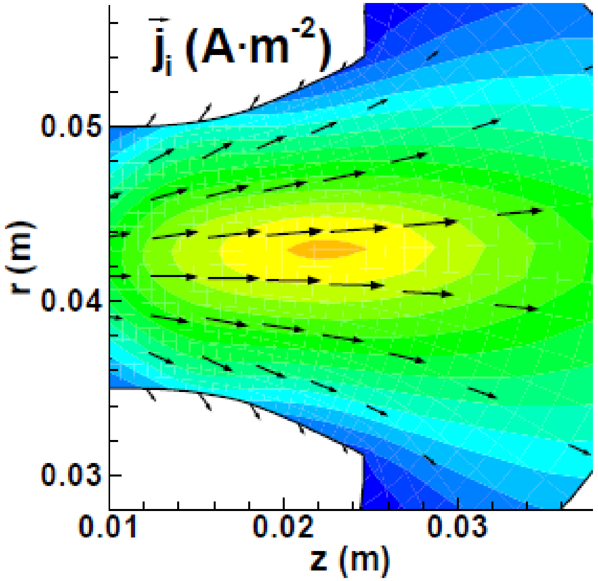
HYPICFLU2





HPHall2 [5]





Ion current density

$$J_i = n_i v_i q$$

Validation: SPT100

Computational Cost

	HYPICFLU2-Serial *	HYPICFLU2-Parallel **
Numbers of CPU	1	36 (1 node)
Total Num. Of Macro-particles	73000	73000
Number of time step to be completed	22000	22000
Time-to-final time step (days)	24	2.5
Time Step / hour	36	360

* Intel(R) Xeon(R) CPU E5-2640 v4 @ 2.40 GHz

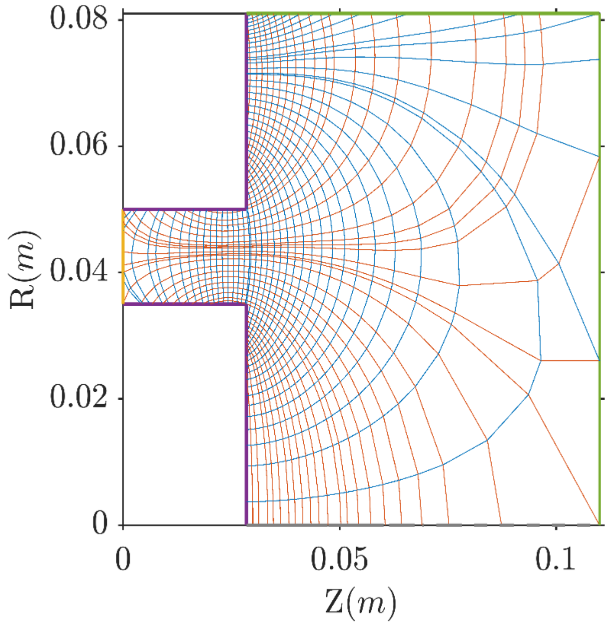
** CIRA cluster (Turing): Num. nodes 40; dual socket Xeon E5-2697 v4 @ 2.30GHz tot: 1440 core

Conclusions

- Described HYPICFLU2: Hybrid Particle-In-Cell + Fluid code for plasma modeling in HETs
- Domain includes channel and near plume (semicircular)
- Elliptic mesh generation capable of following domain geometry modification due to erosion
- Semi-Empirical Electron Mobility Modeling with empirical parameters function of axial position
- Shown validation test case: SPT100

Future Developments

5. PIC grid built from Magnetic streamlines
4. Conversion of the code into Fortran
3. Electron Mobility model studies
2. Exploitation of wall-weigthing algorithms
1. Implementation of secondary ionization



M. Panelli

Acknowledgments

Undergraduate students that contributes to HYPICFLU development and professors who entrusted their student to CIRA:

D. Morfei (Prof. F. Nasuti)
University of Rome, «La Sapienza»

F. A. D'Aniello (Prof. E. Martelli)
University of Campania «L. Vanvitelli»

B. Milo (Prof. R. Savino)
University of Naples «Federico II»

A. Petronelli, G. Brandi (Prof. L. Casalino)
Politecnico di Torino

CIRA colleagues:

D. Cardillo, F. Morlando, I. Iudice, G. Coppola, A. Romano

References

1) Mitrofanova, O.A., Gnizdor, R.Y., Murashko, V.M., Koryakin, A.I., Nesterenko, A.N.: *New generation of SPT-100*. In Proceedings of the 32nd International Electric Propulsion Conference,Wiesbaden, Germany, 11–15 September 2011. IEPC-2011-041

2) Hofer, R.R., Mikellides, I.G., Katz, I., Goebel, D.M.: *Wall sheath and electron mobility modeling in hybrid-PIC Hall thruster simulations*. In Proceedings of the 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cincinnati, OH, 8–11 July 2007. AIAA 2007-5267. https:// doi. org/ 10. 2514/6. 2007- 5267

3) Kawashima, R.; Komurasaki, K.; Schonherr, T.; Koizumi, H. *Hybrid Modeling of a Hall Thruster Using Hyperbolic System of Electron Conservation Laws*. In Proceedings of the 34th International Electric Propulsion Conference, Hyogo-Kobe, Japan, 4–10 July 2015; IEPC-2015-206.

4) Kybeom, K. *A Novel Numerical Analysis of Hall Effect Thruster and Its Application in Simultaneous Design of Thruster and Optimal Low-Thrust Trajectory*. Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA, USA, August 2010.

5) A. Anton and E. Ahedo. *Contour algorithms for a Hall thruster hybrid code.* In Proceedings of the *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. 2006

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Thank you for listening!

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