Hybrid plasma simulations of the HT5k thruster

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ExB Plasmas Workshop 2022

Madrid, online event

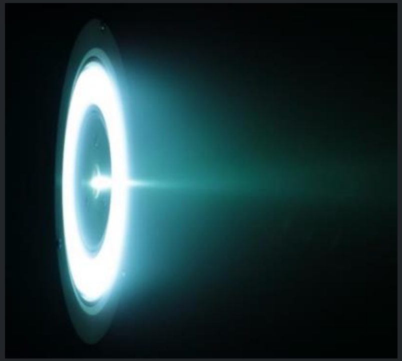
Introduction

- Magnetically-shielded (MS) Hall-effect thrusters (HET)
  - Recently proven as an effective way to reduce wall erosion and energy losses to walls
  - Obtaining significantly extended operational life
- Few prototypes tested up-to-date
  - HT5k thruster, developed by SITAEL
    - With MS topology
    - Centrally-mounted cathode
- Few simulations of MS-HET's comparing simulation and experimental results
  - Comparison required because of lack of predictive models
  - Advances in the validation of the simulation tools are required
- HYPHEN code, developed by EP2-UC3M
  - HYPHEN has been adapted to solve MS-HET's in the framework of EDDA project
- HYPHEN simulations and their comparison to experimental data have allowed to:
  - Characterize the 2D plasma discharge and its relation to performance
  - Identify central aspects of MS and centrally-mounted cathodes

HT5k Thruster

- **HT5k** thruster+ **HC20** hollow cathode: designed and manufactured by **SITAEL.**
  - Development model 3: HT5K-DM3
- Main features of HT5k-TU:
  - **Centrally mounted cathode**
  - **Non-conventional magnetic topology: magnetic shielding**
- Prototypes technical investigations in high vacuum conditions demonstrate:
  - **High and stable performance**
  - **Lower erosion**
  - **Direct-drive operations**

  with the discharge power ranging **from 3kW to 7kW**
- Experimental data of the HT5k-TU-DM3 from SITAEL
  - Testing took place in SITAEL's IV10 facility
  - Pressures of the order of 7E-6 mbar (Xe) while firing at 4.4 kW of discharge power.



HT5k-TU-DM3

V. Gianetti, E. Ferrato, A. Piragino, M. Reza,F. Faraji, M. Andrenucci, and T. Andreussi. HT5k thruster unit development history, status and way forward. In Proc. 36th International Electric Propulsion Conference, Vienna, Austria, IEPC-2019-878, 2019

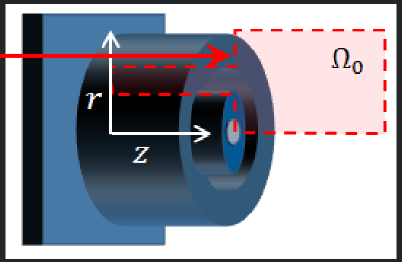
T. Andreussi, V. Giannetti, A. Leporini, M. M.Saravia, and M. Andrenucci. Influence of the magnetic field configuration on the plasma flow in Hall thrusters. Plasma Phys. Control. Fusion, 60(1), 2018

Case	V_s (V)	$\dot{m}_A$ (mg/s)	I_d (A)	F (mN)
1	300	14	14.6	269
2	400	14	14.2	308
3	300	10	10.3	184
4	350	10	10.1	197
5	400	10	9.6	208

HYPHEN

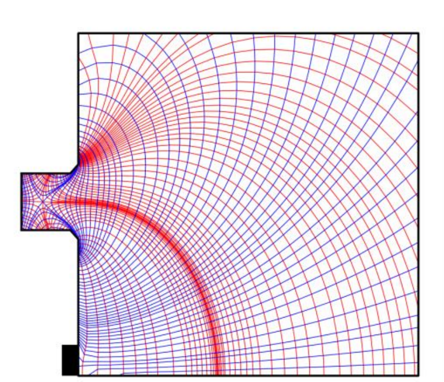
- **HYPHEN: HY**brid **P**lasma thruster **H**olistic simulation **EN**vironment
- **Two main quasineutral modules**: Ion (ions + neutrals) and electron
- **Sheath module**: Coupling with the non-neutral plasma sheaths
- **Interpolation module**: Communication between ion and elec. modules

2D axisymmetric

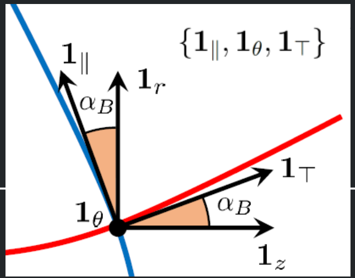


START

Applied $\boldsymbol{B}$ + $\boldsymbol{E} = -\nabla\phi$, $T_e = p_e/n_e$



Unstructured MFAM



Diffusive elec. transport model

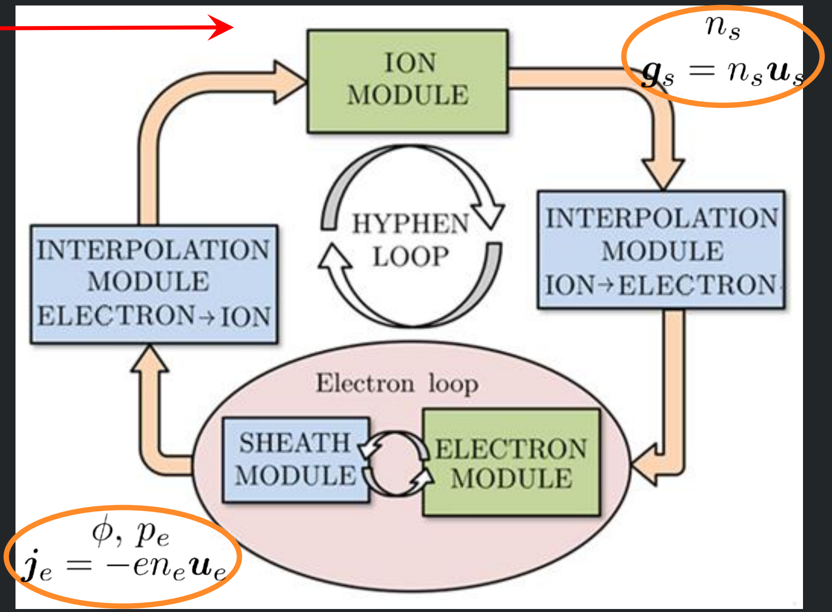
+

Turbulent collisionality, ν_t

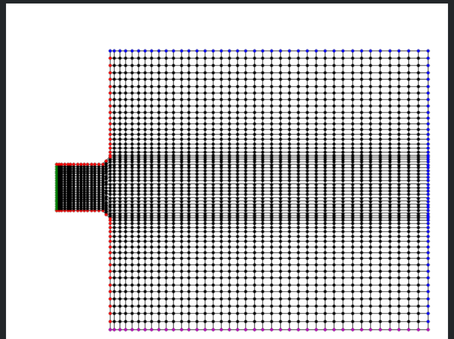
$$\nu_t = \alpha_t \omega_{ce}$$

$$\alpha_t = \frac{\langle n_e' E_\theta' \rangle}{n_e u_{\theta e} B}$$

Ions + neutrals	Particle injection, moving, collisions, weighting, population control



Electrons
- Current continuity + momentum
- Internal energy + heat flux



Structured PIC mesh

Quasineutrality

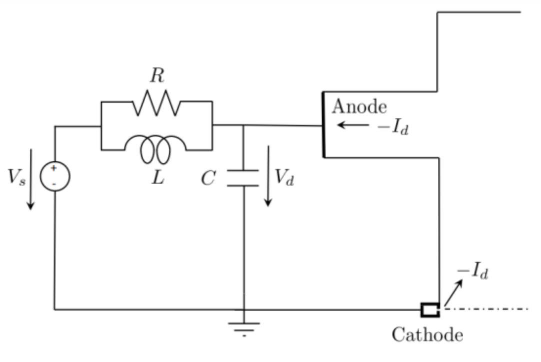
$$n_e = \sum_s Z_s n_s$$

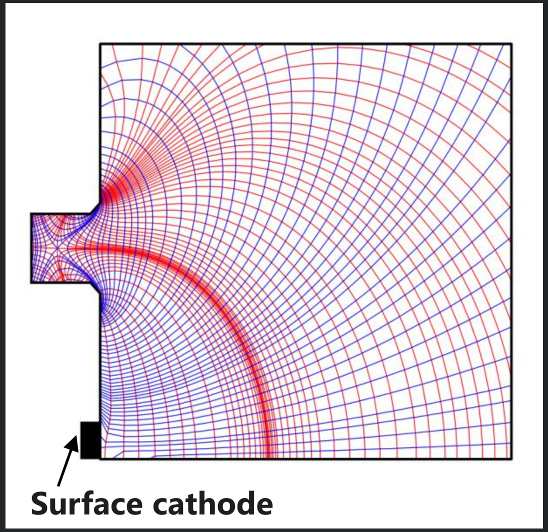
$$\boldsymbol{j}_i = e\sum_s Z_s n_s \boldsymbol{u}_s$$

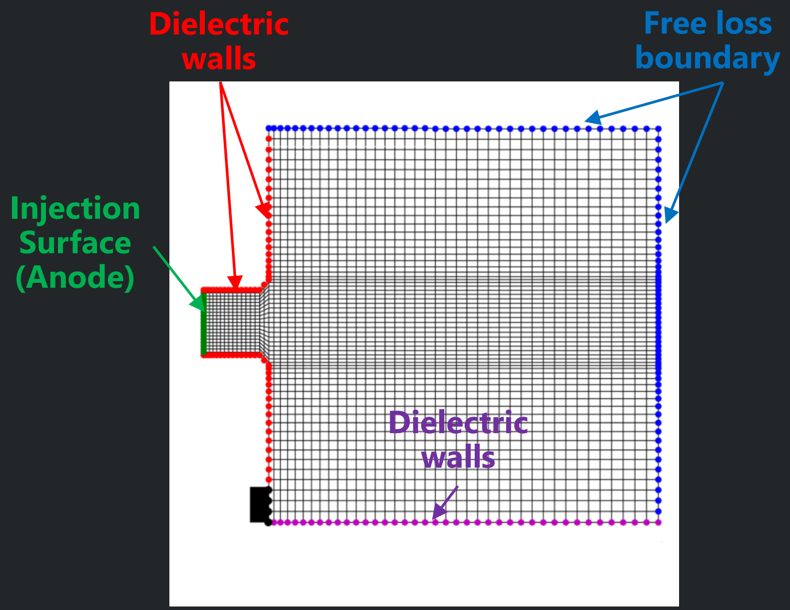
$$\boldsymbol{g}_n = n_n \boldsymbol{u}_n$$

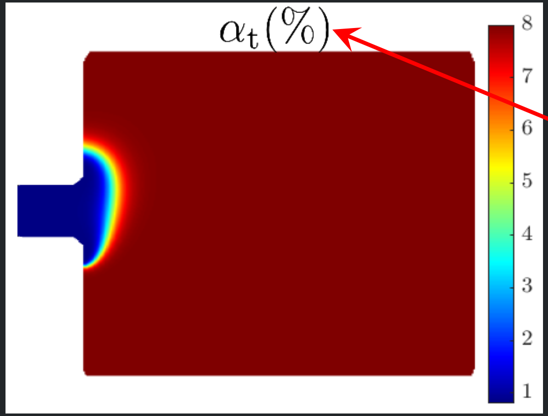
Thruster model

- Xenon anode and cathode mass flow range $(\dot{m}_A, \dot{m}_C)$
  - $\dot{m}_\mathrm{A} = 10, 14\ \mathrm{mg/s}$ | $\dot{m}_\mathrm{C} = 12.5\dot{m}_\mathrm{A}$
- Source voltage range (V_s)
  - $V_\mathrm{s} = [300, 400]\ \mathrm{V}$
- Reference operation point
  - $\dot{m}_\mathrm{A} = 14\ \mathrm{mg/s},\ V_\mathrm{s} = 300\ \mathrm{V}$
- RLC filter simulated





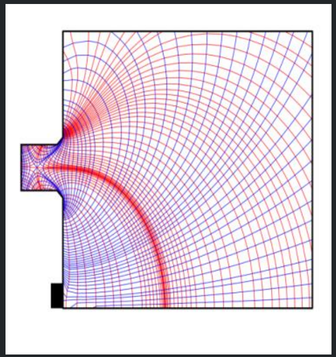




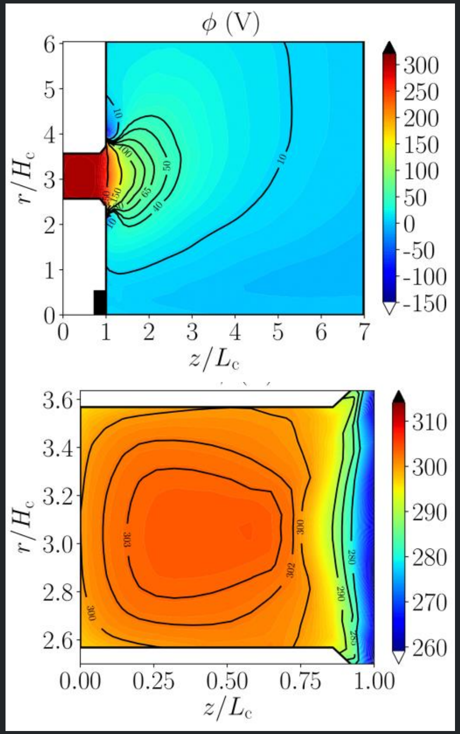
- Stepwise turbulent parameter, $\alpha_t(\%)$
  - **Tuned for each operation** point to fit experimental performance data

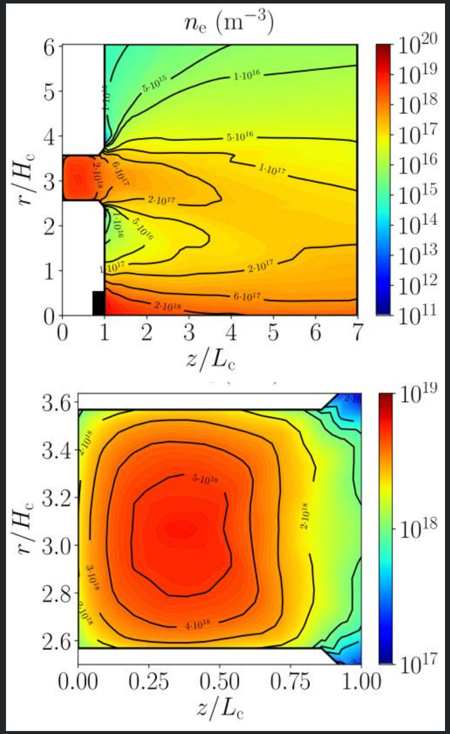
Simulation results (I)

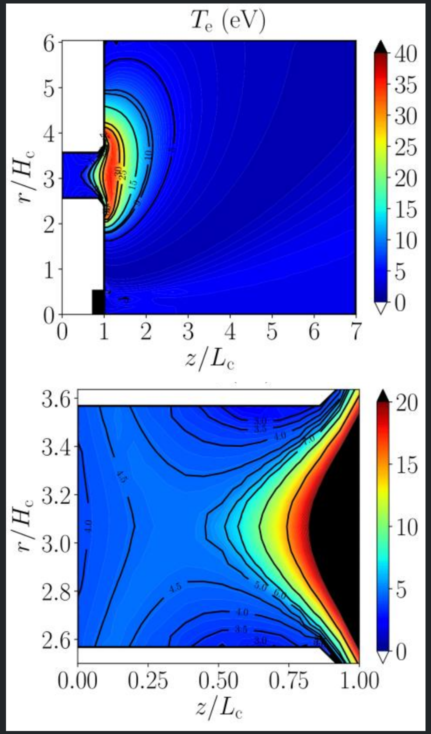
- **Time-averaged** magnitudes
- **The electric potential**:
  - **ϕ outside the chamber** closely **follows magnetic lines**
  - **ϕ inside is nearly flat** and **does not follow** the B lines, because of p_e gradients. **Acceleration region at chamber exit**
- High electron density, n_e, inside the chamber, with maximum around B null point



- **The electron temperature**
  - **Nearly isothermal magnetic lines**
  - **Near chamber walls, low electron temperature** isolines
  - **High T_e isolines penetrate into the chamber** without reaching its walls
- **Main ionization region near the chamber exit**, before acceleration región.

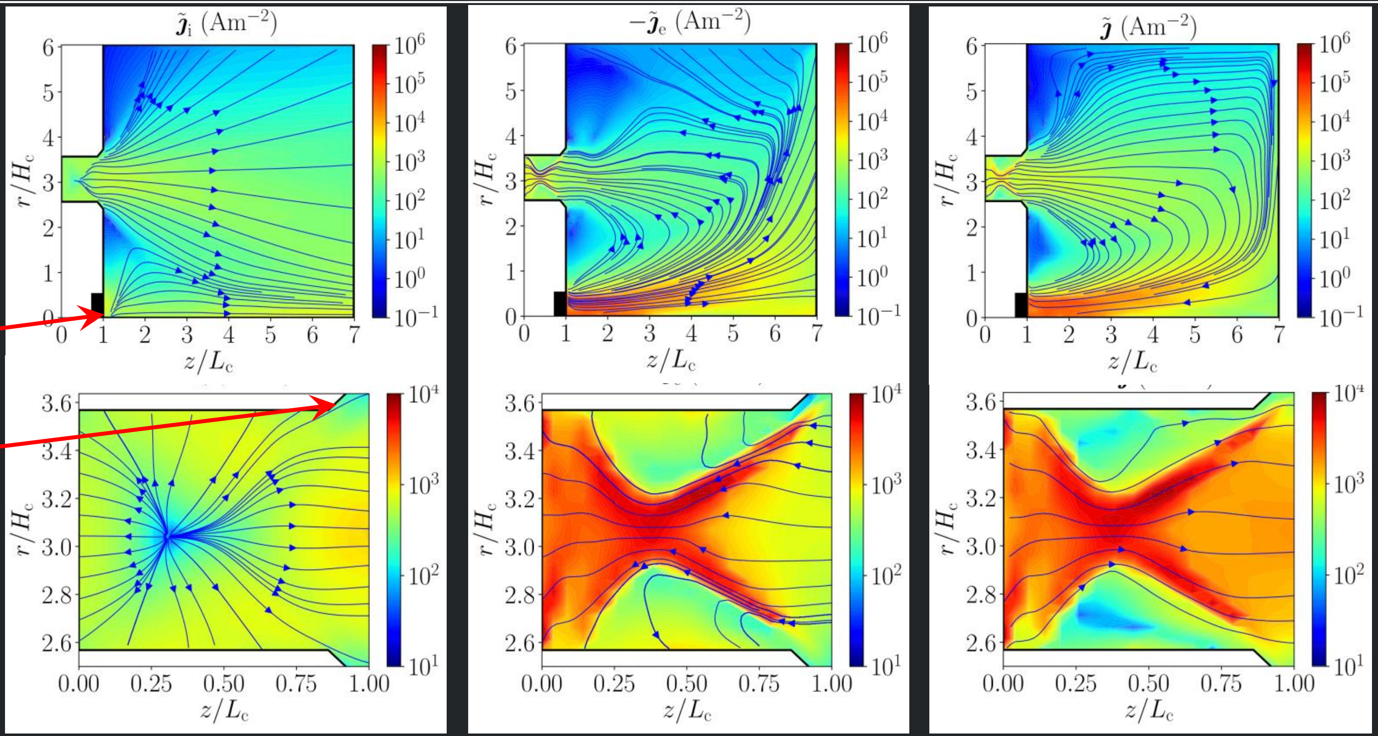


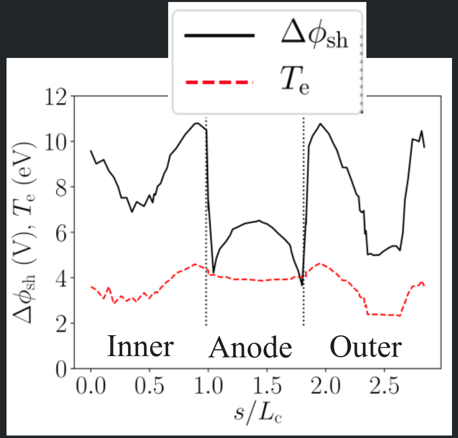


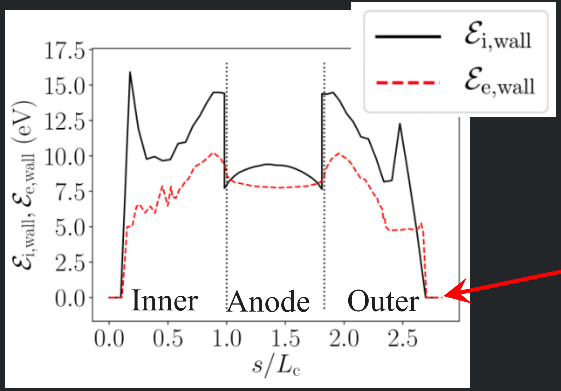


Simulation results (II)

- 2D contour maps: **plasma currents**
  - **Electron current** inside the chamber **forced to flow near** the B field **singularity**
  - **Null ion fluid velocity** (and maximum n_e) **around** the B **singularity**
  - Ion stream from **ionization around the cathode.** It **improves cathode-beam coupling**
  - **Ion streamlines** running nearly **parallel to chamfer**
  - Downstream electron current neutralizes the ion beam to yield zero net current leaving the domain







- Low T_e along the walls yield **small $\boldsymbol{\Delta\phi_{sh}}$**
- **Low ion impact energy** due to small $\Delta\phi_{sh}$, **beyond** typical **threshold** energy **for erosion**
- **Null ion impact energy in the chamfer** → ion current parallel to chamfer
- The results show the **effectiveness of MS against wall erosion/sputtering**

Simulation results (III)

- **Global current balance:**
  - **Relative current losses to lateral walls similar to conventional HET→ lower temperature but higher plasma density**
  - In terms of current to walls, **no clear advantage to conventional HET**

Case	V_s (V)	$\dot{m}_A$ (mg/s)	I_{prod} (A)	$I_{i\infty}/I_{prod}$	I_{iD}/I_{prod}	I_{iA}/I_{prod}	η_u	η_{cur}
1	300	14	27.6	0.42	0.39	0.18	0.94	0.77
2	400	14	33.0	0.36	0.42	0.21	0.94	0.78
3	300	10	17.4	0.45	0.37	0.17	0.91	0.79
4	350	10	18.6	0.42	0.38	0.19	0.90	0.79
5	400	10	18.1	0.44	0.37	0.18	0.92	0.85

- **Global power balance:**
  - While **current losses to lateral walls** amounts to about a **40% of produced current, energy losses** to these walls are **only 7%**
  - **Total wall losses** of around **9-12%**
  - **Significant improvement with respect to conventional HET**

Case	V_s (V)	$\dot{m}_A$ (mg/s)	P (kW)	η	P_{inel}/P	P_D/P	P_A/P	P_∞/P $(=\eta_{ene})$	η_{div}	η_{disp}
1	300	14	4.43	0.57	0.15	0.07	0.05	0.74	0.89	0.87
2	350	14	5.73	0.57	0.13	0.07	0.04	0.74	0.86	0.90
3	300	10	2.91	0.56	0.14	0.06	0.05	0.74	0.88	0.85
4	350	10	3.40	0.56	0.13	0.06	0.05	0.75	0.85	0.88
5	400	10	3.76	0.57	0.11	0.05	0.04	0.78	0.84	0.86

- **Efficiencies:**
  - **Slight increase in plume divergence** with increasing V_s, related to T_e downstream shift
  - **Thrust efficiency** remains **nearly constant**(~56%) **along operation points**

Conclusions

- Need to advance in the validation of codes for HET-MS thrusters
- **The HT5k thruster** has been **simulated with HYPHEN**
- **2D contour maps and 1D wall profiles** have shown the effect of magnetic topology:
  - **Low T_e isolines near the chamber walls and flat ϕ profile inside the chamber**.
  - **Ion streamlines** nearly **parallel to chamfer** walls.
  - **Small ion impact energy** on chamber walls
- **Power losses to walls** have been observed to be **reduced with respect to conventional HET**
- **Magnetic shielding of HT5k** have been proved **effective against erosion and power losses to walls.**

Acknowledgments

The project has received funding from the European Union's Horizon 2020 Space Research Program under Grand Agreement N°870470