Simulation of Hall thruster performances with HYPHEN

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EP2 (Plasmas and Space Propulsion Team) is a university research group

- Large growth in human/material resources during last years:
  - 3 senior / 4 junior postdoc / 12 PhD students
  - New vacuum facilities for EP testing

- Main Goal: Solid know-how of physics of most relevant EP technologies
  - Mature know-how: Hall thrusters (HETs), helicon thrusters (HPTs), ECRTs, magnetics nozzles, plume expansion, active debris removal
  - Incipient one: ion thrusters, hollow cathodes, PPTs, AF-MPDTs

- Holistic approach: Common theor. / simul. framework for different technologies
  - Understanding commonalities/differences → device optimization
  - Understanding modeling/simulation/design/testing/development road

- Modeling/simulation and testing tools are crucial to accelerate EP technology design/development/testing/qualification (from H2020 EP program)
  - (e.g. plasma-wave heating, lifetime testing of multi-mode HET, scalability...)
HYPHEN: A multi-thruster simulator

- Multi-thruster simulation platform for electromagnetic thrusters (EMT) operating with weakly-collisional plasmas

  - EMT with electrodes: HET, AF-MPDT, HEMPT
  - EMT with EM emission: HPT, ECRT, RIT

- Being built from converging developments for individual thrusters:
  - NOMADS (CHEOPS), SURFET (MINOTOR), HELPIC (AirbusDS-F)

- Axisymmetric (2D), hybrid (PIC/fluid), modular, OpenMP-parallelized

  - 2D hybrid codes are efficient tools for R&D: they simulate 1ms of operation (steady state) in few hours with a multicore workstation
  - Specific ‘weaknesses’ are dealt with auxiliary kinetic codes and then implemented in HYPHEN

- HYPHEN shares structure/algorithmics with EP2PLUS (3D code for beam neutralization and far plume expansion)

  - 2020-21: we expect to couple both codes
HYPHEN modular structure

- **Ion module**: PIC-MonteCarlo, multi-species (typically 6 for HET)
- **Electron module**: Highly-magnetized, weakly-collisional fluid
  - Works on full-2D magnetically aligned mesh (*challenging*)
  - Requires auxiliary model for anomalous transport (*pending*)
- **Wave module** (*only for electrodeless HPT, ECRT,...*)
  - Wave energy deposition into plasma (*challenging*)
- **Sheath module**: for plasma interaction w/ different wall types (dielectric,...)
  - Coupled to kinetic code for non-Maxwellian electron VDF (*on-going*)
- **Electrical circuit module**
  - In HET: for anode-cathode connection
  - In HPT, ECRT: essential for overall performance calculation

Module-coupling challenges:

a) Accurate interpolation between the 2-3 module meshes
b) Manage different integration time-steps
HET: Ion and electron meshes

**Ion module**
- Structured mesh
- Independent multiple populations
- Careful population control for
  - Noise reduction
  - Near-axis distributions

**Electron module**
- Finite volume method on Magnetic Field Aligned Mesh
- Avoids numerical diffusion
- But accuracy is delicate
- Very irregular cells, especially at boundaries and null points
- Difficulties with extended plume and boundaries

(Zhou et al, PSST 2019)
Auxiliary full-PIC code for EVDF & wall

- 1D radial full-PIC code for HET
  - Cooperation with CNR-Bari (F. Taccogna)
- It determines electron VDF with strong SEE and low collisionality
- SEE is partially thermalized, partially wall-recollected
- Cylindrical effects are very significant
- Temperature anisotropy
  - \( \rightarrow \) collective magnetic mirror effects
- It provides laws for HYPHEN on
  - Effective SEE yields
  - Primary VDF tail effective depletion

![Diagram of Hall thruster simulation](image)
CHEOPS: SPT-100 reference simulation

- Reference **SPT-100** HET case
- Discharge voltage: 300V
- Xenon Mass flow: 5 mg/s
- No RLC control

**Injection Surface (Anode)**

**Ceramic walls**

**Symmetry axis**

**Free loss boundary**

**Cathode**

**Average B at free loss boundary**

**242.75 G**

**~5 G**
Breathing mode oscillations

Discharge current

Plasma density

Electric potential

Volume averaged densities

Neutral density

Electron temperature

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Breathing mode oscillations

- Breathing mode frequency in 10-30 kHz range
- Large oscillations on propulsion figures (\( I_{d,\text{peak}} \approx 6 \ I_{d,\text{mean}} \))
  - Introduce uncertainties in performance estimates
  - Can lead to erroneous assessments

\[
\eta_{thr} = \frac{F^2}{2m_A P_d} \quad \text{Average } \eta \text{ (last 5 cycles)}
\]

Average \( F / \text{average } P_d \)

\[
\eta_{thr} = 0.48 \quad \text{Average } \eta \text{ (last 5 cycles)}
\]

\[
\text{Average } F / \text{average } P_d = 0.28
\]
Breathing mode oscillations

- RLC control will be implemented in HYPHEN to mitigate oscillations
- Breathing mode very sensitive to operation point
  - Dissappears with decreasing $\dot{m}$ and $V_d$
    - i.e. for lower ionization rate
  - Caution with high $V_d$ (high Isp) larger oscillations
Heat loads and erosion

- Two central results from HYPHEN are
  1. Plasma **energy deposition** into chamber walls → thruster heating
  2. Ion energy distribution of impacting ions → **wall erosion**

- Both depend strongly on sheath physics & e-VDF
  - Auxiliary PIC 1Dr code results are important
Electron inertia effects on transport

- HYPHEN simulations suggest that electron inertia plays a larger role on transport than assumed → part of ‘anomalous’ transport?

- In certain regions (e.g. anode, lateral plume) we find \( u_{\theta e} \sim \sqrt{T_e/m_e} \),
  - breaks conventional small-drift assumption
  - changes electron dynamics: \( u_{\perp e}/u_{\theta e} \neq (\text{Hall parameter})^{-1} \)

- Further investigation is needed on the topic, which is left aside in general.
On anomalous turbulent transport

- By far, the main issue preventing to achieve predictive codes of HET is the lack of a turbulence model for anomalous transport.
- Electron fluid model implemented in HYPHEN
  - identifies separate contributions of correlated turbulence effects in momentum, energy, and heat flux equations

\[
0 = -\nabla p_e + e n_e \nabla \phi + j_e \times B + \mu_e^{-1} (j_e + j_c) + F = \quad F_{\theta t} = -e \langle n'_e E'_\theta \rangle
\]

\[
\frac{\partial}{\partial t} \left( \frac{3}{2} n_e T_e \right) + \nabla \cdot \left( \frac{5}{2} n_e T_e \textbf{u}_e + q_e \right) = \textbf{u}_e \cdot \nabla p_e - e n_e \langle u'_{\theta e} E'_{\theta} \rangle - \mu_e^{-1} \textbf{u}_e \cdot (j_e + j_c) + Q_e - \frac{1}{2} m_e u_e^2 S_e
\]

\[
0 = -\frac{5 p_e}{2 e} \nabla T_e - q_e \times B - \frac{5 p_e}{2 e n_e} \mu_e^{-1} (j_e + j_c) - \mu_e^{-1} q_e + Y_t + Q_t \quad Q_{\theta t} = -\frac{5}{2} \langle p'_e E'_\theta \rangle
\]

- shows high sensitivity of plasma response to these contributions
On anomalous turbulent transport

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Conclusion

- HYPHEN is an advanced 2D (z-r) simulation code for HETs (and other thrusters)
- Its hybrid formulation makes it computationally mild and thus very convenient for R&D on the full thruster
- Future coupling with EP2PLUS will increment the capabilities of both
- CHEOPS-last semester: simulation of Safran’s dual-mode HET and verification with experimental data

- We believe HYPHEN is at the vanguard on modeling
  - axial-radial electron dynamics
  - plasma-wall interaction
- Still, there is a wide margin of improvement in both physics & algorithmics
- But, the lack of reliable anomalous transport models is a very serious setback for achieving a predictive HET code
  - More resources should be invested in this subject
Thank you! Questions?

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