An advanced simulation code for Hall effect thrusters

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Contents

- Plasmas and Space propulsion Team (EP2-UC3M)
- CHEOPS H2020- Project
- NOMADS 2D hybrid code: architecture
- Particularities of PIC segment
- Electron fluid model
- Preliminary simulation results
- Conclusions
UC3M EP2 BACKGROUND

Equipo de Propulsión Espacial y Plasmas

- 16 researchers (~50% are PhD students)

**EP2 main research lines:**

- Theoretical and numerical modelling of Electric Space Propulsion: Hall thrusters, RF-based thrusters
- Modelling of Plasma-wave interaction
- Plasma-wall interaction analyses. Erosion studies. Plume-SC interaction
- Modelling of Magnetic Nozzles and electron cooling
- Active Debris removal

**Main ongoing activities**

- **Helicon Plasma Thruster Development:**
  - Based on Helicon waves (generation) & Magnetic nozzle (acceleration)
  - FP7-HPHCOM
  - HPT05: Joint EP2-SENER Design & Manufacturing (1kW)
- **H2020-MINOTOR: ECR accelerators**
  - Based on ECR (generation and heating) & Magnetic nozzle (acceleration)
  - Goal: to advance on the theoretical & technical development of the thruster
  - EP2 developing a full model of ECRA physics: Microwave-plasma interaction (i.e. heating), ionization, heating, flow, wall interaction, supersonic expansion, final beam energy, thruster performance
- **H2020-CHEOPS: Hall Effect Thrusters**
- **Modexval-ESA (Plasma Cooling)**
- **National Research plans (Electric Propulsion)**
H2020-CHEOPS: Hall Effect Thrusters

**Motivation:** HETs are the technological main solutions in near-earth EP

**CHEOPS (coord. SAFRAN):** large project aimed for development of next generation low-to-high power HET required simulation and testing tools

**Simulation tools:** Reduce development time/costs, reveal optimization opportunities,

**EP2 large experience in modeling/simulating HET**

**EP2 is leader of WP on simulation activities. Main tasks:**

- Development of advanced hybrid (PIC/fluid) code for HET
- Code validation with Safran prototypes

**Main challenges:**

- Full-2D fluid model of magnetized electrons
  - generic magnetic topologies
  - non-Maxwellian features
- Assessment on magnetic shielding physics
- Operation with alternative propellants & non-conventional conditions
- Scaling strategies for very low and very high power
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NOMADS: 2D hybrid code for Hall-effect thrusters

- **Hybrid:** PIC (ion and neutral heavy species) + Fluid (electron population)
- **2D Axisymmetric** (z-r) plasma simulator of chamber & plume
- Heritage from HALLMA and EP2PLUS, but designed with extended capabilities

**Main Design Architecture:**

- Pre and post simulation tools (matlab, python)
- Mesh generators for ion (PIC) and electron modules Magnetic mesh accepts cusps, zeros,...
- **CORE:** FORTRAN
  - PIC module
  - Electron module + Sheath
Particularities of PIC segment

**Algorithms:**
- **Particles stored in individual lists, under population control (PIC noise, controls computational resources)**
- **Macroscopic variables obtained by particle weighting (modifications in axis)**
- **Collisional processes carried out on cell-wise algorithm:**
  \[
  \begin{align*}
  Xe + e & \rightarrow Xe^+ + 2e \\
  Xe^+ + 2e & \rightarrow Xe^{++} + 3e \\
  Xe^+ + e & \rightarrow Xe^{++} + 2e
  \end{align*}
  \]
  Drawin
  Bell
- **Particle-surface interaction, extended surface weighting (time averaging, reduce noise)**
- **Kinetic Bohm correction: algorithmic density reduction forces a response from the electric potential within the domain, prompting sonic or supersonic ions**

---

**Table:**

<table>
<thead>
<tr>
<th>Surface type</th>
<th>Effects on ions</th>
<th>Effects on neutrals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparent</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Free loss</td>
<td>Removal</td>
<td>Removal</td>
</tr>
<tr>
<td>Injection</td>
<td>Stochastic injection</td>
<td>Stochastic injection</td>
</tr>
<tr>
<td>Material wall</td>
<td>Recombination</td>
<td>Reflection</td>
</tr>
<tr>
<td>Sheath*</td>
<td>Normal velocity shift</td>
<td>None</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\bar{n}_{sw}^{(k)} &= \frac{1}{\Delta t \Delta S} \sum_{p=1}^{N_{hit}} \frac{W_p}{v_{\perp,p}} \\
\bar{g}_{sw}^{(k)} &= \frac{1}{\Delta t \Delta S} \sum_{p=1}^{N_{hit}} \frac{W_p v_{\parallel,p}}{v_{\perp,p}} \\
\bar{n}_{sw}^{(k)} &= \frac{\Delta k_{avg} - 1}{\Delta k_{avg}} \bar{n}_{sw}^{(k-1)} + \bar{n}_{sw}^{(k)} \\
\end{align*}
\]
Electrons module

Main Features

• 2D solutions of Electron Temperature and Plasma Potential
• Magnetic Field Aligned Mesh (MFAM) - limiting the impact of numerical diffusion
  • Gradient reconstruction: Weighted Least Squares Face Interpolation
  • Improved by computing in r & z and projecting locally to the field dir.

• Electron population: 12 moment approximation from Bolzmann equation
  • Two-temperature description: \( T_{\text{par}} \& T_{\text{perp}} \)
• Quiasineutral, stationary formulation, Fourier type closure in heat-flow eq.
• Secondary models: Collisions: elastic-Coulomb, inelastic \( Xe + e \rightarrow Xe^* + 2e \)
• Non-classic electron transport modeled as an anomalous transport term
• Sheath model: Anode, Ceramic walls
Preliminary simulation results (I)

**Base SPT-100 configuration:**

- Aligned with Magnetic Field
- Ceramic boundary
- Perpendicular to Magnetic Field
- Exit boundary
- Anode boundary
- Axis

Computational resources:
- $1 \text{ ms} = 1\text{-}2 \text{ days}$
- $10 \mu s = 15\text{-}30 \text{ min}$
**Preliminary simulation results (II)**

**Base SPT-100 configuration:**

<table>
<thead>
<tr>
<th>PPU control</th>
<th>( V_d )</th>
<th>( \dot{m} ) (Xe)</th>
<th>PIC ( \Delta t )</th>
<th>NOMADS ( \Delta t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant voltage</td>
<td>300V</td>
<td>( 5 \frac{mg}{s} )</td>
<td>( 10^{-8}s )</td>
<td>( 10^{-10}s )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( I_d )</th>
<th>( P_d )</th>
<th>Thrust</th>
<th>( I_{sp} )</th>
<th>( \eta_T )</th>
<th>( P_{jet} )</th>
<th>( P_{sheaths} )</th>
<th>( P_{ioniz.+excit.} )</th>
<th>( P_{cahtode} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.41( A )</td>
<td>723( W )</td>
<td>41( mN )</td>
<td>844( s )</td>
<td>0.24</td>
<td>168( W )</td>
<td>165( W )</td>
<td>57( W )</td>
<td>16( W )</td>
</tr>
</tbody>
</table>

No. PIC mesh elements: 1080
Avg. No. macroparticles: 
- \( \sim 10^5 \) Neutrals,
- \( \sim 9 \times 10^4 \) Single Ions,
- \( \sim 9 \times 10^4 \) Double Ions

No. MFAM elements: 1326
No. cores: 20
Computation time: \( 7.17 \times 10^4 \) s (\( \sim 20h \)): 4.6\( \times 10^3 \) s in PIC, 6.6\( \times 10^3 \) s in NOMADS

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Preliminary simulation results (III)

“Singular” SPT-100 configuration:

<table>
<thead>
<tr>
<th>PPU control</th>
<th>V_d</th>
<th>m (Xe)</th>
<th>PIC ∆t</th>
<th>NOMADS ∆t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant voltage</td>
<td>300V</td>
<td>5 mg/s</td>
<td>10⁻⁸ s</td>
<td>10⁻¹⁰ s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I_d</th>
<th>P_d</th>
<th>Thrust</th>
<th>I_sp</th>
<th>η_T</th>
<th>P_jet</th>
<th>P_sheaths</th>
<th>P_ioniz.+excit.</th>
<th>P_cathode</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.94A</td>
<td>881W</td>
<td>48 mN</td>
<td>980 s</td>
<td>0.26</td>
<td>229W</td>
<td>162W</td>
<td>72W</td>
<td>10W</td>
</tr>
</tbody>
</table>

- **No. PIC mesh elements**: 1080
- **Avg. No. macroparticles**:
  - ~10⁶ Neutrals,
  - ~7×10⁴ Single Ions,
  - ~7×10⁴ Double Ions
- **No. MFAM elements**: 2453
- **No. cores**: 20
- **Computation time**: 18.8×10⁴ s (~50h):
  - 4.0×10³ s in PIC,
  - 18.4×10⁴ s in NOMADS

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Conclusions

- Development of a new 2D Hybrid code for HET
  - In the frame of H2020 and EPIC
  - PIC: for heavy particles + fluid for electrons
  - Potentially expandable to other thrusters

- Main characteristics were described

- Preliminary simulations have been obtained, further improvement is required

- Future simulations will include both parallel and total electron temperature

- Future developments: further parallelization, validation with experimental data, additional models,
Thank you! Questions?

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BACK-UP
Electron population fluid model (II)

Current continuity + Momentum eq. → Generalized Ohm’s law:

\[
\{GR\} \cdot \{\phi_E\} = \{D\} + \{GR\} \cdot \{p_{e,E}\} + \{B\} + \{I_{d,E}\}
\]

Thermal Energy Density eq. + Semi-implicit temporal discretization:

\[
\{p_{e,E}\}_{t+1} = \Delta t \left[ \left( \{A\}^t + \{Ex\}^t \right) \cdot \{p_{e,E}\}^{t+1} + \{Q\}^t \cdot \{GR\} \cdot \{p_{e,E}\}^{t+1} + \{CS\}^t \right] + \{p_{e,E}\}^t
\]

Parallel Internal Energy eq. {...}

Ancillary models:

- **Collisional models:**
  - Elastic collisions (\{D\}): e-n (Hayashi), e-\text{i}_Z (Coulomb)
  - Additional inelastic collisions: \text{Xe} + e \to \text{Xe}^* + 2e (Hayashi)
  - Non-classic electron transport modelled as an additional *anomalous* collisionality term:
    \[
    \nu_{e^*} = \nu_e + \alpha_{ano} \Omega_{e,e}
    \]

- **Sheath model:**
  - Anode: \[\mathbf{j}_e \cdot \mathbf{n}_b \bigg|_{F,j} = j_{sheath,metallic} (\Delta \phi_{sheath}, n_e, T_e); \Delta \phi_{sheath} = \phi_{F,j} - \phi_{wall}\]
  - Ceramic walls (BN): \[\Delta \phi_{sheath} \bigg|_{F,j} = j_{sheath,dielectric} \left( \sum_{Z=1}^{2,3,...} j_{iZ} \cdot \mathbf{n}_b, n_e, T_e \right)\]

“Far-field” Boundary Conditions: non-homogeneous Neumann based on imposed current and heat-fluxes:

\[
(j_e + j_i) \cdot \mathbf{n}_b = 0; \quad q_e \cdot \mathbf{n}_b \bigg|_{F,j} = 0
\]
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- **Hybrid**: PIC (ion and neutral heavy species) + Fluid (electron population)
- **2D Axisymmetric** (z-r) plasma simulator of chamber & plume
- **Heritage** from HALLMA and EP2PLUS, but designed with extended capabilities

**Main Design Characteristics:**

- **Mesh generators** for ion (PIC) and electron modules
  - Magnetic mesh accepts cusps, zeros,...
- **Reduced PIC noise:**
  - multiple independent populations
  - cell population control algorithms
- **Electron + electric module:**
  - 2 Temperatures population: $T_{\text{parallel}}$ & $T_{\text{perp}}$
  - Secondary e-emission
  - Accurate sheath/presheath Bohm forcing
  - Variety of wall materials/conditions
Preliminary results (fluid module)

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1 ms = 1-2 days
10 μs = 15-30 min
Updates on Gradient Reconstruction (I)

GR based on the Weighted Least Squares Face Interpolation:

- Based on magnetic coordinates $\lambda$ (magnetic stream function) & $\sigma$ (magnetic scalar potential), for gradients in the parallel and perpendicular directions to the magnetic field:
  - Singular for $B=0$
  - Depends on a good previous calculation (numerical integration) of magnetic coordinates (not defined analytically for the domain)

- Alternatively, it is possible to derive spatially (with respect to $r$ & $z$) and project locally to the perpendicular and parallel directions...

\[
\left. \frac{d\psi}{dx} \right|_{F_{ij}} = \sum_i c_i \psi_i
\]

\[
\begin{align*}
\frac{\partial \lambda}{\partial r} &= -r B_z, \quad \frac{\partial \lambda}{\partial z} = r B_r, \quad \nabla_\parallel \equiv B \frac{\partial}{\partial \sigma} \\
\frac{\partial \sigma}{\partial r} &= B_r, \quad \frac{\partial \sigma}{\partial z} = B_z, \quad \nabla_\perp \equiv r B \frac{\partial}{\partial \lambda}
\end{align*}
\]
Updates on Gradient Reconstruction (II)

Gradient and integration errors for trial function $\psi = z + r$ on a MFAM with a singular point using WLSQRFI 1\textsuperscript{st} Order method:
1st Order derivative errors:

Analytical derivatives for magnetic coordinates are obtained through the Inverse Jacovian.
Errors after integration of 1st Order derivatives