Plasma Thruster Plume Simulation: 
Effect of the Plasma Quasi Neutrality Hypothesis

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Presentation Overview

• Introduction
• PICPluS-2 code overview
• Code validation results
• Quasi-neutrality effect analysis
• Conclusions
Electric thrusters for spacecraft

- **Hall Effect Thrusters** and **Gridded Ion Engines** are consolidating as two of the most effective new spacecraft technologies.

- 5 kW class HET are developed for application in 5-8 year timeframe (next generation GEO telecoms, e.g. **Alphabus**), 1 kW class models were successfully flown on Russian and Western spacecraft (ESA’s **SMART-1**).

- Several GIE were already successfully employed in space (NASA’s Deep Space 1, ESA’s **Artemis**).
Issues about plasma thruster integration with spacecraft

- **Direct ion** impingement onto spacecraft surfaces, sputtering, re-deposition and degradation of material properties, e.g. solar panels
- **Back flow** ion impingement caused by charge exchange plasma collisions
- **Erosion** of acceleration channel walls/grids: erosion products expansion and re-deposition
- **EMI compatibility** issues, plasma interference with telecommunication signals

Therefore necessity of:

- Appropriate **numerical simulation** of device operation
- In flight and vacuum chamber **testing**
Issues about plasma plume simulations

• Detailed physical models (plasma non-neutrality, effect of different plasma species, effect of collisions and their type)

• Reliable and fast numerical methods (Poisson solvers, particle-mesh sorting algorithms, …)

• Realistic data for injection and interaction parameters (possibly experimental)

• Realistic geometric configurations (proper assessment of electric/magnetic interactions and spacecraft surface interactions)

• Validation with respect to vacuum chamber and flight experimental data
EP activity

- Presently involved in virtually all HET/GIE development efforts in Europe
- Own technology (HET, DS-HET) or in partnership with SNECMA Moteurs, Astrium Ltd & Gmbh, QinetiQ, …
- Operating the best array of EP test facilities in Europe, 10 UHV test facilities with size up to 5.7 x 12 m and pumping speed up to 1,500,000 l/s [Xe]
Computational activities

- EP computational activity centered on plume simulation, integration with spacecraft, and complex laboratory configuration simulations
  
  - hybrid PIC (kinetic ions + non isothermal fluid electrons), 2D axially symmetric, non neutral (SOR Poisson solver) for accurate plume calculation and impact of backflow of vehicle surface (simple geometries)
  
  - charge neutral DSMC, 2D axially symmetric, for analysis of complex configurations, e.g. thruster in vacuum chamber with realistic pumping arrangement
PICPluS features

- **2D axisym**, 3 components of velocity
- **Structured grid** with variable cell size (scaled to local Debye length)
- **Xe⁺, Xe++, Xe** simulated particles
- **Elastic, CEX** collisions (2 different algorithms)
- **Effect of background pressure**
- **Input from experimental distributions** or from external simulations (magnetostatic FEM)
- **Simulated engines**: Hall Effect Thruster or Gridded Ion Engine

<table>
<thead>
<tr>
<th>Particle Species</th>
<th>PICPluS v.2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe⁺ ions</td>
<td>Simulated</td>
</tr>
<tr>
<td>Xe²⁺ ions</td>
<td>Simulated</td>
</tr>
<tr>
<td>Xe³⁺ ions</td>
<td>Can be added</td>
</tr>
<tr>
<td>Xe atoms</td>
<td>Can be added</td>
</tr>
<tr>
<td>CEX ions</td>
<td>Simulated</td>
</tr>
</tbody>
</table>

Particle species presently simulated
Algorithms

- **Particle in Cell** with Ruyten weighting
- Nanbu-Kitatani **TPMC** or Szabo **MCC** collisions
- 3 models for collision cross-sections
- Potential from **Poisson solver** (SOR method, Chebishev acceleration, checker-board ordering) or **quasi-neutrality** (Boltzmann relation)
- 3 models for **electron temperature** (constant, adiabatic, first order Chapman-Enskog) or experimental distribution
- Full **DSMC** option for neutrals
- All input fields/distributions from experiments, simulations, or simplified models

\[
T_e = \text{const.} \\
\nabla^2 (T_e) = 0 \\
T_e(r,z) = T_{\text{ref}} \left( \frac{n_e(r,z)}{n_{\text{ref}}} \right)^{\gamma-1}
\]

**Pre-processed**

**Updated step-by-step**

**Electron temperature models**

**Magnetic field: from experiments or simulations**

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 Outputs

• Instantaneous and averaged fields at steady state (species by species)

• Instantaneous and averaged thrust and beam ion current

• Ion current density measured with virtual Faraday’s probe rakes

• Impact history on (possible) solid external surface and related statistics
PICPluS-2 Validation – Test Cases

Code results compared with similar programs and experimental data from literature and in-house tests:

- Four test cases for HET and one for GIE
- All test cases achieved stationary conditions in about 40,000 time steps
- Computed thrust and ion beam current within ±1% of measured values
- Peak on axis (GIE) and slightly low current density at high angles (HET) are usually seen

<table>
<thead>
<tr>
<th>Thruster Model</th>
<th>SPT-100</th>
<th>SPT-100</th>
<th>SPT-100</th>
<th>Alta-XH5</th>
<th>MUSES-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flow Rate [mg/s]</td>
<td>4.99</td>
<td>5.12</td>
<td>5.084</td>
<td>9.2</td>
<td>0.21</td>
</tr>
<tr>
<td>Discharge Voltage [V]</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>350</td>
<td>1500</td>
</tr>
<tr>
<td>Discharge Current [A]</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>11.16</td>
<td>0.14</td>
</tr>
<tr>
<td>Background Pressure [mbar]</td>
<td>2.9 x 10^{-6}</td>
<td>4 x 10^{-5}</td>
<td>5.32 x 10^{-5}</td>
<td>8.32 x 10^{-5}</td>
<td>2 x 10^{-6}</td>
</tr>
<tr>
<td>Thrust [mN]</td>
<td>84.54</td>
<td>90.39</td>
<td>84.07</td>
<td>181.6</td>
<td>8.85</td>
</tr>
<tr>
<td>Ion Beam Current [A]</td>
<td>4.61</td>
<td>4.82</td>
<td>3.87</td>
<td>8.96</td>
<td>0.149</td>
</tr>
<tr>
<td>Domain Size [m]</td>
<td>1.2 x 1.5</td>
<td>1.2 x 1.5</td>
<td>1.2 x 1.5</td>
<td>1.0 x 1.5</td>
<td>1.0 x 2.5</td>
</tr>
<tr>
<td>Total Particle number</td>
<td>~1 x 10^{-6}</td>
<td>~1 x 10^{-6}</td>
<td>~1 x 10^{-6}</td>
<td>~1.5 x 10^{-6}</td>
<td>~0.5 x 10^{-6}</td>
</tr>
</tbody>
</table>
• Injection ion temperature has no big impact on results
• **Electron temperature** has significant effect, especially for ion distribution and impact energy of backflow CEX
• **Divergence angle at inflow boundary** has largest impact on current density and plasma field
Optimal injection distribution (inflow boundary) fitting near and medium distance measurements of current density:

- Gaussian distribution for number density
- Linear distribution (with radius) for average divergence angle
- Gaussian distribution of actual divergence angle around the average value

Good agreement for different background pressure and test conditions (in particular different fraction of double ionized propellant)
SPT-100 Simulations

![Graph showing current density vs. alpha (deg) with various data points and models]

- Express flight data
- Astrium analytical model
- Manzella 85 (2.2e-6 Torr)
- Manzella 95 (6.3e-5 Torr)
- Randolph 94 model
- PICPluS
- PICPluS - Low Press
SPT-100 Simulations

Ion current density

Comparison with near field data (Kim)

Comparison at 0.5 and 1.0 m distance (King)
• Optimal distribution for SPT-100 scaled to 5 kW thruster, showing good agreement with measurement

• Measurement of external magnetic field performed, no significant effect on simulated current density over wide range of variation
Small GIE, **excellent agreement** obtained with simple injection distribution:

- Gaussian distribution for number density
- Linear distribution for divergence angle

Strong **peak on thruster axis**: issue evidenced with other PIC codes, presently under further investigation

**Optimal injection distribution for MUSES-C**

**Radial number density profile comparison**

**Axial number density profile comparison**
Quasi Neutrality – Test Cases

- Quasi-neutrality examined from physical and numerical points of view
- Three configurations chosen:
  - 2 for HET (SPT-100, low/high background pressure)
  - 1 for GIE (MUSES-C)
- Simulations runs performed on 2.5 GHz P4 1Gb RAM, different conditions and models
- As expected plasma appears mostly neutral:
  - non neutral spots in regions where gradients are stronger
  - unbalance always less than 1% ion charge density
Quasi Neutrality – Numerics

Computational cost of Poisson and quasi-neutrality solvers increases with grid size and total number of simulated molecules, but:

- QN not always the winner, for fine grid and large number of simulated particles
  Poisson can be faster

- QN more stable in any condition, especially for unregular grid geometry

<table>
<thead>
<tr>
<th>Test Case</th>
<th>QN/Poi</th>
<th>Grid size</th>
<th>Particle #</th>
<th>Step Length [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>QN</td>
<td>50x65</td>
<td>5-10^3</td>
<td>1.27</td>
</tr>
<tr>
<td>2</td>
<td>Poi</td>
<td>50x65</td>
<td>5-10^5</td>
<td>1.30</td>
</tr>
<tr>
<td>3</td>
<td>QN</td>
<td>100x120</td>
<td>5-10^2</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>Poi</td>
<td>100x120</td>
<td>5-10^5</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>QN</td>
<td>100x120</td>
<td>1-10^6</td>
<td>2.72</td>
</tr>
<tr>
<td>6</td>
<td>Poi</td>
<td>100x120</td>
<td>1-10^6</td>
<td>2.69</td>
</tr>
</tbody>
</table>

Computation speed test case matrix

Simulation time for cases 3 and 4
**Quasi Neutrality – Ion Density**

- **HET**: no significant difference between Poisson solver and QN approach
- **GIE**: differences in back-flow region, QN under-predicting ion density

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Number density field for HET

Number density field for GIE
Quasi Neutrality – Ion Current

- Ion current density and backflow impact energy distribution not significantly affected by QN approach.

**Ion current density at 0.5 m from SPT-100 exit plane**

**Back-flow impact energy**
PICPluS – Future Developments

Code Developments

• Upgrade to 3D configurations (3D version presently under alpha testing)
• Routines for plasma-wall interaction (partnership with Univ. Bari)
• Routines for re-deposition of sputtered particles (DSMC method)
• Extension to HET inner channel (ionization, acceleration, …)
• Integration of channel/plume codes

New Test Cases

• Double Stage HET (collaboration with SNECMA Moteurs)
• HET Beam steering (3D, collaboration with SNECMA Moteurs)
• HET cluster on realistic geometry (3D)
Conclusions

• Effect of plasma quasi-neutrality (QN) assumption on ion/plasma thruster plume simulations was examined using 2D hybrid PIC code

• Validation runs show that consistently good agreement can be obtained with respect to experimental data: key role played by plasma inflow boundary

• Effect of QN is mostly small except for backflow region of GIE cases, where charge density is under-predicted by QN algorithm

• Poisson solver solution is not significantly slower than QN approach, although algorithm is more sensitive to mesh geometry and initial conditions

• Few issues still to be addressed (especially for GIE), probably related to inconsistencies in hybrid formulation of plasma model
Questions?