Hybrid Modelling of Single and Double Stage Hall Thrusters

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Outline

- How a Hall thruster works?
- Hybrid Model
- Single Stage Hall thruster
- Double Stage Hall thruster concepts
- Double Stage Hall thruster
- Conclusions and future work
A Single Stage Hall Thruster (HT)

Credit: Raphaël Vilamot

Xe\(^+\) ions

cathode

channel

anode

xenon injection

magnetic circuit

coils

Hall current

HT = closed electron drift thruster
Definitions

- **Thrust**: produced by the ejection of propellant at high velocity
  \[ T = \dot{m}v_e \] [N]

  - propellant mass flow (kg/s)
  - velocity of ejection (m/s)

- **Specific impulse**: related to the propellant velocity
  \[ I_{sp} = \frac{v_e}{g_0} \] [s]

  - gravity on Earth (9.81 m/s²)

- **Efficiency**: conversion of electric power in kinetic power of the jet
  \[ \eta = \frac{P_{kine}}{P_{elec}} = \frac{\dot{m}v_e^2}{2P_{elec}} \]

  - electric power (W)
### Performances

<table>
<thead>
<tr>
<th>Thruster</th>
<th>SPT-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>External diameter (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Power (W)</td>
<td>1350</td>
</tr>
<tr>
<td>Isp (s)</td>
<td>1600</td>
</tr>
<tr>
<td>Thrust (mN)</td>
<td>80</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.5</td>
</tr>
<tr>
<td>Lifetime (hours)</td>
<td>9000</td>
</tr>
</tbody>
</table>

- Adapted to satellite station keeping and long trip missions (saving propellant mass thanks to high Isp)

- Near future: orbit transfer mission (replace chemical thruster)
2D Hybrid modelling hypotheses

- **hypothesis 1: quasineutral plasma**
  - Sheath size \( s << L \)

- **hypothesis 2: fluid description of electrons**
  - Maxwellian EEDF
  - Electric field obtained from Ohm’s Law

- **transport of ions: kinetic description**
  - Calculation of plasma density
  - Time step constrain (CFL- \( \Delta t \sim \text{few} \ 10^{-8} \, \text{s} \))

- **transport of atoms: kinetic description**
  - (90 \% of neutral flux is ionized)

- **static magnetic field**
  - (induced magnetic field from Hall current negligible)
Anomalous transport

- flux normal to the magnetic field – drift-diffusion form
  \[ \Gamma_{e,\perp} = -\mu_{e,\perp}(nE_{\perp} + \nabla_{\perp}(nT_e)) \]

- mobility
  \[ \mu_{e,\perp} = \frac{e}{mv} \left( \frac{1}{1 + (\omega/v)^2} \right) \approx \frac{e}{mv} \frac{n}{\omega^2} \]

- \( \nu \) frequency of momentum exchange
  \[ \nu = \nu_{\text{coll}} + \nu_{\text{ano}} \]

- \( \nu_{\text{ano}} \) frequency of effective collisions
  - Wall and turbulence effects
  - Empirical way to account for them (adjustable coefficients)
  - Mobility profile deduced from LIF experiments

- \( \mu_{e-w} \propto \alpha \nu_{e-w}/B^2 \)
- \( \mu_{\text{turb}} \propto k \nu_{\text{turb}}/B^2 \propto k/B \)
HT operation @ 300V, 5 mg/s

J. Bareilles et al., PoP 11, 3035 (2004)
Single Stage HT in different regimes

Efficiency vs. Applied voltage (V)

kinetic power/electric power

PPS®1350
PIVOINE
Orléans

P. Dumazert et al.
AIAA (2003)
Limit of (conventional) SSHT

Future missions need a versatile thruster
- High T, low Isp: orbit transfer (large $m$ and low applied voltage)
- Low T, high Isp: station keeping (low $m$ and large applied voltage)

magnetic field

electric field

acceleration of ions

Heat electrons & ionization

difficult to adjust separately

thrust and specific impulse
Double Stage Hall Thruster concepts (DSHT)

- Acceleration stage: magnetic barrier as standard HT

- Ionization stage: generates a plasma

- Microwave source? (Kuwano, IEPC-2007-085)

- Helicon source? (Palmer, JPP 30-664, 2014) (Peterson, IEPC-2011-269)

- Kaufman source?

- Magnetic confinement?
LGIT (NASA/Univ. Michigan)

Ionization chamber – Kaufman
- Same as GIE for NSTAR mission
- Internal emissive cathode
- DC power supply (low voltage)
- Magnetic confinement – multicusp shape

Acceleration stage – Hall stage
- Emissive external cathode
- Magnetic field barrier as in standard SSHT

P.Y. Peterson et al., AIAA-2004-3936
Operation of the LGIT

- **Two modes tested**
  - single stage
    - external cathode: e- for discharge and neutralization
    - disconnect DC power supply and coils
    - floating internal cathode
  - double stage
    - external cathode: e- for neutralization
    - connect DC power supply (few ten’s of V) and coils
    - Internal cathode: e- for discharge

- **Performances in DS mode**
  - low efficiency: ion trajectories un-controlled
  - interface between ionization and acceleration

- **Helicon Hall Thruster**
  - promising results @ high mass flow ($\eta \sim 0.5$)
  - different gases tested

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**Graphs**

- Efficiency vs. Acceleration voltage (V)
- $P.Y. \text{ Peterson et al., AIAA-2004-3936}$

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Int. Workshop on Ion Propulsion and Accelerator Industrial Applications – March 2017, Bari, Italy
**Galatea – magnetic confinement**

- Magnetic confinement system proposed in 60-70’ (Sov. Union) for fusion machine
- Trap electrons to reach very high plasma densities
- Tokamak systems prefered

*A.I. Morozov et al., Physics Uspekhi (2003)*
SPT-MAG – magnetic configuration

O. Secheresse et al.

ionization stage (chamber) | acceleration stage (channel)
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coils
magnetic circuit

myxina coil
magnetic field lines

zero B
symmetry axis
cathode

SPT-MAG = half-GALATEA + HT
SPT-MAG - electrodes

Ionization stage (chamber)

 Separatrix

 Xe

 Acceleration stage (channel)

 Anode 1

 Intermediate electrode

 Cathode

 Anode 2, metallic walls – electrodes
Electron trajectories

magnetic field lines ~ same electric potential

anode 1
300 V

anode 2
350 V

cathode
0 V

300 V 350 V
Simulations predict the formation of a potential well (magnetic field lines are almost equipotentials)

- Plasma density $\sim 10^{12} \text{ cm}^3$
- Ions are guided towards the acceleration stage
- 300 W needed to form the plasma
Non electric potential well is formed
Large ion losses on walls
Ionization takes place at the entrance of acceleration stage
Interest for a ionization stage?
Separate the two stage operations if the ignition is influenced by the external cathode?

Conclusions and future work

- **Hybrid model**
  - Able to describe the thruster working (linked with experiments)
  - Need improvements in electron anomalous transport (electron drift instability, see Vivien Croes Talk)

- **Double stage Hall thruster**
  - Demonstration of efficiency not achieved
  - Role of ionization stage? Electric power cost?
  - Key issue of DSHT: guide the ions towards the acceleration stage
  - Joint project between Laplace & Icare laboratories, France, with Cnes funding is starting
Snecma PPS®1350 on ESA Smart-1 probe
Hall Thruster in the world

PPS1350 Snecma, Fr

Sitael – Italy, HT400

PPS20K Snecma, Fr

NASA-JPL – 6kW

Univ., low power HT - Japan

Fakel, Russia – SPT100

Int. Workshop on Ion Propulsion and Accelerator Industrial Applications – March 2017, Bari, Italy
Ion trajectories

ionization stage

Acceleration stage

350V

V

350 200 100

C. Boniface et al. 
IEEE TPS 33, 522 (2005)
SPT-MAG tested in the PIVOINE facility

- **Ionization stage**
- **Acceleration stage**
- **external cathode**
- **plasma jet**

### Conditions
- Xenon mass flow: 4 mg/s
- Voltage in the acceleration stage: 300 V
- Voltage in the ionization stage: 50 V