Theoretical and Experimental characterization of an electron cyclotron resonance plasma thruster

Félix CANNAT – felix.cannat@onera.fr

PhD Student 3rd year
ONERA Palaiseau, DMPH/FPA

Thesis Supervisor: Pascal CHABERT, Ecole Polytechnique (LPP)
ONERA Supervisor: Julien JARRIGE, DMPH/FPA
Patent Onera: coaxial ECR plasma thruster

Particularity:
• Microwave power transfer by Electron Cyclotron Resonance (ECR).
• Plasma expansion by magnetic nozzle.
• Quasi-neutral, current-free plasma exhaust (No neutralizer).
• No grid acceleration (no erosion).
• Coaxial geometry (reduce size to compare wave-guide).
• \(\mu\)N to mN thrust / Low power consumption.


Principle of ECR Thruster

- Radio frequency electric field at the electron cyclotron frequency.

Frequency MW 2.45 GHz → B=875 Gauss

\[ \omega_{ce} = \frac{eB}{m_e} \]

- Magnetic nozzle: Diverging Magnetic field
  - Electrons acceleration: Conversion of gyrokinetic energy into longitudinal energy
  - Space charge at the thruster exit
  - Ambipolar acceleration of ions
Thesis Objectives:

• Improve Theoretical understood of the ECR thruster:

  ▪ The absorption of microwave power by electron cyclotron resonance & microwave-plasma coupling.
  ▪ Ion acceleration process and detachment in the magnetic nozzle

• Improve Thruster performances and efficiency:

  \[
  \eta_T = \eta_m \eta_e \eta_D = \frac{T^2}{2 \dot{m}_g P_{MW}}
  \]

  \[
  \eta_m = \frac{I_i m_i}{\dot{m}_g q} = \frac{\dot{m}_i}{\dot{m}_g}
  \]

  \[
  \eta_e = \frac{I_i E_i}{P_{MW}}
  \]

  \[
  \eta_D = \frac{T}{\dot{m}_i v_i}
  \]

\[
T = \int_{-\pi/2}^{\pi/2} J_i(\theta) \frac{m_i}{q} v_i \pi D^2 \sin(\theta) \cos(\theta) d\theta
\]
Theoretical/numerical work: Simulation of electromagnetic wave propagation in a magnetoplasma in a coaxial geometry.

Electromagnetic wave equation

\[ \mathbf{k} \times (\mathbf{k} \times \mathbf{E}) + k_0^2 \varepsilon_r \mathbf{E} = 0 \]

\[ \varepsilon_r = \begin{pmatrix} 1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{pe}^2} & \frac{-\omega_{pe} \omega_{ce}^2}{\omega (\omega^2 - \omega_{ce}^2)} & 0 \\ -\frac{\omega_{ce} \omega_{pe}^2}{\omega (\omega^2 - \omega_{ce}^2)} & 1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{pe}^2} & 0 \\ 0 & 0 & 1 - \frac{\omega_{pe}^2}{\omega^2} \end{pmatrix} \]

\[ \omega_{ce} = \frac{eB}{m_e} \]

\[ \omega_{pe} = \frac{n_e e^2}{m_e \varepsilon_0} \]

EM wave absorption in a ECR magnetoplasma

2.45 GHz - norm E - GradB -0.5G/mm

MW input

2D axisymmetric finite element – EM wave propagation in an coaxial ECR magnetoplasma
Theoretical/numerical work: Simulation of ambipolar acceleration of ions in a diverging magnetic field

- Model 1D fluide self-consistent
- Conservation flow rate
- Conservation energy
- Isothermal Electrons
- Bohm Velocity at the open end

$$u_B = \sqrt{\frac{k_B T_e}{m_i}}$$

Acceleration of ions in a purely diverging magnetic field

Electron Temperature key parameter for delta-V ions
Experimental Characterization: prototypes and diagnostics

- Experimental Characterization: prototypes and diagnostics

Electrostatic probes for plume characterization:
- Gridded Faraday probes (Ions current)
- RPA + ion analyzer (Ions energy)
- Langmuir probe (Electron Temperature)

Electric Propulsion Laboratory at DMPH/FPA ONERA Palaiseau - B61 Facility
- 4 m length x 1 m diameter – vacuum $10^{-7}$ mbar
- 8000 l/s de pompage xenon
Experimental Characterization: Influcence of geometry size on ECR thruster performances

**Configuration 1**
Outer diameter 13 mm

The current density on axis is higher with a higher open end exit.

Reduce the percent of walls losses

**Configuration 2**
Outer diameter 27 mm

Angular current density first configuration

Angular current density second configuration
When the diameter increases, a larger ratio of ions is extracted from the thruster than is lost to the walls. Consequently, more ions are usefully used to generate thrust, and lower power losses are predicted.
ECR thruster Performances.

ECR thruster performances at the beginning

<table>
<thead>
<tr>
<th>Gaz</th>
<th>Débit [mg/s]</th>
<th>Puissance Absorbée [W]</th>
<th>Energie d'ion [eV]</th>
<th>Courant d'ion [mA]</th>
<th>Poussée [mN]</th>
<th>Isp [s]</th>
<th>Rendement d'utilisation massique %</th>
<th>Rendement de puissance %</th>
<th>Rendement de divergence %</th>
<th>Rendement total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon</td>
<td>0,1</td>
<td>40,4</td>
<td>280</td>
<td>29,7</td>
<td>0,57</td>
<td>585</td>
<td>40%</td>
<td>21%</td>
<td>70%</td>
<td>4,1%</td>
</tr>
<tr>
<td>Xenon</td>
<td>0,2</td>
<td>40,7</td>
<td>125</td>
<td>65,4</td>
<td>0,84</td>
<td>430</td>
<td>45%</td>
<td>20%</td>
<td>70%</td>
<td>4,4%</td>
</tr>
</tbody>
</table>

Current ECR thruster performances

<table>
<thead>
<tr>
<th>Gaz</th>
<th>Débit [mg/s]</th>
<th>Puissance Absorbée [W]</th>
<th>Energie d'ion [eV]</th>
<th>Courant d'ion [mA]</th>
<th>Poussée [mN]</th>
<th>Isp [s]</th>
<th>Rendement d'utilisation massique %</th>
<th>Rendement de puissance %</th>
<th>Rendement de divergence %</th>
<th>Rendement total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon</td>
<td>0,1</td>
<td>30,0</td>
<td>248,5</td>
<td>45,5</td>
<td>0,98</td>
<td>1001</td>
<td>62%</td>
<td>38%</td>
<td>83%</td>
<td>16,1%</td>
</tr>
<tr>
<td>Xenon</td>
<td>0,2</td>
<td>30,0</td>
<td>101</td>
<td>71,3</td>
<td>0,98</td>
<td>500</td>
<td>49%</td>
<td>24%</td>
<td>83%</td>
<td>8,0%</td>
</tr>
</tbody>
</table>

Improved global efficiency by factor 4 at 0.1 mg/s
by factor 2 at 0.2 mg/s
Conclusions/Prospect

Conclusions:

• Progress on theoretical physics and simulation of ECR thruster
• Improved technology of thruster and diagnostics.
• Improved global thruster efficiency from 4 % to 16 %.

Prospect:

• Scale-up ECR thruster and limit geometry research
• Use new diagnostics on ECR Thruster, Thrust Balance, Tomography LIF
• Improve model predictions for thruster design investigations
• Industrial contract (CNES, Airbus) new development on ECR thruster.
Scientific communication

**List of communications:**

Abstract accepted:


Oral presentation:


« Electromagnetic wave propagation in a coaxial ECR thruster » **Félix Cannat**, Julien Jarrige: Journées scientifique Labex Plas@Par 2014 Paris

« Modélisation et caractérisations d'un propulseur plasma à résonance cyclotronique des électrons » **Félix Cannat**: Journées Industrie Labex Plas@Par 2014 Paris

**Liste of Article:**

Article in review process:

« Optimization of a coaxial electron cyclotron resonance plasma thruster with an analytical model » AIP, Physics of Plasma, **Félix Cannat**, Trevor Lafleur, Julien Jarrige, Pascal Chabert, Paul-Quentin Elias, Denis Packan.
Thanks you for your attention / Questions ?