Development and performance evaluation of an ECR plasma thruster

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Abstract: The electron cyclotron resonance (ECR) plasma thruster is an electric propulsion device that combines the high ionization performances of an ECR source and the simultaneous acceleration of electrons and ions in a magnetic nozzle. A coaxial ECR thruster under development at ONERA is tested using argon as a propellant gas. The influence of mass flow rate and microwave power on ion current and ion energy distribution is evaluated. Mass utilization efficiencies up to 14% and ion energy up to 240 eV have been obtained with a microwave power less than 50 W.

I. Introduction

Electric propulsion has become widespread for satellites control and deep space scientific missions. Several technologies have been developed (Hall Effect Thrusters, Gridded Ion Thrusters, High Efficiency Multistage Plasma Thrusters), which are all based on ionization of a gas (currently xenon) in a plasma source and electrostatic acceleration of the positive ions with an external electric field. As a positive ion beam exits the thruster, the use of an auxiliary electron source is necessary to avoid charging of the satellite.

Recently, interest has increased for new technology thrusters able to produce an electrically neutral beam (ions and electrons are ejected simultaneously) using combined effects of a plasma source and a magnetic nozzle. In this paper, we describe an electron cyclotron resonance (ECR) thruster under development at ONERA (ONERA patent).

II. Principle of ECR thruster

Our thruster principle is based on electron heating in an ECR source and plasma acceleration in a magnetic nozzle (i.e. a diverging magnetic field), as illustrated in Figure 1. Electron cyclotron resonance is obtained when applying a radio-frequency EM field at the electron cyclotron frequency \( f_{ce} \) defined by:

\[
    f_{ce} = \frac{eB}{2\pi m_e},
\]

where \( B \) is the externally applied magnetic field, \( e \) the elementary charge of the electron, and \( m_e \) the mass of the electron.

For a standard magnetron microwave (MW) frequency of 2.45 GHz, ECR effects are observed at a magnetic field of 875 Gauss. Bulk electrons in the resonance region are heated and gain gyrokinetic energy. Inelastic collisions with neutrals then lead to an efficient ionization of the propellant gas (and production of secondary electrons).

Electrons are accelerated along the magnetic field lines under the effect of magnetic field divergence: electron thermal energy is converted to translational kinetic energy. Ions, which are much heavier than electrons and are only partially magnetized, can be considered as stationary during electron acceleration. Thus, while electrons exit the source, a space charge is formed in front of the thruster, and the resulting ambipolar electric field then accelerates the ions.

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ECR thruster has three main advantages over existing electric propulsion technologies:

- The plume is electrically neutral (both ions and electrons are accelerated). Therefore, contrary to existing technologies, there is no need for a cathode neutralizer downstream. Moreover, there is no limit to ion current density related to space charge.
- There is no grids, so no surface exposed to an intense ion bombardment.
- No additional power supply is required to accelerate ions.

III. Experimental setup

The ECR source consists of a coaxial cavity powered by microwaves (at 2.45 GHz) and of permanent magnets ensuring a resonance region for electrons in the cavity, as shown in Figure 2. The coaxial structure enables to reduce the plasma source diameter (typically 1.3 cm in our experiments) in comparison to waveguides systems. The position of the magnets is adjusted to produce a purely diverging magnetic field in the source and the magnetic nozzle.
The MW power transmitted to the ECR source is measured using a coupler equipped with diode detectors. The MW generator used for this study is a standard commercially available magnetron at 2.45 GHz. The experimental measurements are led in B09 vacuum tank at ONERA Palaiseau (Figure 3). The vacuum tank, 2 m long and 0.7 m in diameter, is equipped with three turbo-pumps (total pumping speed: 6000 L/s for nitrogen) that ensure limit vacuum pressure below $10^{-7}$ mbar, and an operating pressure of a few $10^{-5}$ mbar with gas flow.

Figure 3. B09 vacuum chamber at ONERA Palaiseau.

IV. Diagnostics

A set of electrostatic probes have been developed for plume characterization. The ion current density is measured using a gridded Faraday probe which is composed of a collector placed downstream a grid. The collector is biased negatively such as all electrons are repelled and only ions are collected. The grid, whose potential is floating, acts as an electrostatic screen between collector potential and plume potential, which prevents from disturbing the incoming beam. The current collected at the collector is measured with a Keithley pico-ammeter.

The ion energy distribution in the plume is determined with a 4-grids retarding potential analyzer (RPA). The first floating grid screens the plume potential (floating). The second grid is biased negatively in order to repel all electrons. The potential of the third grid (analysis grid) is scanned positively to filter the ions as a function of their energy. Only ions with a kinetic energy (in eV) higher than the analysis grid potential can reach the collector. The role of the fourth grid is to repel secondary electrons produced by impact of ions inside the RPA. The ion energy distribution function (IEDF) is then obtained by derivation of collector current versus analysis grid potential:

$$f_i(V) \propto \frac{dI_{collected}}{dV}$$

A schematic of the RPA with an example of V-I curve and IEDF are shown in Figure 4.
A further characterization of the plume is performed with the Hiden PSM ion analyzer, which is used to make simultaneous scans of mass (up to 300 amu) and energy (up to 1000 eV). The electrostatic probes are placed on a three axis translation stage system, while the thruster is mounted on a rotation stage in order to perform angular scans of the beam properties.

V. Results

In the experiments, the thruster was operated with argon. A typical plasma plume produced using argon as propellant gas is shown in Figure 5. The thruster was mainly operated at mass flow rates below 0.3 mg/s where better performances were observed. The gridded Faraday probe was placed at 30 cm from the thruster for all ion current measurements.

Figure 4. Schematic of the RPA and example of V-I curve and IEDF obtained from RPA measurements.

Figure 5. Plume of ECR thruster operated with argon.
The thruster performances are evaluated in terms of total ion current, estimated thrust, and mass utilization efficiency. Total ion current $I_i$ is obtained by integration of current density $J_i(\theta)$ over the beam profile:

$$I_i = \int_{\theta} J_i(\theta) \pi D^2 \sin(\theta) d\theta$$

where $D$ is the distance to the thruster.

The thrust $T$ can be estimated from ion current profile and ion velocity $v_i$ (assuming that the ion velocity is uniform over the profile):

$$T = \int_{\theta} J_i(\theta) M_{i} \pi D^2 \cos(\theta) \sin(\theta) d\theta$$

with $v_i = \sqrt{\frac{2E_i}{M_{i}}}$

where $E_i$ is the ion energy and $M_{i}$ is the ion mass.

The mass utilization efficiency $\eta_m$ is the ratio of ion mass flow over gas mass flow. It represents the fraction of gas that is effectively used for the thrust:

$$\eta_m = \frac{I_{i} M_{i}}{m_{i} e} = \frac{m_{i}}{m}$$

The evolution of ion current density on the thruster axis with MW power is shown in Figure 6. For both tested mass flow rates (0.1 and 0.2 mg/s), $J_i$ increases with MW power, so the mass utilization efficiency is improved. Angular profiles of ion current have been performed at these mass flow rates in Figure 7. The results show that the mass flow rates and the power do not influence significantly the beam shape: most of the ion current is measured at the centre of the plume.

The influence of MW power and mass flow rate on ion energy distribution is also investigated. IEDF depends strongly on argon mass flow, as indicated in Figure 8. When the mass flow is reduced, ion peak energy increases and reaches 200 eV at 0.1 mg/s (i.e. an Ar$^+$ ion velocity of 44 km/s). On the other hand, MW power does not influence significantly ion energy. It is noteworthy that only the ambipolar field produced in the magnetic nozzle is implied in ion acceleration (no acceleration grids are used).

![Figure 6. Evolution of ion current density on the plume axis with MW power for two argon mass flow rates.](image-url)
Figure 7. Angular profile of ion current density in the plume for different argon mass flow rates.

Figure 8. Influence of argon mass flow rate (left) and MW power (right) on ion energy distribution function of Ar$^+$ ions.

Figure 9 shows the angular profile of IEDF measured at 0.15 mg/s with the RPA. It can be seen that ion energy does is nearly identical for all angular positions, with a peak around 150 eV. Therefore the thrust can be estimated directly from the ion current profile and a constant ion velocity. The performances of the thruster in the conditions of Figure 7 are summarized in the following table:

<table>
<thead>
<tr>
<th>Qm(argon)</th>
<th>0.1 mg/s</th>
<th>0.2 mg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ii</td>
<td>27.3 mA</td>
<td>29.4 mA</td>
</tr>
<tr>
<td>ηm</td>
<td>11.3%</td>
<td>12.2%</td>
</tr>
<tr>
<td>T</td>
<td>35 W</td>
<td>47 W</td>
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<tr>
<td></td>
<td>55.8 mA</td>
<td>66.7 mA</td>
</tr>
<tr>
<td></td>
<td>11.6%</td>
<td>13.9%</td>
</tr>
<tr>
<td></td>
<td>310 μN</td>
<td>500 μN</td>
</tr>
</tbody>
</table>
VI. Conclusion

Using argon as a propellant gas, the thrust produced by our coaxial ECR thrusters was estimated around 500 µN for a mass flow rate of 0.2 mg/s. Ion energies up to 240 eV and mass utilization efficiency up to 14% have been obtained with MW power less than 50 W. Recent investigations using xenon have shown a significant improvement of thruster performances. Due to its lower ionization potential, the mass efficiency can reach 45% at 0.2 mg/s, with a thrust close to 1 mN.

Figure 9. Angular profile of ion energy distribution. Argon mass flow rate: 0.15 mg/s.