Experimental investigation of magnetic gradient influence in a coaxial ECR plasma thruster

F. Cannat, J. Jarrige, P.-Q. Elias, D. Packan

Experimental investigation of magnetic gradient influence in a coaxial ECR plasma thruster.

Space Propulsion – 2014 – 2980728
Presented at the Space Propulsion 2014
Maritim Hotel, Cologne, Germany
19th to 22nd May 2014

Félix Cannat[1], Julien Jarrige[2], Paul-Quentin Elias[3], Denis Packan[4]

ONERA – The French Aerospace Lab, Palaiseau, France

[1] Ph.D. Student, Physics and Instrumentation Department, felix.cannat@onera.fr

[2] Research Scientist, Physics and Instrumentation Department, julien.jarrige@onera.fr

[3] Research Scientist, Physics and Instrumentation Department, paul-quentin.elias@onera.fr

[4] Research Scientist, Physics and Instrumentation Department, denis.packan@onera.fr

Abstract

A technology of electrical propulsion is under development at ONERA: Electron Cyclotron Resonance (ECR) thruster. The principle is based on the resonant heating of electrons in a magnetic field by microwave power, and the ejection of a quasi-neutral plasma in a magnetic nozzle. The plume is electrically neutral, thus no neutralizer is needed, and no power supply other than the microwave supply used to create the plasma is required to accelerate the ions. The influence of the magnetic field on ion current and ion energy distribution is evaluated and the performances with different magnetic field topologies are compared.

I. Introduction

Electric thrusters provide better mass efficiency than chemical rocket engines due to a high specific impulse (I_{sp}), and thus future satellite platforms will rely more heavily on electric propulsion. Several technologies have been developed (Hall Effect Thrusters, Gridded Ion Thrusters, High Efficiency Multistage Plasma Thrusters), which are all based on ionization of a propellant gas in a plasma source and electrostatic acceleration of ions. The positive ion beam that exits the thruster then needs to be neutralized with an auxiliary electron emitter to avoid charging of the satellite.

In this paper, we present a type of a quasi-neutral electric propulsion system, namely the Electron Cyclotron Resonance (ECR) Plasma thruster. Several studies and characterization of the ECR thruster have been led in the past [1, 2, 3, 4, 5, 6]. The originality of the ECR plasma thruster developed at ONERA lies in its coaxial geometry, its magnetic field configuration and the low power consumption (50 W). To investigate the influence of the magnetic field configuration on thruster efficiency, an experimental setup with a water-cooled tunable coil has been installed. Position of the source can be translated inside the coil and the magnitude of the magnetic field is adjustable. Another magnetic configuration is investigated by adding an annular magnet inside the coil. The principle of the thruster and its design are presented in section II, the experimental setup and diagnostics in section III and the experimental results are presented in section IV. Finally, section V summarizes the results and gives concluding remarks on this investigation.

II. Description of ECR Thruster

A. Principle of ECR Thruster

The ECR thruster is based on the energy transfer between microwave power and propellant gas. To efficiently transfer the microwave power we use Electron Cyclotron Resonance. In the presence of a magnetic field, the charged particle gyrate around the field lines at the cyclotron angular pulsation $\omega_{ce,i}$ defined by the Lorentz force.

$$m_{e,i}\frac{d\overrightarrow{v_{e,\iota}}}{dt} = \vec{F} = q(\vec{E} + \overrightarrow{v_{e,\iota}} \times \vec{B})$$

$$\omega_{ce,i} = \frac{qB}{m_{e,i}}$$

where B is the magnetic field strength, q the electric charge of particle and $m_{e,i}$ the mass of charged particle. When applying a micro-wave (EM) field at the cyclotron angular frequency, the charged particle are continually heated around the magnetic field lines and the micro-wave energy is absorbed. For a standard magnetron frequency of 2.45GHz, the ECR conditions are met with a magnetic field of 875 Gauss. Inelastic collisions between electrons and neutral then lead to high ionization of the gas. The acceleration of charged particle occurs with the diverging magnetic field: the gyrokinetic energy of electron is converted to longitudinal kinetic energy by the conservation of the electron energy ε and of the magnetic moment μ.

$$\varepsilon = \frac{1}{2}m_e v_\parallel^2 + \mu B(z)$$

$$\mu = \frac{m_e v_\perp^2}{2B}$$

Where $v_\parallel$ is the electron longitudinal velocity (parallel to the magnetic field lines), $v_\perp$ is the electron perpendicular velocity and m_e is the electron mass.

Ions are much heavier and colder than electrons, and are not magnetized. Their acceleration occurs due to the ambipolar electric field created by the electron accelerated in the diverging magnetic field. The ECR Thruster has two main advantages over existing electric propulsion technologies:

- The plume is electrically neutral (no need for a cathode neutralizer downstream).
- The ion acceleration is only due to the ambipolar field formed in the magnetic nozzle. Therefore, no high voltage grid is required to accelerate ions.

The magnetic field configuration is key to control the thruster efficiencies.

B. ECR Source design

The ECR thruster under development at ONERA is based on a compact coaxial geometry inside a magnetic field, as show in **Figure 1** with coils. A more compact version with permanent magnet has already been studied [5, 6], and would be the basis of a mature thruster design, but the use of a coil instead of the permanent magnets in the presented version allows to vary the magnetic field and thus to study more in depth the importance of its topology.

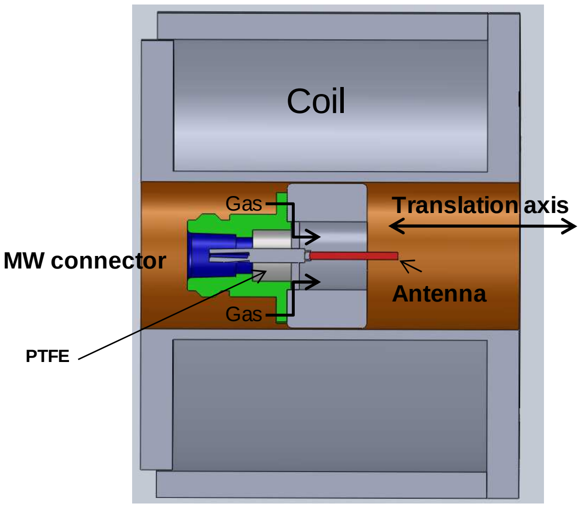

Figure 1 – ECR source design

The coaxial source has an inner diameter of 1.5 mm (antenna) and an outer diameter of 13 mm (cylinder). The length of the source is 15 mm, and its impedance in vacuum is 153 Ohms. The coaxial source is connected to the microwave power supply by a coaxial cable. A DC-block is inserted in the line to enable the antenna and the cylinder to be floating at their own potential. A dielectric material plate is used to insulate the back of the cavity from plasma. The gas is injected radially through two holes 1 mm inner in diameter. The electric field generated by MW power at 2.45 GHz is therefore in TEM mode in the line and quasi-TEM mode in the cavity because of the effects of the magnetic field on the plasma [7]. The coaxial source is inserted inside a water cooled coil made of 10 turns over 5 layers of copper tube with a total section of 5.49 mm^2 and a water passage 3 mm in diameter. The mean radius of the coil is 61.5 mm and his length is 55 mm. A current supply in the range 0-160 A is used to generate the magnetic field. The magnetic profile on the axis at 100A is shown in Figure 2.

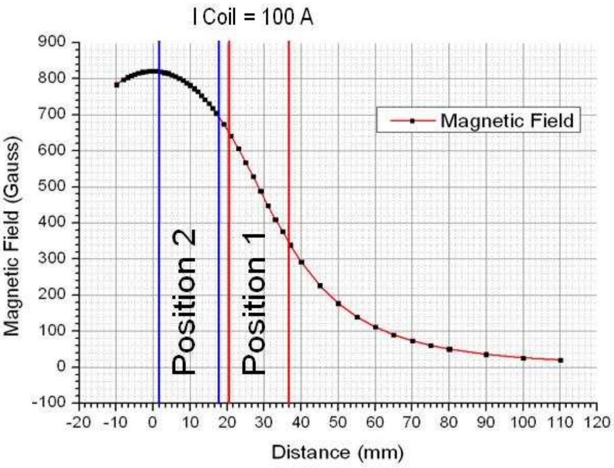

Figure 2 – Magnetic field profile on axis thruster and position of coaxial source.

The increase of axial magnetic field intensity with the current measured in middle on the coil axis is presented in figure 3. The longitudinal position of the coaxial source inside the coil can be varied with a motorized translation stage and the magnetic intensity can be adjusted in order to study the effect of the magnetic topology on the ECR thruster performances.

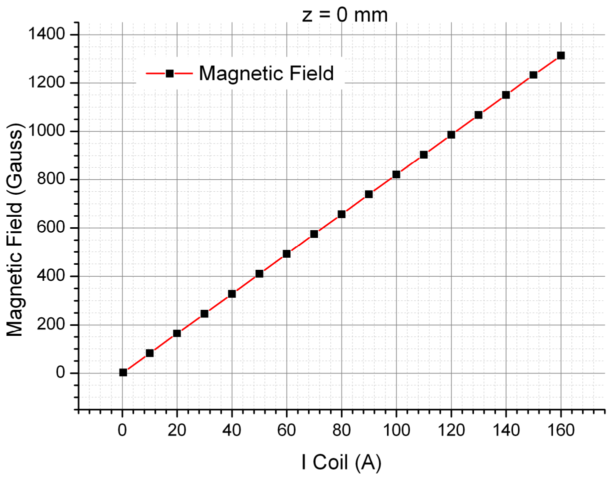

Figure 3 – Magnetic field intensity vs coil current

III. Experimental apparatus

The experiments are performed in B09 facility at ONERA Palaiseau center. B09 is a cylindrical vacuum chamber 2 m long and 0.8 m in diameter equipped with three Pfeiffer Hipace 2300 turbomolecular pumps that ensures a base pressure below 10^{-7} mbar. An MKS 999 Quattro multi-sensor transducer is used to monitor the pressure in the chamber. The argon and xenon flow into the thruster is regulated with a Bronkhorst El-flow and Brooks 5850E series mass flow controllers. In the conditions of the experiments the background pressure was in the range [$4x10^{-6}$ – $2x10^{-5}$ mbar]. The effective pumping speed of the vacuum chamber is estimated at about 2500L/s for xenon and 4000L/s for argon. The thruster is powered by a Kuhne Electronic signal generator with a tunable microwave frequency between 2.3 and 2.6 GHz and a linear power amplifier with an adjustable output power from 0 to 100 W. A circulator with a 50 Ohms load is used to dissipate the reflected power from the thruster. The power absorbed by the thruster was monitored with a bidirectional coupler and diode detectors in the chamber just before the DC-block.

Two diagnostics are used for plume characterization: a gridded Faraday probe for ion current density measurement and a Hiden PSM ion analyzer to make simultaneous scan of mass and energy of the plume. The ECR thruster is mounted on a rotation stage inside the vacuum chamber in order to perform angular scans of the plumes properties. The Faraday probe is placed 30 cm away from the thruster for all measurements presented in this paper. The collected ion current is measured with a Keithley picoammeter, and the ion current density is then obtained dividing this current by the ion collection aperture (6 mm in diameter), taking into consideration the grid transmission (50%). This probe transmission was validated by comparing the current of several probes of different types in the same conditions.

From the experimental measurements (angular profile of ion current density and ion energy), several typical thruster parameters listed below can be calculated [8].

Total ion current I_i is obtained by integration of ion current density $J_i(\theta)$ over the plume profile (assuming the axisymmetric of the plume):

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

where D is the distance between the probe and the thruster and θ the angle to the thruster axis.

The mass utilization efficiency η_m is the ratio of ion mass flow over gas mass flow. Its represents the fraction of propellant gas that is effectively ionized and used for the thrust:

$$\eta_m = \frac{I_i m_i}{\dot{m}_g e} = \frac{\dot{m}_i}{\dot{m}_g}$$

Where m_i is the ion mass, and $\dot{m}_g$ is the propellant mass flow.

The thrust T can be estimated from the ion current density profile and the mean ion velocity v_i at centerline (assuming that the velocity is uniform over the angular profile, which was checked in some conditions using an RPA probe and ion analyzer):

$$T = \int_{-\pi/2}^{\pi/2} J_i(\theta) \frac{m_i}{e} v_i \pi D^2 \sin(\theta) \cos(\theta)\, d\theta$$

The energy efficiency η_e compares the power necessary for ion acceleration and the power supplied to the thruster P:

$$\eta_e = \frac{I_i E_i}{P}$$

where E_i is the ion energy in electron-volt.

The divergence factor η_D is used to correct the divergence of the plume that causes a decrease of the produced thrust:

$$\eta_D = \frac{T}{\dot{m}_i v_i}$$

The usual thruster "efficiency" η_T is a figure of merit of the thruster and is defined as:

$$\eta_T = \frac{T^2}{2\dot{m}P} = \eta_m \eta_e \eta_D^2$$

The specific impulse I_{sp} (in seconds), which is the ratio of the thrust to the rate of propellant consumption, is another typical measure of the thrust efficiency:

$$I_{sp} = \frac{T}{\dot{m}_g g}$$

IV. Results

A. Argon results

The ECR thruster performances were investigated as a function of the magnetic topology in the coaxial source. A typical plume produced by the ECR thruster is shown in **Figure 4**. Two typical positions of the source are investigated: the first one with the ECR source at the end of the coil and the second one with the source in the middle of the coil. The magnetic field profile in the source for the two positions is indicated on Figure 2. The magnetic gradient is weaker on the position 2 compared to the position 1.

Figure 4 – Typical plasma plume produced by ECR source

For each position, the current density on thruster axis was measured as a function of coil intensity. The results are presented in **Figure 5**, the conditions for each position are the same.

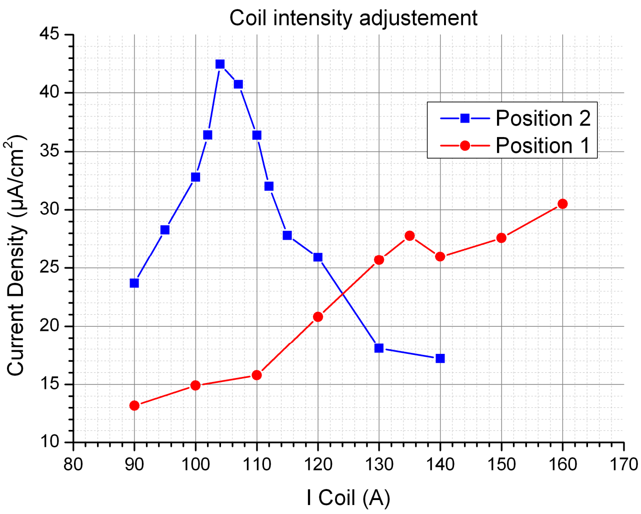

Figure 5 – 0.1 mg/s Argon, 22 W at 2.45 GHz

The maximum current density corresponds to ECR condition close to the back of the source with a weak magnetic gradient (ECR condition on a higher zone), on position 2.

The maximum ion energy (figure 6) increases with the magnetic field, but the maximum energy does not correspond to the maximum current density in particular for the position 2. The magnetic field has an important effect of the EM wave energy transfer, plasma confinement and ambipolar field extraction [9].

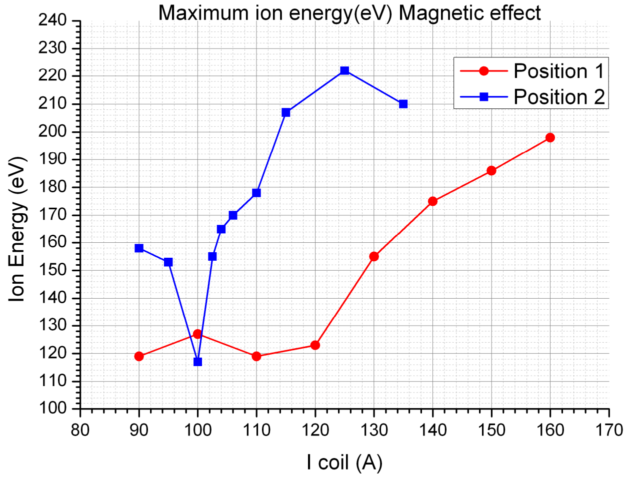

Figure 6 – Maximum ion energy with coil adjustments - Argon

At the optimum operating magnetic field condition for the current density for each position, microwave power scans and angular current density distribution are measured to estimate thruster performances. They are presented in figure 7 and 8.

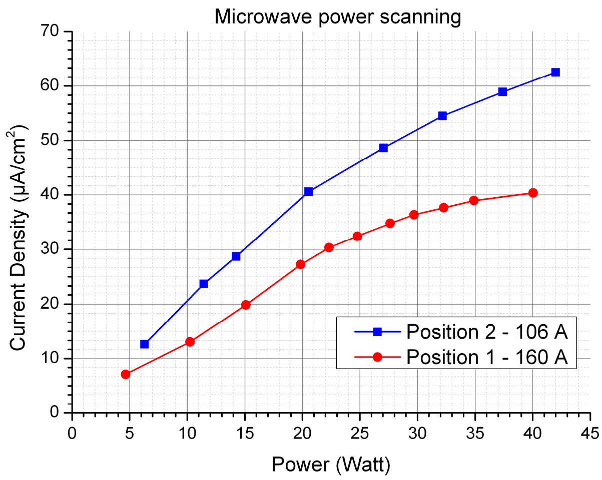

Figure 7 – 0.1mg/s Argon, 2.45GHz, at optimum coil intensity

In both positions, the ion current increases with power and tends to saturate.

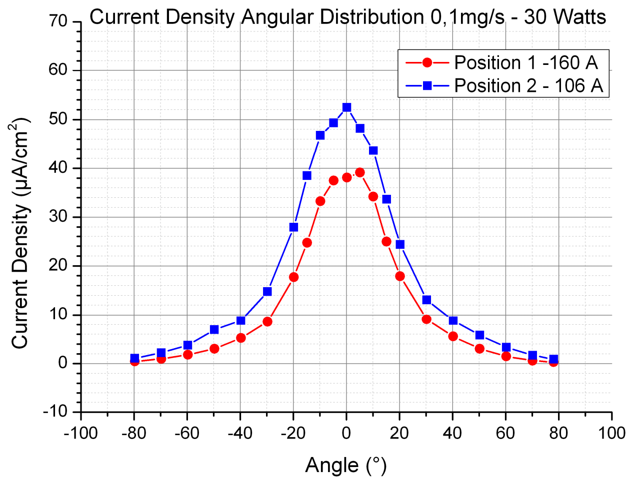

Figure 8 – Angular current density distribution - Argon

The angular distribution of ion current density shows that the maximum current is on thruster axis and the values of position 2 are higher over the whole angular profile. The total ion current is 24.2 mA for the position 1 and 39.65 mA for the position 2, i.e. respective mass utilization efficiencies of 10% and 16.4%.

B. Xenon result

Previous works on the ECR thruster [6] had shown better performances with xenon compared to argon. The effect of magnetic field profile on ECR thruster performances is also investigated using xenon, with the source in position 2. The influence of coil intensity on ion current density is presented in figure 9.

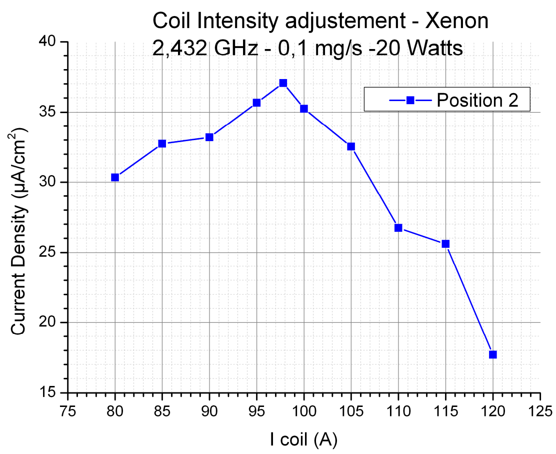

Figure 9 - Current density with coil intensity adjustments - Xenon

Angular distributions of current density at the optimum magnetic field are shown in **Figure 10** for different mass flow rates and microwave powers.

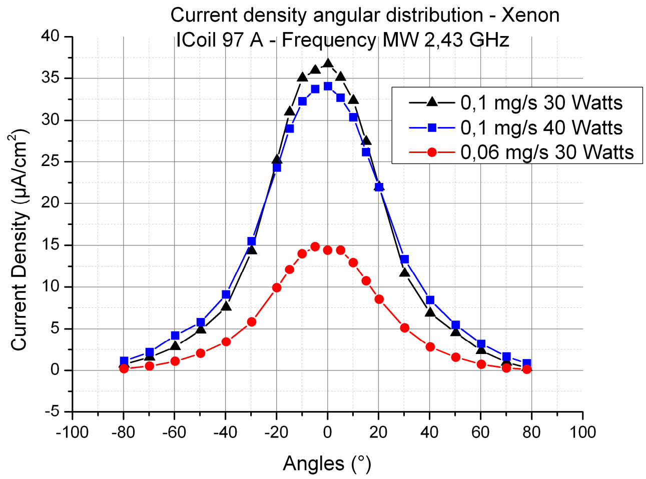

Figure 10 – Angular current density distribution - Xenon

The magnetic field topology has a lower effect on ion current using xenon gas compared to argon. The peak of ion current density is found at a lower coil current. On the angular current density distribution, the total ion current is 12.73 mA for 0.06 mg/s, i.e 29% mass utilization efficiency, and 32 mA and 35.6 mA, i.e 44% and 48.5% mass utilization efficiency, for 0.1mg/s at 30 and 40 watts, respectively.

C. Improved magnetic field configuration

The last experiment presented in this paper is performed with an additional annular permanent magnet in order to obtain a quasi-null magnetic gradient around the resonance region. The goal is the obtain a broader region where ECR resonance can occur, thus increasing the residence time of the gas in the ECR region, in order to obtain a better ionization and an improved mass utilization efficiency. The experimental magnetic field measured on axis is shown in **Figure 11** with a 134.5 A coil current intensity.

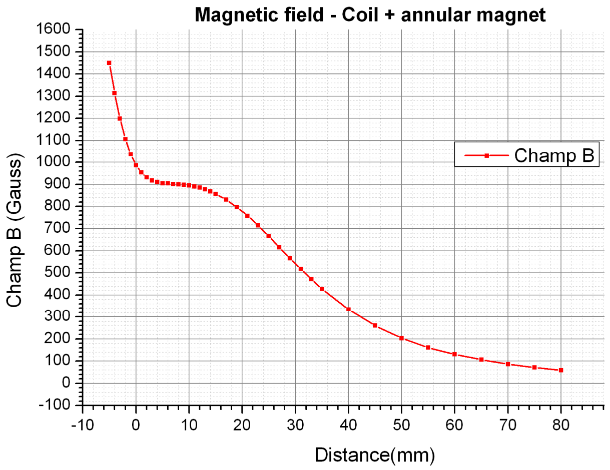

Figure 11 – Magnetic field profile on axis thruster with an additional annular permanent magnet.

The last point on the left correspond to the back plate of the thruster in figure 11. The quasi-null magnetic gradient is found around 905 Gauss and corresponds to a 2.53GHz microwave frequency. The effect of magnetic field modification is investigated for different mass flow rates with argon gas. On Figure 12 the current density is higher with 0.06 mg/s flow rate than with 0.1 mg/s. The maximum of the current density is not found when the ECR condition is on the quasi-null magnetic gradient but when the ECR condition is close to the back plate of the thruster. The Angular distribution of current density is shown in Figure 13 for optimal coil conditions. The total current for 0.06 mg/s and 0.1 mg/s at 26 Watts found is respectively 31,7 mA and 31.9 mA, i.e. 21,9% and 13,2% of mass utilization efficiency.

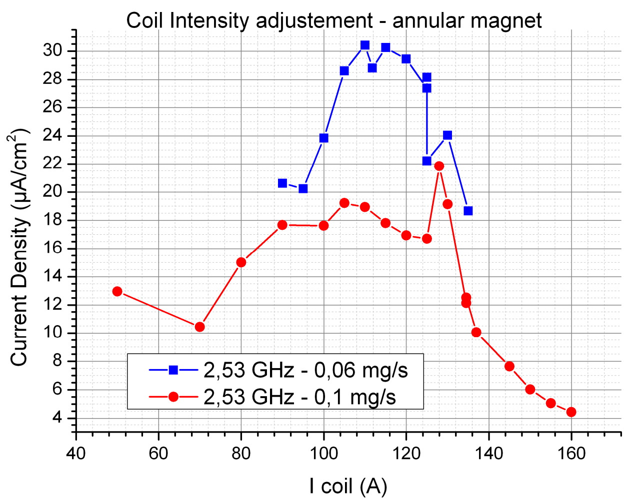

Figure 12 - Current density on axis with permanent magnet - Argon

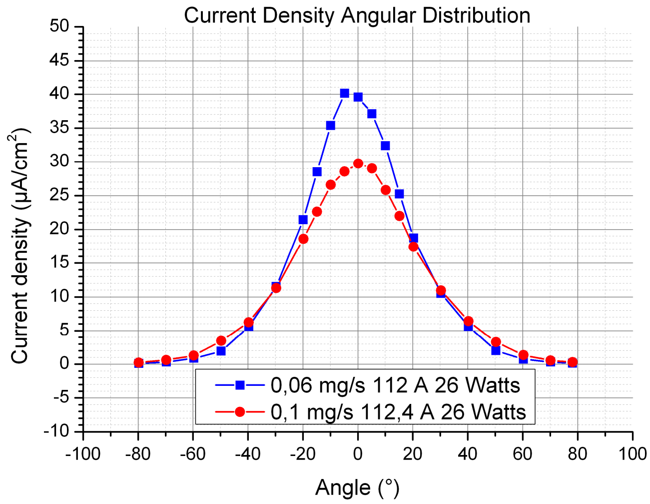

Figure 13 – Angular current density distribution - Argon

This last magnetic configuration has improved the mass utilization efficiency and diverging factor of the thruster with argon gases but only for lower flow rates.

The performances of the ECR Thruster are summarized in **Table 1**.

	Position 1	Position 2				Coil + annular magnet	
Gas	Argon	Argon	Xenon			Argon	
Mass Flow [mg/s]	0,1	0,1	0,06	0,1	0,1	0,06	0,1
Incident Power [W]	30	30	30	30	40	28	28
Ions Current [mA]	24,2	39,65	12,73	32	35,65	32,59	34,35
Ion Energy [eV]	200	170	300	120	140		
η Mass utilization	10,0%	16,4%	28,9%	43,6%	48,5%	22,5%	14,2%
ηenergy	16%	22%	13%	13%	12,48%		
ηdivergence	84%	82%	83%	82%	79%	87%	85%
Thrust [mN]	0,31	0,47	0,36	0,58	0,55		
Isp [s]	317	479	618	589	560		
Thruster efficiency	1,1%	2,5%	2,5%	3,8%	3,8%		

Table 1 – Global performances ECR thruster

The performances of ECR thruster are better in position 2, in particular regarding the ionization rate. The addition of annular magnet improves also the thruster performances but only for the lower mass flow rates. In comparison with the results of [6], the thruster efficiency with argon gas increases from 1.07% to 2.5% and with xenon gas from 3.3% to 3.8% in same conditions.

V. Conclusion

In this paper, we have described an electron cyclotron resonance (ECR) plasma thruster under development at ONERA. Different investigations on magnetic topology were performed using a coiling instead of permanent magnets, in order to observe the plasma behavior and to increase the thruster efficiencies. For particular magnetic topologies, the performance increases. The knowledge of the optimum profile of magnetic field will eventually allow the design of permanent magnet configuration. Better performances were obtained with xenon compared to argon, probably due to the lower ionization potential and larger ionization cross-section.

References

1. *Experiments with an Electron Cyclotron Resonance Plasma Accelerrator.* **Miller, D. B., and Gibbons, E. F.** 1, s.l. : AIAA journal, 1964, Vol. 2.

2. *Cyclotron Resonance Thruster Design Tehcniques.* **Miller, D. B., and Bethke, G. W.** 5, s.l. : AIAA, 1966, Vol. 4.

3. *Plume characteristics of an ECR plasma thruster.* **Kaufman, D.A, Goodwin, D.G.,.** Seattle : 27th IEPC, 1993.

4. *Electron-Cyclotron-Resonance (ECR) Plasma Acceleration.* **Sercel, J.C.** Hawaii : AIAA 19th fluid Dynamics, Plasma Dynamics and Lasers Conference, 1987.

5. *Characterization of a coaxial ECR plasma thruster.* **Jarrige J., Elias P.Q., Cannat F., Packan D.** San Diego : 44th AIAA Plasmadynamics and lasers conference, 2013. Vol. 44.

6. *Performance comparison of an ECR Plasma Thruster using Argon and Xenon as propellant Gas.* **Jarrige J., Elias P.Q., Cannat F., Packan D.** Washington, D.C : IEPC, 2013. 420.

7. *Electromagnetic wave propagation in a magneto-plasma filled coaxial structure.* **H. W. Askins, D. B. Miller.** 3, Lafayette : IEEE transactions on plasma science, 1975, Vol. 3.

8. *Fundamentals of electric Propulsion: Ion and Hall Thrusters.* **Goebel, D. M., Katz I.** s.l. : JPL Space Science and Technologies, Wiley, 2008.

9. *Principles of plasma discharges and materials processing.* **Micheal A. Lieberman, Allan J. Lichtenberg.** s.l. : John Wiley & Sons, inc., 1994.