Microwave power absorption to high energy electrons in the ECR ion thruster

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Abstract
The microwave power absorption efficiency of the μ10 ECR ion thruster, utilized in the Japanese asteroid explorers Hayabusa and Hayabusa2, is investigated in order to allow performance measurement and provide information for its improvement. A model detailing the local electron behavior in a real ECR plasma discharge, based the magnetic field characteristics, is presented. Three methods to evaluate the microwave power absorption efficiency are proposed: an estimation based on the chamber geometry and magnetic field characteristics, a measurement based on performance parameters and a measurement performed with Langmuir probes. The equations used for each method are analytically derived. The local electron behavior model is confirmed with a Langmuir probe experiment. Measurement of the microwave power absorption efficiency is performed with the two independent methods proposed. Results from the two experiments show good agreement with each other and with the theory. Finally, a diffusion model explaining the different electron temperature distributions observed in the chamber is proposed. The model and experiments clarify the physics behind previously observed performance variations and give valuable hints for future chamber improvement.

Keywords: xenon, ion thruster, electron cyclotron resonance, electric propulsion, microwave absorption

1. Introduction

Electric propulsion is a general classification that includes all the space engines that utilize electricity to increase the exhaust velocity (to increase the specific impulse). While their thrust is lower than chemical rocket engines, they require a considerably lower amount of propellant to accomplish the same space mission, allowing deep space exploration and prolonged satellite lifetime.

Among them, ion thrusters are those offering the highest specific impulse and reliability, making them the most suitable for interplanetary robotic missions. These engines produce plasma in a discharge chamber, and accelerate it through high-voltage grids. The discharge chamber layout has taken different paths for the main ion thruster developing countries, with the US using DC discharges, Europe using RF waves and Japan adopting microwave electron cyclotron resonance (ECR) heating.

The μ10 ECR ion thruster and its ECR neutralizer were developed to tackle the potential lifetime issues of DC thrusters, especially the use of hollow cathodes used for primary electron generation and ion beam neutralization [1, 2]. Thanks to the high reliability achieved, μ10 was capable of powering Hayabusa, the first asteroid sample return mission (towards the Itokawa asteroid), successfully completed in June 2010 [3]. An upgraded version of the thruster is presently utilized in the Hayabusa2 probe [4, 5], launched in December 2014 and targeting the Ryugu asteroid, as it will be in the future for the DESTINY + mission.

The physics behind plasma formation in the thruster, especially with regard to performance improvements achieved in the past [6], have not been fully understood yet. This paper will build upon the 0-dimensional model for ECR thruster, based on our previous work [7], and develop a 2-dimensional (the thruster has rotational symmetry) theoretical framework that will prove useful in the engineering process of μ10.
0-dimensional model for ECR thruster includes several parameters, such as the microwave transmission rate, the baseline plasma ion energy cost and the ion current ratio, which are easily measured. The input microwave power will be distributed to the reflection power $P_R$ from the discharge chamber, the wall loss $P_w$ in the chamber, the heating to unconfined electrons and the heating to confined electrons, of which only the final component contributes to generate ion. The microwave power absorption efficiency $\alpha$, which is defined as the ratio of microwave power transferred to high energy electrons confined in the mirror magnetic field (which in turn ionize neutrals) to the net microwave power input, has not been investigated yet. This paper aims to develop the theory about $\alpha$ and to quantify it.

2. Methods

2.1. The $\mu_{10}$ ECR ion thruster

$\mu_{10}$ is an ion thruster with 10 cm diameter high-voltage grid system. It utilizes an ECR discharge to ionize xenon gas. Propellant enters the chamber through multiple injectors, while 4.25 GHz microwave power input comes from an antenna located in the waveguide (far from the plasma discharge to increase its lifetime). Permanent magnets, with 0.4 T magnetic field strength at their surface, are located in the discharge chamber, and form the magnetic mirror where the ECR discharge occurs. Xenon ions produced in the discharge are extracted through a high-voltage ion acceleration grid system, that ejects them at high velocities $[8]$. The thruster schematic is shown in figure 1.

The $\mu_{10}$ ion thruster and its neutralizer have already achieved, through a series of improvements, fully satisfactory levels, surpassing the mark of 10 000 h continuous operation.

$\mu_{10}$ has been improved since the first flight version, and its 40% total efficiency qualifies it as one of the best performing sub-500 W electric propulsion systems.

However, the plasma physics behind its improvement have not been revealed yet. To understand these processes, a 0-dimensional ion production model for ECR ion thrusters has been developed in 2007 $[7]$, following the outline of its equivalent DC thruster model $[9]$. Equivalent models have been developed for RF ion thrusters $[10]$, and are supporting the development of such systems. The 0-dimensional ECR model pointed out the necessity of investigating the microwave power absorption efficiency, especially focusing on the operational and design parameters affecting it.

2.2. 2-Dimensional model for the ECR discharge chamber

ECR occurs when the cyclotron gyration frequency of an electron in a magnetic field corresponds to the frequency of the microwave power input from a given source. In a real geometry, electrons

Figure 1. $\mu_{10}$ ECR ion thruster schematic.

Figure 2. Schematic of the ECR heating in a magnetic mirror.
will go through an isomagnetic surface, gaining an energy \( \varepsilon_{\text{ECR}} = eV_{\text{ECR}} \), where the ECR voltage \( V_{\text{ECR}} \) is defined as [11]:

\[
V_{\text{ECR}} = \frac{\pi E_{\text{ECR}}}{\nu} \frac{\partial B}{\partial s}_{\text{ECR}}.
\] (1)

As a single passage is not sufficient to bring the electrons to the energies required for ionization, ECR discharge chamber normally involve magnetic mirror confinement. In closed magnetic mirrors as in figure 2, electrons will be trapped or lost to the magnets depending on the pitch angle \( \theta \) between their velocity and the magnetic lines. This will be represented by the loss cone factor (or mirror ratio) \( R \):

\[
R = \frac{1}{\sin \theta_{\text{mag}}} = \frac{B_{\text{mag}}}{B_{\text{min}}},
\] (2)

where \( B_{\text{mag}} \) and \( B_{\text{min}} \) are respectively the maximum (found on the magnet surface) and minimum magnetic field on the magnetic tube. Similarly, we can define \( \theta_{\text{ECR}} \) as in equation (2) but using \( B_{\text{ECR}}/B_{\text{min}} \) electrons with a pitch angle between these two are confined and pass through the ECR region multiple times while mirrored in the magnetic mirror. It must be pointed out that this description is valid, for a single electron, as long as it does not collide with other particles, since collisions will change its momentum and pitch angle. However, considering the whole population of electrons, this effect will be balanced by equal and opposite momentum transfers, meaning that our definition will remain valid on average. A schematic representation of ECR heating in a magnetic mirror is shown in figure 2.

Due to further constraints, such as electron drifts and beam extraction, the configuration chosen for \( \mu \text{10} \) and other ECR ion thrusters involves two opposite polarity magnetic rings, forming a curved magnetic mirror. It can be noticed how this configuration has magnetic lines not crossing the ECR and open-ended magnetic bottles. We can separate the chamber in three regions, as shown in figure 3, which we will define as:

- **Region 1**: closed magnetic mirrors crossing the ECR isomagnetic. Electrons cross it multiple times gaining \( E_{\text{ECR}} \) at each passage.
- **Region 2**: closed magnetic mirrors not crossing the ECR isomagnetic. No electron heating occurs.
- **Region 3**: open magnetic bottles crossing the ECR isomagnetic. Electron can gain up to \( 2E_{\text{ECR}} \) before being lost to the system walls.

Following these considerations, it is clear that the plasma density in Region 1 is expected to exceed those of Region 2 and 3.

### 2.3. The microwave power absorption efficiency equations

#### 2.3.1. Estimation of \( \alpha \) from the microwave power distribution based on chamber geometry

The simplest method we propose to estimate the microwave power absorption
efficiency is based on the analysis of the discharge chamber geometry.

Microwave power coming from the antenna in the waveguide is absorbed at the ECR isomagnetic surface, shown in figure 3, where microwave frequency and electron cyclotron frequency are equal [12]. Based on the three regions model, this will lead to:

- Region 1: power is effectively transferred to electrons.
- Region 2: no power is absorbed, as electrons do not cross the ECR region.
- Region 3: power is dissipated by the electrons.

Furthermore, in Region 1 only electrons with a pitch angle smaller than \( \theta_{ECR} \) and larger than \( \theta_{mag} \) are effectively heated by microwave due to multiple passes through the ECR region. Electrons with a pitch angle larger than \( \theta_{ECR} \) never reach the ECR region, while those with a pitch angle smaller than \( \theta_{mag} \) absorb the microwave power and dissipate it into the wall.

\( \theta_{ECR} \) and \( \theta_{mag} \) are calculated from equation (2) using \( B_{ECR}/B_{min} \) and \( B_{mag}/B_{min} \) respectively. The ECR magnetic field intensity \( B_{ECR} \) is 0.15 T associated with 4.25 GHz microwave. In other words, the microwave power is transferred to Regions 1 and 3, but the only part of the microwave power absorption is based on the analysis of the discharge chamber geometry.
electrons in Region 1 contribute to generate ions. The ratio of the microwave power transferred to ionizing electrons against those to Regions 1 and 3 is equivalent to \( \alpha \). Taking into account the power loss \( P_W \) (direct wall heating) and the power reflection \( P_R \) from the chamber, we can formulate the microwave power absorption efficiency equation as:

\[
\alpha = \left( 1 - \frac{P_W + P_R}{P_{in}} \right) \frac{A_{R1}}{A_{R1} + rA_{R3}} \left( 1 - \frac{1 - \cos \theta_{mag}}{1 - \cos \theta_{ECR}} \right)
\]

In which \( A_{R1} \) and \( A_{R3} \) are the surface areas of the ECR isomagnetic plane in each region \( (A_{R2} \), based on the considerations we made, is zero). The electrons in Region 1 must absorb microwave power more effectively, as its density is much larger than that of Region 3 (as discussed in section 3), so we introduce the density ratio \( r \).

Using this equation, we can estimate the microwave power absorption efficiency exclusively from the thruster design parameters. With \( \theta_{ECR} = 54^\circ \), \( \theta_{mag} = 28^\circ \), \( A_{R1} = 74 \text{ cm}^2 \), \( A_{R3} = 68 \text{ cm}^2 \), \( r = 0.14 \) and neglecting \( P_W \) and \( P_R \), this leads to \( \alpha = 0.52 \). This estimation, which does not take into account losses and other features of real operations, will be kept as a guideline upper limit.

2.3.2. Estimation of \( \alpha \) from the ion production performance.

The second method we will use to measure the microwave power absorption efficiency, in order to strengthen our considerations with experimental results, is based on the equation relating \( \alpha \) with the ion production cost \( C_i \), for which the derivation can be found in the 0-dimensional ion production model [7]:

\[
\alpha = \frac{\varepsilon_i^\#}{C_i f_i \left( 1 - e^{-C_0 \varepsilon_i(1 - \eta)} \right)}.
\]

In which \( \varepsilon_i^\# \) is the baseline plasma ion energy cost, \( f_i \) is the ion current ratio \((\approx 0.4)\) and \( C_0 \) is the primary electron utilization factor. Equation (4) is represented in figure 4 with the \( \alpha-C_i \) chart for selected values of the propellant utilization efficiency \( \eta \).

As \( C_0 \eta \approx 10 \) [7], we can simplify (except for \( \eta \rightarrow 1 \)) equation (4) as:

\[
\alpha \approx \frac{\varepsilon_i^\#}{C_i f_i}.
\]

This represents a horizontal asymptote in the \( \eta-C_i \) chart, as shown in figure 5, for cases in which the baseline plasma ion energy cost \( \varepsilon_i^\# \) is independent on the neutral density, such as DC ion thrusters [9]. For ECR ion thrusters, as electrons are heated progressively, a higher neutral density will lead to a lower electron energy; hence, at high values of \( \eta \) (low \( \eta \)), \( C_i \) and \( \varepsilon_i^\# \) are expected to increase [7]. Considering the dependence of \( \varepsilon_i^\# \) on \( \eta \), we can maintain the consideration that \( \alpha \) is independent on \( \eta \), and measure it from the left asymptote. Since both \( \eta \) and \( C_i \) are calculated from input and performance parameters \( (\eta, \text{the microwave power input } P_W \text{ and the ion beam current } I_b) \), we will then be able to evaluate \( \alpha \) without the disturbance caused by probes.

2.3.3. Estimation of \( \alpha \) from the electron heating process.

The microwave power absorption efficiency \( \alpha \) is defined as [7]:

\[
\alpha = \frac{4V_{ECR} I_e}{P_{in}},
\]

where \( P_{in} \) is the microwave power input, \( I_e \) is the electron current across the ECR isomagnetic surface and the 4 factor is introduced as an electron will cross the ECR 4 times in a single cycle (as shown in figure 2) before returning to its initial position.

We will seek now to obtain a more informative equation for \( \alpha \), showing which design parameters affect it and allowing its measurement with Langmuir probes. We start by representing electrons at a given temperature in the velocity space as spheres of radius \( v \) (dependent on the electron temperature \( T_e \), as shown in figure 6).

Multiple spheres will define the distribution function \( F(v) \). We can easily determine the current flowing from the truncated spherical sector \( dS \) to the ECR region as:

\[
dI = ev \cos \theta A_{min} \sin \theta \, dv \, d\theta = 2ev F(v)
\]

\[
\times A_{min} \cos \theta \sin \theta \, dv \, d\theta,
\]

where \( A_{min} \) is the area of the magnetic mirror at the minimum magnetic field. By substituting equations (1) and (7) in
equation (6), the microwave power absorption efficiency is rewritten as follows:

\[
\alpha = \frac{2 \pi E_{\text{ECR}}^2}{v \cos \theta} \int \int dI = \frac{2 \pi \rho_{\text{ECR}} E_{\text{ECR}}^2}{P_\mu \frac{\partial B}{\partial \nu}} \int_0^{+\infty} F(\nu) d\nu \int_{\theta_{\text{mag}}}^{\theta_{\text{ECR}}} \sin \theta d\theta.
\]

(8)

In which \( \theta_{\text{mag}} \) and \( \theta_{\text{ECR}} \) are calculated from equation (2), using \( B_{\text{mag}}/B_{\text{min}} \) and \( B_{\text{ECR}}/B_{\text{min}} \) respectively.

The first integral is easily solved, as it is in fact \( n_e \), while the integration boundaries of the second allow us to consider only the electrons crossing the ECR and not being lost to the walls. Hence, we get:

\[
\alpha = \frac{2 \pi \rho_{\text{ECR}} E_{\text{ECR}}^2}{P_\mu \frac{\partial B}{\partial \nu}} \int_0^{+\infty} F(\nu) d\nu \int_{\theta_{\text{mag}}}^{\theta_{\text{ECR}}} \sin \theta d\theta.
\]

(9)

This formulation, while less synthetic, offers valuable information about the operational and design parameters affecting microwave power absorption. From an experimental point of view:

- \( \rho_{\text{ECR}} \), \( \theta_{\text{ECR}} \), \( \theta_{\text{mag}} \) and \( \partial B/\partial s \) are determined by the ECR ion source geometry
- \( P_\mu \) is the microwave power input
- \( E_{\text{ECR}} \) is measured by electro-optical probes [13]
- \( n_e \) is measured by Langmuir probes

3. Results

3.1. Measurement of the plasma properties

Our first experiment aims to observe the plasma properties of Regions 1, 2 and 3, as considerations made in section 2.2.
suggest there should be differences between them. Three Langmuir probes are placed on the downstream magnet’s surface (to minimize the Langmuir probes disturbance to the microwave electric field) in correspondence of the three regions (the numbering in figure 8 corresponds to figure 3, zoomed on the downstream magnet). Due to the high plasma density and magnetic field strength, both the Debye length $\lambda_D$ and the Larmor radius of gyration $r_g$ are in the order of $10^{-100}$ μm. Since the increment in the probe effective area is smaller than the manufacturing tolerance, this will not be accounted in the measurements. The overall uncertainty in the results caused by this factors will be lower than 5%. The setup is shown in figures 7 and 8, with the experimental conditions reported in table 1.

A sample of the Langmuir probe raw data, collected under ion beam extraction, is shown in figure 9. From the direct analysis of the Langmuir probe curves we obtain the values for $n_e$ and $T_{el}$ reported in table 2.

Density in Region 1 is one order of magnitude larger than Region 2 and 3, as predicted in section 2.2. On the other hand, an unexpected feature of these two is that they have a higher electron temperature compared to Region 1.

To obtain a complete analysis of the electron temperature distribution, we apply the so called ‘Medicus method’ [14], which allows us to obtain it from the Langmuir probe curves. This is based on the equation:

$$ F(V) = \left( \frac{4}{n_e} \right) \sqrt{\frac{m_e}{2\,e\,V}} \frac{\Delta I_{\text{probe}}}{\Delta V}. $$

(10)

The resulting electron energy distribution, shown in figure 10, show that the temperature distributions in Regions 2 and 3, while resembling the pattern of Region 1, are shifted towards higher temperatures. All these three are non-Maxwellian, a known feature of ECR discharges. The slightly higher temperature in Region 3 is plausibly due to the moderate ECR heating in the region.

### 3.2. Measurement of the microwave power absorption efficiency by curve fitting

As mentioned in the methods section, we choose to measure the microwave power absorption efficiency with a non-invasive method as well as with Langmuir probes. The curve fitting approach we propose has a lower resolution compared to the Langmuir probe technique as it requires the assumption that $\alpha$ is independent on $m_\gamma$ (its validity will be discussed in the next paragraph). Hence, we will obtain one value for each microwave power input.

In this experiment, $\mu_10$ is operated in a wider range of conditions, reported in table 3, in order to visualize the different plasma modes occurrence. Note that the reflected power does not increase linearly with the input power, but instead has its minimum at the optimal operation point (enlarged in figure 11), and increases at both higher and lower values of $\eta$. Errors within 3% might occur due to the beam current data resolution. The results will be shown by plotting $C_i$ as function of $\eta$, as from this plot the value of $\alpha$ is obtained by interpolating the left asymptote. This approach is visually represented in figure 11.

We notice how, as discussed in 2.3.2, an increasing $C_i$ at low values of $\eta$ leads to a diagonal left asymptote, in
agreement with the predictions of the 0-dimensional ion production model [7]. We interpret its slope as a variation of $\varepsilon_p^*$, since our assumption states that $\alpha$ is independent on $m$ (hence on $\eta$). This allows us to evaluate $\alpha$ from equation (5).

We fit the asymptote linearly (with the parameters $a$ and $b$) and assume that the optimal value of $\varepsilon_p^*$ (30 eV [7]) is reached at the optimal operation point (enlarged in figure 11), and obtain $\alpha$ as:

$$C_i = a - b\eta,$$

$$\alpha = \frac{\varepsilon_p^{*\text{OPT}}}{C_i^{\text{OPT}} J_s}$$

$C_i^{\text{OPT}}$ is the ideal value of $C_i$ along the asymptote, calculated using the highest value of $\eta$ in equation (12). We plot the results for $\alpha$ as function of $C_i$ in figure 12; results are in good agreement with the theory. Data points lie all within the lines constructed from the theory (we take $\eta = 0.75$ and $\eta = 0.9$ from figure 4), and follow a clear pattern for which increasing $P_\mu$ leads to lower values of $\alpha$ and higher values of $C_i$. We will verify this with the next experiment as well. In this case, errors within 3% might occur due to the beam current data resolution.

### 3.3. Measurement of the microwave power absorption efficiency by Langmuir probes

As pointed out by the three regions model, and confirmed by the largely different electron density measurements in 3.1, measuring the microwave power absorption efficiency is meaningful only in Region 1.

From a finite elements FEMM (finite element method magnetics, available at www.femm.info) simulation of the magnetic field, we can obtain the geometrical parameters as: $A_{\text{min}} = 27 \text{ cm}^2$, $\theta_{\text{mag}} = 28^\circ$, $\theta_{\text{ECR}} = 54^\circ$ and $\partial B / \partial s = 0.1 \text{ T cm}^{-1}$. Data regarding $E_{\text{ECR}}$ is obtained from a previous investigation of the electric field intensity inside the discharge chamber as $1 \text{ kV m}^{-1}$ [13]. $n_e$ is measured with the central Langmuir probe (R1 probe in figure 8). In this experiment, we measure $\alpha$ in multiple operating conditions, as reported in table 4.

We start by observing the results for $\alpha$ as function of $P_\mu$ (figure 13) and $m$ (figure 14).

We observe how, at 2.1 sccm, the transition to high beam mode (more effective plasma generation) still has not occurred, which considerably lowers performance compared to higher mass flows. Hence, comparing these data points with others is not meaningful. For all the other operating conditions, from the first graph we can observe a clear decreasing trend in $\alpha$ at higher $P_\mu$, maintained consistently at all values of $m$. This is in good agreement with the considerations we made from the previous experiment. On the other hand, no clear dependence of $\alpha$ on $m$ is observable from figure 14, having small discrepancies that can be attributed to Langmuir probe disturbances and experimental error. Potential sources of error are the measured values of $E_{\text{ECR}}$ and $n_e$ (from the electron saturation current), within a range of 10%. The range

### Table 3. Microwave power absorption efficiency measurement by curve fitting experiment conditions.

| Mass flow        | 1.35–3.3 sccm (0.15 sccm step) |
|------------------|--------------------------------|
| Microwave power  | 28–40 W (3 W step)            |
| Reflected power  | 0.4–4 W                       |
| Screen grid voltage | 1500 V             |
| Acceleration grid voltage | −350 V |

![Figure 10. Electron energy distribution function in the three regions.](image-url)
of values observed for $\alpha$ has a good agreement with predictions coming from the 0-dimensional ion production model [7]. We can observe this in figure 15 by plotting $\alpha$ as function of $C_i$ both for experimental data points and theory predictions (as in figure 12, we plot the theoretical lines of $\eta = 0.75$ and $\eta = 0.9$). Excluding those taken before the transition to high beam mode (for which $\alpha$ is substantially lower), other data points lie within the theoretical lines, and follow the same pattern observed in the experiment presented at 3.2.

### Table 4. Microwave power absorption efficiency measurement by Langmuir probes experiment conditions.

| Mass flow       | 2.1–2.85 sccm (0.15 sccm step) |
|-----------------|--------------------------------|
| Microwave power | 28–40 W (3 W step)            |
| Screen grid voltage | 1500 V                   |
| Acceleration grid voltage | $-350$ V                |
| Probe voltage (A) | $\pm 80$ V                  |

![Figure 11. Measurement of the microwave power absorption efficiency by curve fitting approach.](image1)

![Figure 12. Microwave power absorption efficiency as function of the ion production cost (with curve fitting).](image2)
4. Discussion

4.1. Interpretation of the electron temperature results

The representation given in section 2.2, based on particle dynamics, would lead to presence of plasma only in the Region 1. However, due to the plasma collective behavior (diffusion), plasma is found also in the other two, as shown by the experiments in 3.1. Furthermore, the electron temperature distribution of Regions 2 and 3 considerably differs from what is observed in Region 1.

We try to give an interpretation of the phenomenon observed by introducing a multi-temperature diffusion model.

\[ \Gamma = nv = -D \nabla n, \]  \hspace{1cm} (13)

where $D$ is the diffusion coefficient. A common assumption while analyzing ECR ion thrusters is weak ionization: charged particles will interact prevalently with neutrals [12]. Building upon this, we make the further consideration that no interaction with other charged particles implies no interaction with other charged particles with a different energy. This allows us to treat electrons with a different temperature as distinct species. Making this consideration,
we can replace the density in equation (13) with an arbitrary electron distribution:

$$\Gamma(v) = -D\nabla F(v).$$  \hspace{1cm} (14)

We show the implications of this approach for a Maxwell–Boltzmann distribution of electrons (peaking at 4 eV, as in the case of $\mu10$) in Region 1, and assuming $n_{R2} = n_{R3} = 0$ in the other two, so that the gradient can be simplified (we have seen from the experiments how densities of Region 2 and 3 are small compared to Region 1). We disregard the actual value of $n_{act}$ and $D$ by normalizing the results, in order to observe the general case. As we can see in figure 16, this model predicts that the temperature of the electrons outflowing from Region 1 will have a peak at 10 eV. The outcome will only depend on the $F(v)$ and diffusion model selected (classical or neo-classical), while the magnetic field intensity will influence the actual value of $\Gamma$.

Finally, we introduce the density and magnetic field parameters found in $\mu10$ in the diffusion model we have proposed. This is done by splitting the magnetic field lines

\begin{table}[h]
\centering
\caption{Predicted electron flux from Region 1.}
\begin{tabular}{lcc}
\hline
Region 1–Region 2 & $6.8 \times 10^{13}$ particles m$^{-2}$ s$^{-1}$ \\
Region 1–Region 3 & $2.1 \times 10^{14}$ particles m$^{-2}$ s$^{-1}$ \\
\hline
\end{tabular}
\end{table}
dividing Region 1 from Region 2 and 3 in small segments, and calculating $D$ based on the local magnetic field. Results are shown in Table 5.

Based on this model, the average electron flux towards Region 3 is expected to be approximately three times the flux towards Region 2.

The diffusion model proposed brings theoretical justification, both in terms of electron energy and density, to the experiment results presented in 3.1.

4.2. Microwave power absorption efficiency

This paper shows three methods to evaluate $\alpha$. In the first, $\alpha$ is introduced from the point of view of the microwave power distribution in the discharge chamber. The second method is derived from the ion production characteristics. The third one is associated with the electron heating process. Investigation of the microwave power absorption efficiency added valuable information to the 0-dimensional ion production model for ECR discharge ion thruster previously developed, while also confirming the predicted values of 0.3–0.5. Based on these results, we can further calculate the bidirectional current at the ECR surface with equation (6): results range from 8 to 12A. The theoretical formulation of equations (3) and (14) pointed out how $\alpha$ is affected by $B_{\text{mag}}$ and $B_{\text{ECR}}$: large $B_{\text{mag}}$ and small $B_{\text{ECR}}$ will improve $\alpha$. $B_{\text{mag}}$ is dependent on the permanent magnet characteristic: since the space-qualified ion thrusters are operated at very high temperature, the Samarium–Cobalt magnets are utilized instead of Neodymium, so that $B_{\text{mag}}$ is around 3 kG. $B_{\text{ECR}}$, on the other hand, is proportional to the microwave frequency: lowering it would potentially improve $\alpha$, but due to the plasma cut-off phenomena this would lead to a lower plasma density, and hence thrust. The $\mu$10 ion thruster utilizes 4 GHz microwave as a tradeoff solution. On the other hand, $B_{\text{min}}$ has a relatively small influence on $\alpha$, and can in fact be simplified for small values of $\theta_{\text{min}}$ and $\theta_{\text{ECR}}$.

Results from the Langmuir probe measurements and the curve fitting approach point out how $\alpha$ decreases for increasing microwave power input. On the other hand, the first also shows how this parameter is not affected by the mass flow. This cannot be verified with the curve fitting method, as it requires the independence on $m_i$ as an assumption. We can finally compare the results from the two different methods, as done in figure 17: averaging results for a certain $P_{\mu}$, Langmuir probes register regularly a 10% lower performance, compared to the curve fitting approach, both in terms of $\alpha$ and in terms of $C_i$. This can be easily explained by the disturbance caused by the Langmuir probes to the ECR discharge, which was observed during the experiments to decrease the beam current. The averaged Langmuir probe results follow the pattern of the curve fitting experiment, appearing shifted due to this performance drop, but showing the same characteristics of lower $\alpha$ and higher $C_i$ for increasing values of $P_{\mu}$. Furthermore, the good agreement between these methods points out how power losses at the discharge chamber wall should be negligible.

Both the curve fitting and the Langmuir probe approaches to measure the microwave power absorption efficiency present sources of measurement uncertainty, that should be addressed in future research. In the first, we assume most parameters of equation (4) as constants to simplify the curve fitting. Further investigation on parameters such as $e_p$ and $C_0$ and their dependence on $m_i$ and $P_{\mu}$ would improve the accuracy of these measurements and further improve our understanding of the ECR ion thruster performance. As for the second method, other than the disturbance caused by the Langmuir probes themselves, the main uncertainty is about $E_{\text{ECR}}$. The electro-optical measurement technique utilized to measure this parameter [13] is complex to implement and has a relatively low resolution, so in this research we utilized a

![Figure 17. Microwave power absorption efficiency as function of the ion production cost (with curve fitting and averaged Langmuir probes).](image-url)
standard value of $E_{ECR}$ for the measurement of $\alpha$. Improved measurement techniques for electric fields in ECR plasma would make this method more accurate.

5. Conclusion

The research presented in this paper focused on the modeling of the microwave power absorption to high energy electrons through ECR and its subsequent measurement. The results can be summarized as follows:

(1) The subdivision of three regions in the ECR discharge chamber was proposed and verified. Experimental results are consistent with the initial hypothesis that plasma ionization occurs virtually only in Region 1, where the magnetic mirror confines the high energy electrons gradually heated by passing multiple times through the ECR region. Furthermore, from these findings, a model attempting to explain the electron temperature distribution observed in Region 2 and 3 has been proposed.

(2) An investigation of the microwave power absorption efficiency in the ECR ion thruster has been performed. It involved the derivation of equations useful to measure this parameter and to understand the physics behind the power absorption process. Three methods were proposed to measure it: an analysis of the microwave power distribution to the discharge chamber, a global measurement based on the ion production characteristics and a local measurement based on the electron heating process and performed with Langmuir probes. These measurements pointed out the dependence of the microwave power absorption efficiency with the power input, with values ranging from 0.3 to 0.5.

These conclusions provide a justification for previously achieved performance improvements [4]: as ionization occurs mostly in Region 1, injecting propellant from input ports close to it increases the thruster efficiency. Moreover, they are presently supporting the development of upgraded discharge chambers for the $\mu 10$ ion thruster. Future work in this field should involve a method to optimize the magnetic field design of the chamber to maximize the microwave power absorption efficiency by enlarging Region 1, increasing $B_{mag}$ or reducing $B_{ECR}$. Furthermore, the electron diffusion across plasma regions should be investigated more in detail, as it was found to cause loss of heated electrons, hence affecting the overall thruster performance.

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