Investigation of the Electron Behavior in ECR Ion Thruster Chamber

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Abstract

A more detailed investigation of the electron behavior has been performed in an attempt to define regions negatively affecting microwave power absorption efficiency in µ10. A three regions model, valid for most types of ECR ion sources, has been developed based on theory and simulations, and is discussed here. The influence diffusion should have in the non-ideal behavior of the magnetic mirrors is modeled by combining classical theory with an assumed Maxwellian distribution of electrons. Experimental verification has been performed by placing multiple Langmuir probes in low disturbance areas, enhancing the quality of data analysis with the "Medicus method" for electron distribution.

Nomenclature

α: Microwave power absorption efficiency
Γ: Electron flux
σ: Cross section
ω_c: Cyclotron frequency
B_{ECR}: Magnetic field at ECR
k: Boltzmann constant
n: Plasma density
P_μ: Microwave power
R: Loss cone factor
T_{el}: Baseline electron temperature

1. Introduction

µ10 is a 10cm class ion thruster, having the key characteristic of relying on electron cyclotron resonance (ECR) heating for plasma production[1]. The thruster has been utilized by JAXA for both Hayabusa and Hayabusa2 missions[2),3)].

Electron cyclotron resonance is a plasma physics phenomenon typically utilized for producing or heating plasma. Electrons, spiraling between the two ends of a magnetic mirror with frequency dependent on B, are subject to a superimposed oscillating electric field (microwave). On a defined isomagnetic surface, cyclotron and microwave frequency will be the same, producing resonance and accelerating electrons by consequence[4].

In an effort to improve the system performance, detailed analysis of the plasma behavior and its causes are currently performed at the JAXA Electric Propulsion Laboratory[5]. Previous investigation regarding the microwave power absorption efficiency (α) pointed out the presence of multiple regions in the plasma discharge chamber, not necessarily behaving as described in Fig.1, and the consequent need to study them separately[6].

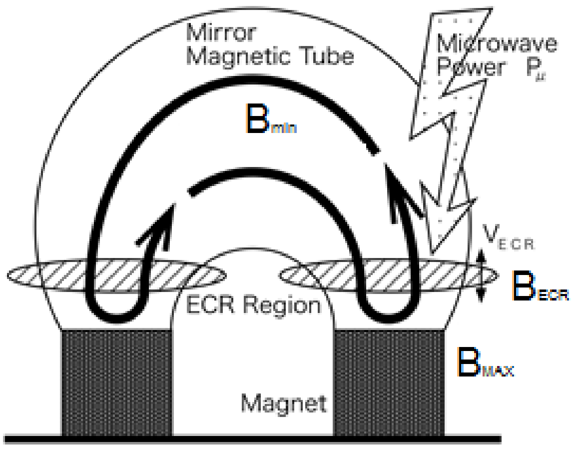

Figure 1: ECR heating mechanism schematic

2. Three Regions Model

2.1 Model Description The presence of regions with different plasma characteristics was at first proposed after performing a FEMM (Finite Elements Method Magnetics) simulation of the µ10 plasma chamber.

By plotting the ECR isomagnetic contour at 0.15T and the magnetic field lines, the chamber can be divided in three regions (Fig.2):

1) Hot region: B_{min}>B_{ECR}, electrons are mirrored without being heated up. Due to the low R, electrons are lost to the magnets after a few passages.

2) Active region: $B_{min}<B_{ECR}$ and the magnetic mirrors don't intercept the walls, effective ECR heating and plasma production occur (same as Fig.1).

3) Loss region: $B_{min}<B_{ECR}$, but electrons are lost after one passage of the ECR, since Bmin takes place outside the chamber, without reaching Teh, necessary to ionize neutrals.

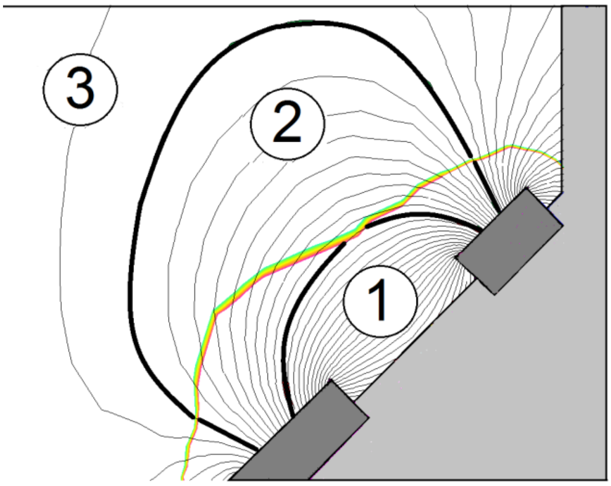

Figure 2: Hot, Active and Loss regions model

This model tentatively defines which portions of the discharge chamber have a role in the plasma production process and which portions don't. The considerations made are valid for ECR ion sources with comparable geometric characteristics.

2.2 Ion Beam Profile In an ideal case of perfect magnetic confinement, no presence of plasma would be observed in regions 1 and 3, since no electron heating can theoretically occur. Taking into account diffusion, what turns out is that these regions should have a lower plasma density, produced by the electrons flowing out of region 2.

Initial support for this model came from previous research performed in this laboratory regarding the ion beam profile outside the thruster[7].

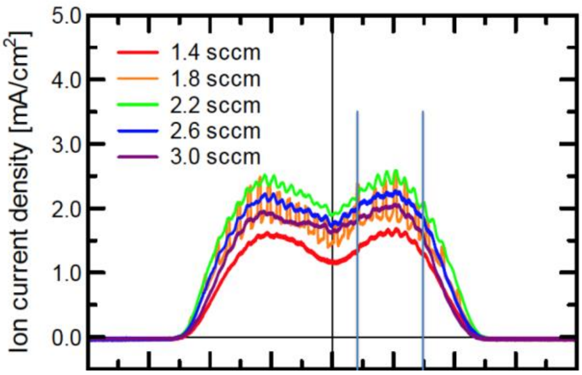

Figure 3: Ion beam profile

The active region limits correspond to the blue vertical lines in Fig.3. As we can see, this corresponds to the peak of beam current density with very good precision.

3. Multiple Temperature Diffusion Model

3.1 Diffusion Theory Background As mentioned, plasma diffusion is likely to be the cause of the observed beam profile. Giving a quantitative prediction of the electron flux flowing between the different regions would probably not provide valuable insights: the physics behind it have still large uncertainties, with classical, Bohm and neoclassical diffusion models giving results differing by orders of magnitude.

Hence, what we developed is a diffusion model that predicts the electron temperature distribution of the resulting flux, remaining substantially independent from its total value.

In the theoretical development here presented, there will be three simplifying assumptions:

- Isothermal plasma with Maxwell-Boltzmann distribution
- Uniform magnetic field
- Uniform plasma density in the *Active* region

Diffusion Model Development The average velocity of plasma is in general defined as:

$$\bar{v} = \frac{1}{mn\nu}(\pm en\bar{E} - kT\nabla n)$$

In our case, the effects of the first term is neglected, since excluding the walls plasma is globally at $V_p \approx V_{sc}+25V$.

The collision frequency ν is defined as:

$$\nu = n_n \overline{\sigma v}$$

Then, if we define the diffusion coefficient D:

$$D = \frac{kT}{m\nu}$$

And obtain the following formulation of flux Γ of a certain species of particles inside a plasma in absence of an electric field:

$$\bar{\Gamma} = n\bar{v} = -D\nabla n$$

To introduce the confining effect of the magnetic field, we need to modify the D term to D_B, as:

$$D_{\bar{B}} = \frac{D}{1+\frac{\omega_c^2}{\nu^2}}$$

and replace it into the flux equation[8].

Clearly, ω_c changes with B in our case, we will consider at first the case in the ECR region for simplicity.

The further step we'll make, compared to previous literature, is to modify the flux equation previously presented to fit for the analysis of our case. Instead of n, which does not consider the electron temperatures, we will introduce a Maxwell-Boltzmann distribution, with baseline temperature of 4ev:

$$F(v) = 4\pi\left(\frac{m}{2\pi kT_m}\right)^{3/2} n_m v^2 \, exp\left[-\frac{mv^2}{2kT_m}\right]$$

The equation we are utilizing now becomes:

$$\bar{\Gamma} = -D_B \nabla F(v)$$

Then, if we consider that the n density is much lower in regions 1 and 3, in agreement with our initial hypothesis, we can reasonably neglect plasma presence there, allowing us to write the density gradient as:

$$\nabla n = \frac{n_{act}}{d}$$

where d is taken as 1cm.

Multiplying it by D_B, we will obtain the flux as shown in Fig.3. It's useful to plot in the same figure F(v) as well (not to scale), to compare their shape.

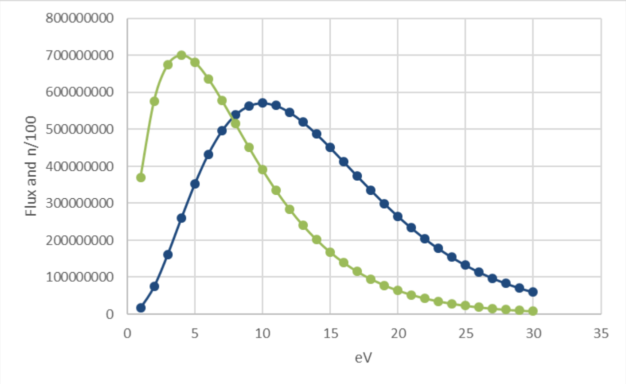

Figure 4: Given Maxwellian distribution in 1 and resulting flux to 2 and 3 (F(v)=G, Γ=B)

4. Experimental Verification

4.1 Three Regions Model To provide direct experimental verification of the model proposed, a Langmuir probe experiment was set up[9)].

Three 2mm wide 10mm long stainless steel probes were placed on the downstream magnet, in correspondence of the proposed regions. During the experiment, they have been swept between -80V and 80V. An example of the curves obtained is shown in Fig.5 (linear) and Fig.6 (semi logarithmic):

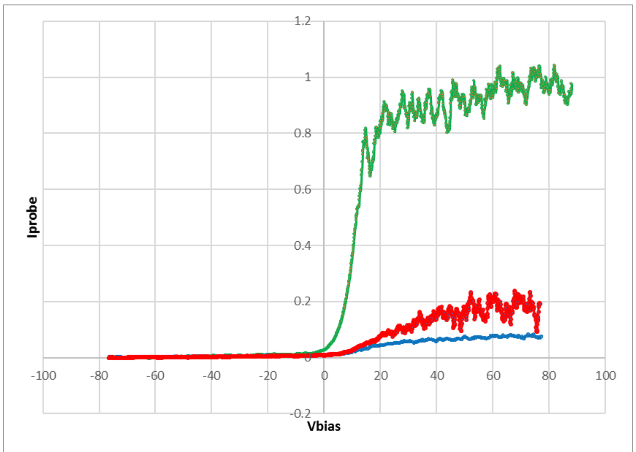

Figure 5: Langmuir probe linear plot (B=1, G=2, R=3)

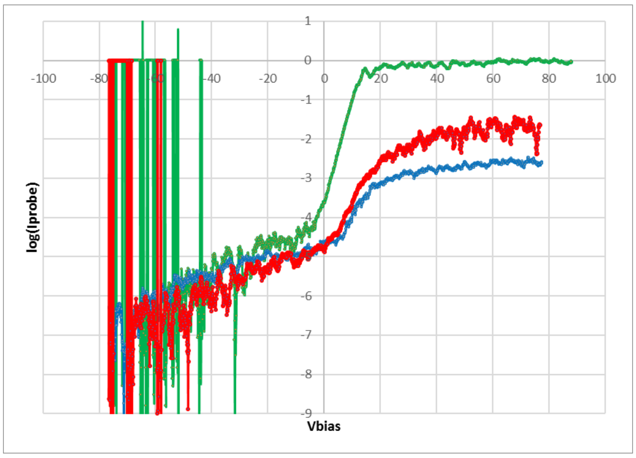

Figure 6: Langmuir probe semi logarithmic plot (B=1, G=2, R=3)

Plasma density can be measured from the linear data, and results are:

- n_{p1}=1.06*10^{15} particles/m^3
- n_{p2}=3.33*10^{16} particles/m^3
- n_{p3}=4.42*10^{15} particles/m^3

Region 2 (*active*) has density one order of magnitude larger than 1 and 3, supporting the hypothesis of lack of relevant production in the latter two.

4.2 Multiple Temperature Diffusion Model Analysis of the semi logarithmic plot pointed out that the baseline electron temperature was much higher in region 1 and 3 than in region 2, respectively:

- T_{e1}=7.79 eV/h_B
- T_{e2}=4.01 eV/h_B
- T_{e3}=7.65 eV/h_B

Although this might seem counterintuitive, since we mentioned that there's no electron heating in these regions, the higher mobility of high energy electrons justifies this observation, which furthermore is in agreement with our diffusion model.

To get a more detailed experimental verification of the diffusion model results, the "Medicus method"[10)] has been applied to the data coming from Langmuir probes. The method has been derived for a homogeneous plasma with zero net charge, and, while still based on slope analysis, gives the full velocity profile of a plasma, starting from Langmuir probe data. The main equation involved is:

$$f(v) = \frac{4}{n}\sqrt{\frac{m}{2e * V}}\frac{\Delta i}{\Delta V}$$

Which is applied to the transition region of a linear Langmuir probe curve, corrected by the plasma potential. Results obtained for regions 1 and 2 are shown in Fig.7.

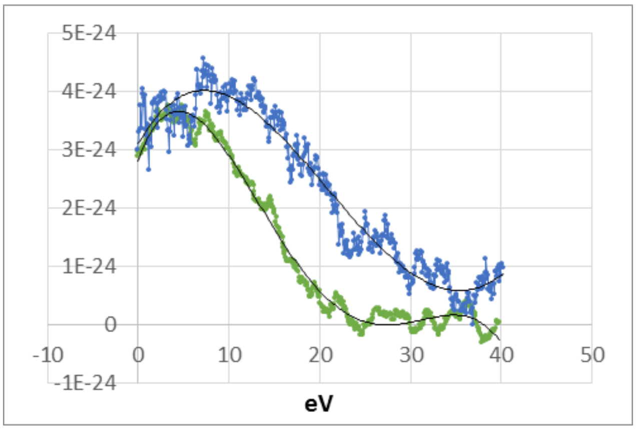

Figure 7: Electron energy distribution

Results show very good agreement with calculation, with region 1 curve resembling an 8-10eV distribution. The reason of this very low order of magnitude is not fully clear. Looking at the equation, it would seem normalized (dividing by n), but results are in the order of 10^{-24}. However, this is only a matter of constants, as:

$$f(v) \propto \frac{1}{\sqrt{V}} \frac{\Delta i}{\Delta V}$$

The same analysis was attempted with region 3, but due to higher disturbances it was impossible to obtain relevant data. The Medicus method, because of its structure, requires higher precision than simpler Langmuir probe analysis.

5. Conclusions

A new model describing the contribution to plasma production of different regions in an ECR ion source chamber has been proposed in this paper. Combining it with an enhanced plasma diffusion model allowed to set up experiments which supported our hypotheses, giving substantial verification to the "three regions model" proposed.

The quantitative value of electron flux across the magnetic mirrors is not yet accurately predicted, and further investigation is needed in order to improve it (for example, selecting the most appropriate among classical, Bohm and neoclassical model[11]), together with analysis of the regions in which plasma is produced more effectively.

However, the results obtained so far have already good potential to benefit the design of future ECR ion thrusters.

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