High Energy Electron Current Measurement Techniques for µ10 Thruster

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Introduction

Ion thrusters are very efficient and reliable space engines, using the Coulomb effect for propulsion. Low pressure gas in injected into the waveguide and, in our case, ionized using microwave (other thrusters using the standard anode-cathode configuration are typically less durable). Ions are guided through the chamber by the magnetic field, and after entering the grid region they are accelerated by the strong potential difference between the grids to velocities in the order of 30-40Km/s.

Main advantage of these thrusters is the very high specific impulse, useful for long distance missions, while the main drawback is their low thrust (in the order of mN), that makes them not suitable for manned spacecrafts.

Plasma Diagnostics

Plasma diagnostics has been widely developed in JAXA, especially in the Electric Propulsion Lab, mainly in order to better understand the behavior of µ10 thruster, but the techniques used can be easily implemented on different engines or for other purposes. Optical fiber has been proven to be a convenient alternative to the standard probes traditionally used because of its composition: being an insulator, optical fiber can be used in high voltage conditions, and doesn’t create relevant disturbances as metallic materials would do (Tsukizaki, 2011). Langmuir probes are the instruments used for the first exploratory studies in plasma engineering, and although they were producing relevant disturbances in the microwave distribution due to their conductivity, it can be assumed that very small versions of these probes will correctly measure the properties we are interested in.

Microwave Power Absorption Coefficient

The continuous development of the µ10 thruster led to requiring the determination of the microwave power absorption coefficient by plasma electrons (α). A theoretical model to describe the behavior of microwave plasma thrusters has been developed in JAXA (Usui, 2007), mathematically proving (as it was before suggested by the experiments) that this configuration provides clear advantages with respect to the hollow cathode version (Brophy, 1983).

The only thing missing for the completion of this model is the determination of α. What makes it not trivial is its possible dependence on the mass flow and the microwave power, together with the relative difficulties in its measurement. α is defined as:

\[ \alpha = \frac{I_F V_{\mu}}{P_m} \]

Where:
- \( I_F \) is the high energy electron emission current
- \( V_{\mu} \) is the microwave discharge voltage
- \( I_p \) is the ion production current

An equivalent formulation is:

\[ \alpha = \frac{\Phi \Delta P}{P_m} \]

Where:
- $\Delta P$ is the heating energy of an electron going through the ECR region
- $\Phi$ is the high energy electron flux
- $P_m$ is the microwave power

$P_m$ is known since it’s one of the inputs, $\Delta P$ can be estimated with reasonable precision, so $\Phi$ is the object of our study.

About the physics of the phenomenon, electrons are bouncing between the two magnetic rings, being accelerated through the ECR region while rotating for Larmor motion and drifting.

Two different approaches are currently being adopted to measure the high energy electron current, as discussed in the following paragraphs.

**Fluorescent light emission measurement**

The first method we are implementing for the measurement of the high energy electron flux is based on the working principle of VFD displays. Electrons hitting a fluorescent material make it shine with different intensity depending of the voltage difference between cathode and anode.

The current experiment setup is applied to the neutralizer rather than on the thruster itself, to make it easier to develop the method without requiring too many ad-hoc components. Just like in the VFD displays, there’s a grid in front of the fluorescent material, but the purpose is different: normally, it’s negatively biased to block electrons emitted by the filament cathode while the display is turned off. On the contrary, in our setup the grid (“punching metal”) will be used to attract the electrons, that will later cross it and hit the luminescent part. In this configuration, the neutralizer is used as cathode and the grid is positively biased to provide electron extraction.

A couple of issues were encountered during the first experiments. First, although there’s some uncertainty because of the lack of a proper spectrometer (will be provided soon), it appears that the luminescence is not only function of the number of electrons hitting the fluorescent material, but also of the energy of the single electron, making the determination of the high energy electron current more complicated. Then, the neutralizer emits ultraviolet radiation, and it produces luminescence as well (potentially producing errors in the data acquired). For this issue there are different solutions that can be adopted, but the easiest to implement is to block the electrons while letting the ultraviolet radiation hit the fluorescent material, and then subtract this component. To do this, one solution is flipping the standard phosphor coated glass used in fluorescent lamps, to measure either both components or only the one due to the radiation. For the instrument to be used inside µ10, this procedure would need a glass cover added to the probe, requiring high precision techniques to build the tool itself. The opposite solution, blocking UV while letting the electrons flow, is harder to implement, and so not considered at first.
Another similar solution is to run the neutralizer without punching metal, or without biasing it, in order to prevent electron extraction.

This configuration would be easier to implement in the actual experiment, since it does not require additional components.

**Langmuir micro-probe**

Because of the complications encountered in developing the previously mentioned technique, Langmuir probe measurements were implemented as well. Since their size has been limited to 2x10mm, it’s assumed that the disturbance they will produce will not be an issue for our measurements.

The shape adopted is mainly due to the effects of loss cone factor effect in the data analysis. Since it changes considerably between different magnetic tubes, reducing the length of the probe leads to more precise results. Also, the magnetic field shape (stronger at the magnet sides) reduces the possibilities for using different materials: as an example, iron probes, that would be conveniently sticking to the magnets, can’t be used in the central region.

Experiments are currently being performed in different conditions, that we can mainly divide in Hayabusa1-Hayabusa2 mode and Ion Acceleration-No Ion Acceleration.

Ion and electron saturation currents can be derived from the linear data plot of the current flowing through the Langmuir probe, deriving the microwave power absorption coefficient $s$:

$$\alpha = 16R \frac{S V_{ecr} I_{ehs}}{s P_m}$$
Results acquired so far are qualitatively reasonable, but some of them still have to be investigated. Especially, the hysteresis process that can be observed while sweeping forward and backwards the probe voltage produces strong variations in \( \alpha \). Multiple measurements in the same conditions would be useful, but the severe conditions inside the thruster tend to induce probe sputtering and melting, limiting the actual possibility of testing.

On the other hand, from the analysis of the logarithmic plot we can derive electron temperatures, necessary to obtain other plasma parameters such as high-low energy electron ratio and to determine the influence of different electron-ion interactions taking place inside our thruster. This analysis also proved to be more sensitive to disturbances, leading in some cases to the impossibility of obtaining the high electron temperature.

A MATLAB code has been developed in order to speed up the analysis, since future plans will require more data to be evaluated.

Focus will be now on final improvements of the testing method and analysis of the data acquired, in order to get a reasonable estimation of the microwave power absorption efficiency and information about the parameters influencing it.

References


