Study on charge neutralization effect by electron cyclotron resonance plasma source in high vacuum

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Abstract. Electric charge deposition is cause of failures in a variety of in-vacuum manufacturing processes. Therefore, high efficient charge neutralization method is required. The goal of our study is to improve the charge neutralization speed in vacuum. Our research aims to the application of an electron cyclotron resonance(ECR) plasma source as neutralizer in vacuum. ECR neutralizer has been developed to neutralize ions emitted by ion thrusters, preventing the spacecraft from charging. We improved the neutralization current and investigated the charge neutralization of insulating film as an application for roll-to-roll system. Conveying films at high speed in vacuum, the films are entangled with each other because of friction charging. By placing the ECR neutralizer at 1.5m from a roll-to-roll system, we can convey the film roll at 1000m/min, the highest speed currently used in the industry. Our neutralization system runs at a gas flow rate of just 0.05mg/s of xenon. The 10W class ECR neutralizer is hence proved to be an effective charge neutralization method also for non-propulsion applications in high vacuum.

1. Introduction

In vacuum, electric charge deposition is the cause of failures in a variety of processes, such as film deposition and semiconductor manufacturing. For example, conveying thin films at high speed in vacuum, contact and friction charging occurs between the roll and the film, which leads to the films being entangled with each other. To solve this problem, electric charge is typically neutralized by passive discharging of Paschen condition by cyclically lowering the pressure in vacuum, which reduces production efficiency. Therefore, the goal of our study is to improve the speed of charge neutralization in vacuum. Our research aims to the application of the electron cyclotron resonance plasma source as neutralizer in high vacuum of $10^{-1}$Pa to $10^{-4}$Pa or more. ECR neutralizer has been developed by the Japan Aerospace Exploration Agency for in-space thruster application such as asteroid explorers Hayabusa and Hayabusa2.[1][2] The device neutralizes the ion beam emitted by the ion thruster, preventing the spacecraft from negatively charging by emitting electrons.[3][4] We investigated the charge neutralization of thin films as another application by ECR neutralizer. Furthermore, we parametrically studied a structure which can emit not only electrons but also ions to neutralize negative charge, and improved the neutralization current.
2. Electron Cyclotron Resonance neutralizer

Fig. 1 shows a sketch of an ECR neutralizer. It consists of permanent magnets, magnetic circuits, a discharge chamber, an antenna and an orifice. As shown in Fig.1, the plasma is generated by the Electron Cyclotron Resonance, ECR: ECR is a resonance between the microwave frequency and the electron cyclotron frequency \( \omega_c \) as shown equation (1).

\[
f = \frac{\omega_c}{2\pi} = \frac{eB}{2\pi m_e}
\]

Here, \( e \) is the elementary charge, \( m_e \) is the mass of the electron and \( B \) is the magnetic field density. Microwaves at a frequency of 4.25GHz are transmitted from the antenna into the discharge chamber. A magnetic circuit generates a mirror magnetic field, and ECR heating occurs at 0.15T. Xenon gas is injected into the discharge chamber, where electrons are continuously accelerated by the ECR and trapped by the mirror magnetic field. During ECR heating, electrons motion is a combination of Larmor motion around the magnetic field lines, reciprocatory motion between the magnetic mirrors, and azimuthal motion by the curvature and gradient B drifts. Therefore, the ECR neutralizer generates plasma by collision between the high energy electron and neutral particle of xenon.

3. Distribution of charge neutralization current density

3.1. Methods

We investigated the distribution of the charge neutralization current density generated by neutralizer in high vacuum. As shown in Fig.2, we used a vacuum chamber with diameter of 1.5m and a length of 3.0m. ECR neutralizer system is composed of propellant supply system and microwave supply system. The gas container and gas flow controller supply constant mass flow of xenon. The microwave supply system is composed of an oscillator and an amplifier. The 50mm square copper plates were placed at a distance of 1.0m, 1.5m, 2.0m from the ECR neutralizer. Voltage of \( \pm 200V \) was applied to this copper plate, and the neutralizing current was measured. The charged plates were exposed to plasma on only one side. The experimental conditions are as shown in Tab.1.

As shown in Fig.3, the shapes of the anode and the orifice were changed to investigate the difference of the neutralizing current. The anode is used for generating a positive plasma column, in addition to the ECR plasma inside the discharge chamber, downstream of the orifice by applying a voltage of about +30V. The positive plasma column is generated by collisions
between extracted electrons from the discharge chamber by the applied electric field and neutral particles. Our tests have been performed with 4 types of anode, cylinder anode which is a cylinder of 10mm in diameter and 10mm in length, 85×55mm punching metal anode, Φ20mm punching metal anode and Φ10mm disk anode. All anodes were installed 10mm downstream of the orifice. The extraction current from discharge chamber to anode is kept constant at 135mA.

Two orifice types have been used: conventional orifice of thickness of 5mm and 4mm diameter, which is the same shape as the asteroid explorer Hayabusa and Hayabusa2 and punching orifice with 1mm thick opening ratio 32.6%.

### Table 1. Experimental conditions for measurement of neutralization current

| Items                      | values          |
|----------------------------|-----------------|
| Gas Flow Rate of Xenon     | 0.05mg/s        |
| Microwave Power            | 8W              |
| Microwave Frequency        | 4.25GHz         |
| Back Pressure              | 3 × 10⁻³Pa      |
| Anode Current              | 135mA           |
| Charged Plate Voltage      | ± 200V          |

### 3.2 Results

The charge neutralization current density distribution is shown in Fig.4. As a common tendency for positive charging and negative charging, it was found that the current density decreases by 1-2 orders of magnitude when the distance from the neutralizer is increased from 1m to 2m. In addition, the positively charged neutralization current density was 3 orders of magnitude larger than the negative charge. Therefore, it was found that negatively charged neutralization performance is rate limiting.

According to Fig.4, when the positive column was generated by the anode compared to without the anode (conventional orifice), the neutralization current was large. Furthermore, the neutralization current density also increased in the punching orifice when the number of orifices was increased more than the conventional orifice. In the negative charge neutralization, the neutralization current density was improved up to 5 times as much as the conventional orifice. The punching orifice does not require an additional power supply for anode. When adopting it, the structure of neutralizer is simplified.

In Fig.4, the necessary current density $j_{limit}$ for conveying a 1m wide film at 1000m/min is shown. It can be determined by equation (2) where $V_T$ is film conveying speed and $\sigma$ is the max charging density in general roll-to-roll system.[5]

$$j_{limit} = \sigma V_T = 27 \times 1000/60 = 0.45mA/m^2$$  

In positive charging, it was found that this condition is satisfied up to the distance of 2m even with the conventional neutralizer. Using anodes and orifices, neutralization current density increases by 1-2 orders of magnitude. In negative charging, the conventional neutralizer fulfills this condition at a distance of 1m. By using the punching orifice it is possible to extend the distance up to 1.5 m.

### 3.3 Discussions

It is considered that the mass difference between electrons and ions is the reason for the positive charge neutralization current density being 3 orders of magnitude larger than that of the negative
Figure 4. Comparison of charge neutralization current density. Two orifice types and 4 anode types have been used.

charge. Because the electron has a smaller mass, the mobility $\mu$ shown in equation (3) is large and the large flux reaches the charged object.

$$\mu = \frac{|q|}{m\nu} \quad (3)$$

Here, $q$: charge, $m$: charged particle mass, $\nu$: collision frequency.

The effect of the positive plasma column is considered as a cause of the large neutralization current as compared with the conventional neutralizer. Since neutralizers with an anode generate positive plasma column in addition to the ECR plasma, they have large neutralization currents.

The neutralization current tends to be larger in the case of a smaller anode than a large anode. This is because the movement of the electrons and ions is disturbed by the anode.

In Fig. 4, we interpret the high plasma conductance as the reason for the large neutralization current density of the punching orifice. The opening area of the punching orifice is 1 order of magnitude larger than conventional orifice and the thickness is also 1/5. Therefore, it is considered that more plasma is exhausted from the discharge chamber, and the neutralization current density is increased.

4. Conclusion
We applied the space-qualified ECR plasma source as a positive and negative charge neutralizer. In addition, we investigated the charge neutralization current density distribution. When the neutralizer is placed within 1.5m, it was found that film conveyance can be carried at 1000m/min. Furthermore, we studied the orifice and anode shape to improve the plasma transparency and accomplished the charge neutralization current density 5 times higher than the conventional type. These findings suggest that $\Phi 3$cm and 10W class ECR neutralizer is effective for charge neutralization in high vacuum.

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