Operational Characteristics of Microwave Discharge Neutralizer

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Abstract

An emission current imbalance phenomena involved in the clusterization problem were experimentally investigated using a microwave discharge neutralizer. Fundamental properties and their related phenomena such as a plasma bridge between the ion beam and the neutralizer, I-V characteristics were measured. The condition of the plasma coupling for the neutralization was evaluated and an advisable method to suppress the imbalance was proposed.

Introduction

Institute of Space and Astronautical Science (ISAS) plans the asteroid sample return missin (MUSES-C). A spacecraft of 360 kg will be launched by a Japanese M-V rocket on July 2002 and rendezvous the asteroid named Nereus and pick up some of the surface materials to the earth by a reentry capsule. The ion thruster will propel the spacecraft to the transfer orbit toward Nereus and the return orbit to the earth. The electric propulsion for this mission is expected to be light weight and long life over 13,000 hours.

The electric propulsion division in ISAS has been developing the microwave discharge ion thuster in these years.[1,2] Several types of ion sources were examined and compared each other, such as an off-resonant ion source with a microwave cavity and resonant types with and without a cavity. The performance has been improved year by year. It is concluded that the ion source assisted with electron cyclotron resonance (ECR) is the most appropriate to the use of the ion thruster. A neutralizer is also employed with the use of ECR discharge. The microwave ion thruster has following advantages :
1) A thruster system is drastically simplified with respect to a power supply sub system,
2) Plasmas in an ion source and neutralizer are ignited without any preheat sequence,
3) The microwave plasma generation frees from the erosion of the discharge electrodes.

The microwave neutralizer, however, has an issue of lower electron emissivity than a hollow cathode having an emission heater inside. A cluustered operation of the neutralizers will bring about a current imbalance and an increase of the ion sputtering against their bodies, resulting in the degradation of the lifetime. Even the use of a conventional hollow cathode, such a phenomena was observed in an orbital experiment by ETS-VI satellite.[3] This motivates us detail investigations of the microwave discharge neutralizer with respect to the operational characteristics and the physical phenomena related to the current imbalance at the neutralization process. In these reasons, the objectives of present paper are to

1) observe and classify operational modes of two neutralizer operation,
2) parametrically evaluate the condition that the interaction occurs,
3) propose the method of stably control of two neutralizers.

Experimental Apparatus

The electron cyclotron resonance discharge generates the plasma for both the ion source and the neutralizer. The ion source is a cylindrical chamber of 12 cm in diameter and has two magnetic tracks which forms a ring cusped magnetic field. The magnetic field works not only for the resonant plasma formation but also the confinement of the primary electron as well as a conventional DC discharge ion source. The microwave is injected through a circular wave guide attached on the endplate of the ion source. The propellant gas is xenon.

The cross sectional view of the neutralizer is illustrated in Fig.1. The microwave which generates plasma is irradiated from the L-shaped antenna. The primary electron is trapped inside the magnetic tube of a banana-shape-region and moving along the gradBxB drift orbit, accelerated by electron cyclotron resonance to ionize the gas.

The block diagram of the thruster system is represented in Fig.2. The signal of the 4.2 GHz

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oscillator is injected into four solid-state amplifiers. The microwave of a single power supply is distributed to the ion source and the neutralizer. The power of 45 W at maximum is supplied to the main ion source and 5 W for the neutralizer. The ion source is electrically insulated with a DC cutter by inserting in the microwave coaxial cable and a gas isolator in the gas feed line since it is highly biased with a positive potential against the power supply, the control system and other instruments. The neutralizer is electrically grounded to the vacuum chamber. The vacuum chamber has the size of 1.5 m in diameter and 2.5 m in length and is evacuated by two oil diffusion pumps of 12,000 liter/sec.

The experimental setup for the current imbalance using two neutralizers was shown in Fig.3. The two neutralizers were installed symmetrically against the center of the ion beam in the vacuum chamber. One was the microwave discharge neutralizer and another the emission heater which simulated the interference caused by an electron current influx from other neutralizer. The heater has the convenience for the experiment because of the ease to change the emission current continuously. The heater was made of tungsten which contained 2% thorium and hade the size of 7cm in length. The current of each electron source was independently controlled using current limitter circuits by a personal computer. During the experiment, both the ion engine and the microwave neutralizer were operated as the following conditions.

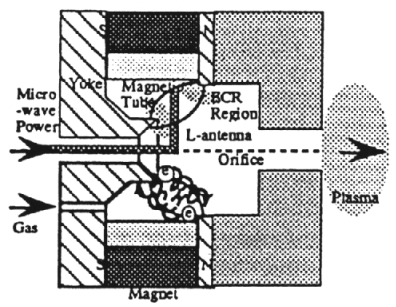


Fig.1 Microwave discharge neutralizer

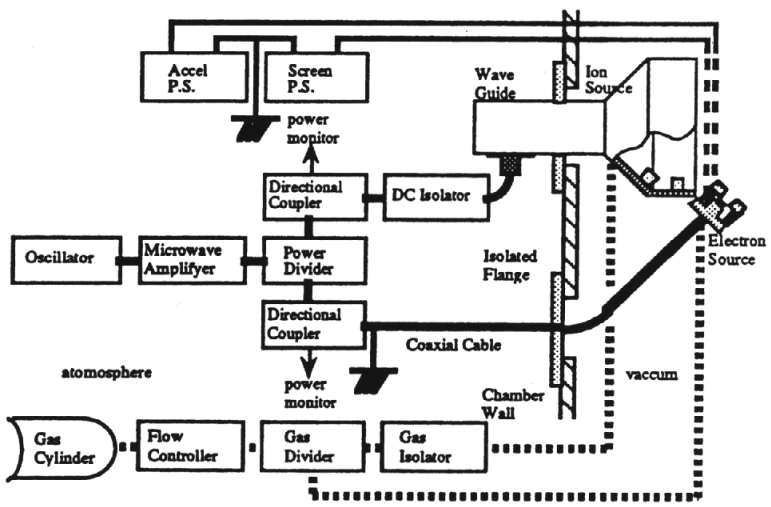


Fig.2 Microwave Ion Thruster

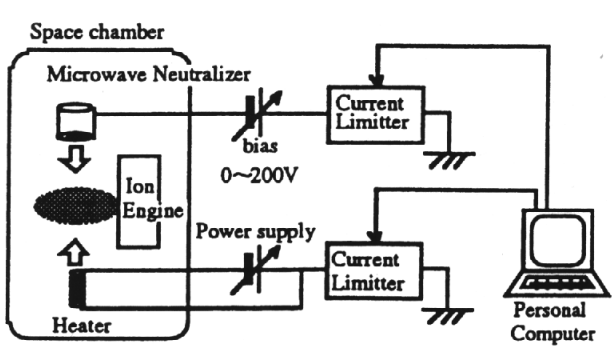


Fig.3 Apparatus for two neutralizer operation

Table 1 Operational condition

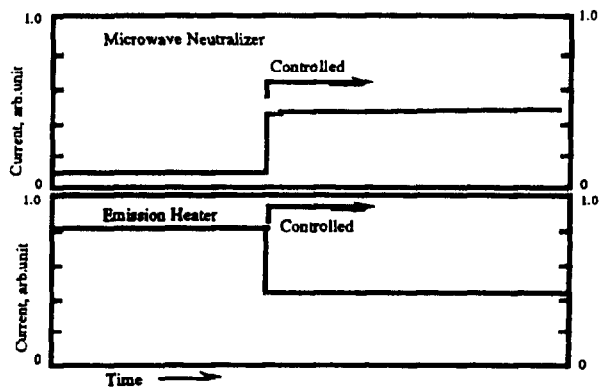
1) Microwave Ion Thruster
- screen voltage : 1kV
- screen current : 80 mA (nominal)
- accel. voltage : 0.3kV
- mass flow rate : 2 sccm
- microwave : 30W

2) Microwave Neutralizer
- mass flow rate : 0.5 sccm
- microwave : 5 W
- bias voltage : 0-200 V

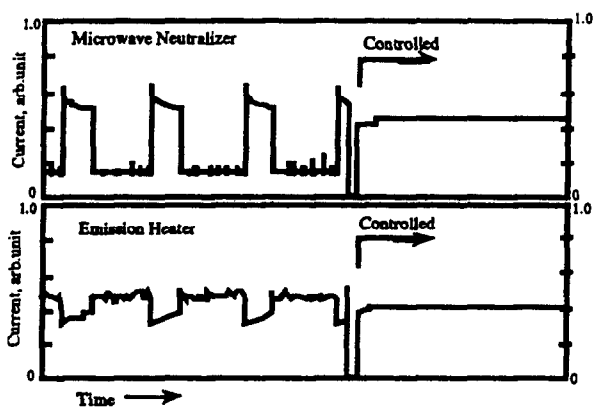
Experimental Results

Electron current imbalance at two neutralizer operation

The operation of the microwave neutralizer was drastically changed depending on the current influx. Two modes were observed. In terms of of the emission level of the microwave neutralizer, there exists a high and low emissive modes. Fig.4 represents the typical current pattern of the two neutralizer operations. As seen in Fig.4 (a), the currents were exhibited onesided in most case. The current levels were 10 mA for the microwave neutralizer, 80 mA for the heater respectively. Another imbalance was also observed as represented in Fig.4 (b), in which each emission current oscillates and their amplitudes change alternatively.



(a) Heater is superior.



(b) Flip-flop oscillation

Fig.4 Operation of two neutralizers

The current influx interference on the current voltage (I-V) characteristics of the microwave neutralizer was investigated. The interference level was continuously changed from 0 to 100% by adjusting the heater emission, the bias voltage being parameters. Figure 8 represents the result of the I-V characteristics monitored, where the horizontal axis is plotted against the potential gap between the ion beam and the bias voltage of the microwave neutralizer, V_{beam} - V_{bias}. Regardless of the bias voltage differences, the I-V characteristics exhibit the same trend depending on the potential gap. When the low heater emission, the microwave neutralizer exhibits the high current mode with a potential gap of 100 V. As increasing the influx from the emission heater, it becomes difficult to sustain the plume for emitting the electron, transiting to the low current mode where the total electron current is insufficient for the beam neutralization, resulting in the beam potential leaping up over 200 V. Further more electron emission from the heater relieves the neutralization and the potential gap becomes lower.

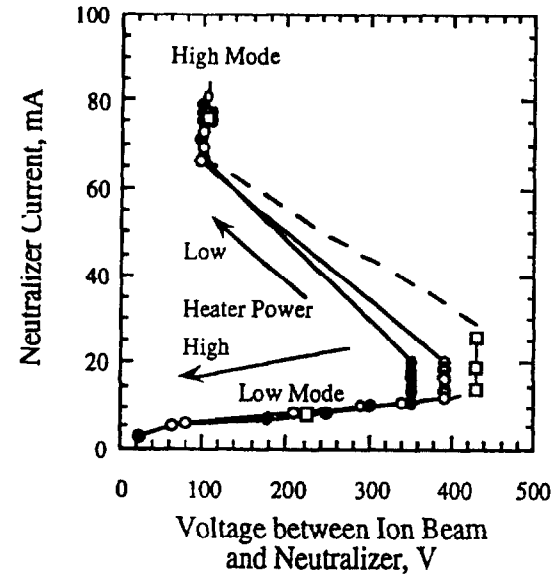


Fig.5 Current - Voltage characteristics of microwave neutralizer when the interference from an emission heater exists.

An operation of two neutralizer was mapped with respect to the heater emission level and the bias voltage of the microwave neutralizer. The emission level of the heater heater was normalized using the relation of between the input power and the emission current as shown in Fig.6. It is defined as the following relation:

Heater Emission Level = (Heater emission current) / (Ion beam current of 80mA).

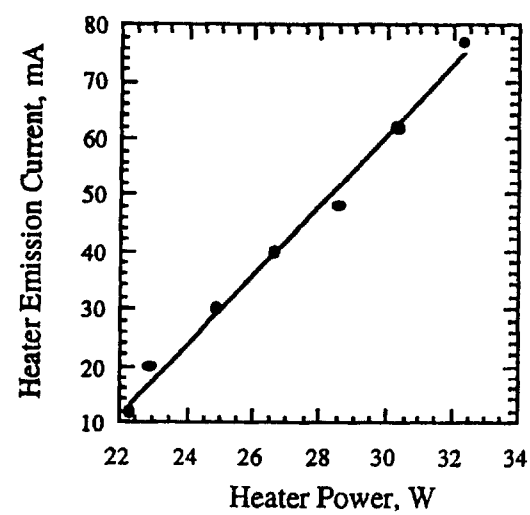


Fig.6 Electron emission versus heater power

It is important to note that the heater can supply the enough current for neutralization when the heater emission level is larger than unity. Fig.7 represents to be classified to the four modes: (I) heater superior, (II) microwave neutralizer superior, (III) both existing and (IV) flip-flop oscillating modes, respectively. In the region of (III), both of them can stably exist but not be realized at the same time. In this classification, the previous operational example of Fig.2 (a) categorizeded in the region (I) and Fig.2 (b) the region (IV), respectively.

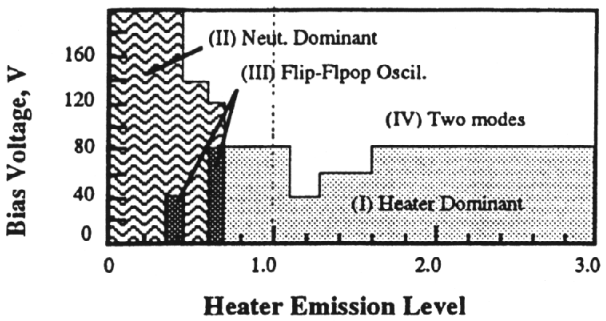


Fig.7 Mapping of free operation

Effect of imbalanced operation upon the ion beam centroid

The ion beam centroid drift was also measured using a beam centroid probe in the following three cases:
(I) Microwave neutralizer = ON, heater = OFF,
(II) Microwave neutralizer = OFF, heater = ON,
(III) Microwave neutralizer = ON, heater = ON (Emission Level = 0.5).
The experimental method is schematically shown in Fig.8. The beam centroid probe tracked to find the center of the ion beam was controlled by a personal computer.[4] Estimating the relative beam shifts between these three cases, only a minor beam drift less than 0.1 degree was revealed at most.

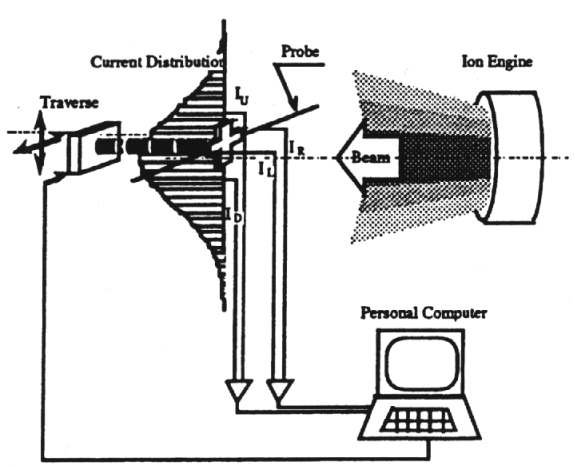


Fig.8 Ion beam centroid measurement

Potential distribution near neutralizer

Spatial distributions of the beam potential (= floating potential) were measured by a single probe when the two neutralizers were operated in the region of (I) and (II). The measured area of the neutralization is represented in Fig.8 and the results are shown in Fig.6 (a) and (b). In Fig.6 (a) the plasma plume from the microwave neutralizer is clearly observed. When the emission of the neutralizer is low, the plasma is localized in front of the orifice and the plume was not formed as seen in Fig.6 (b).

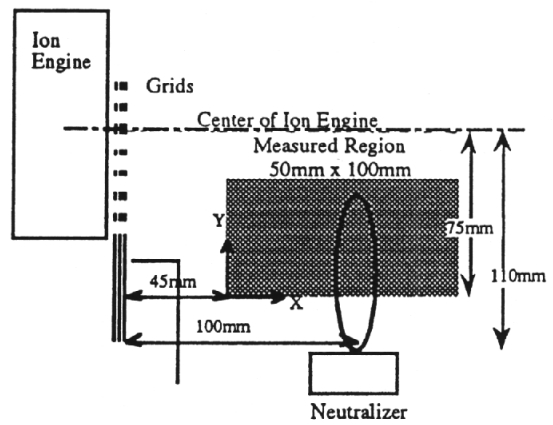
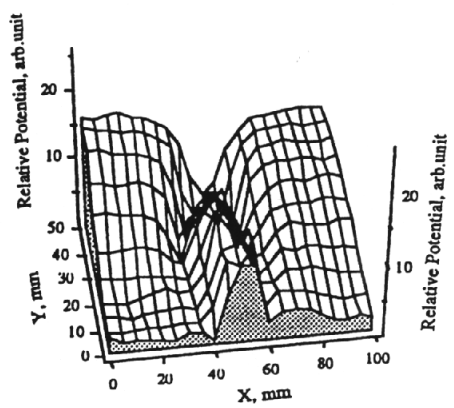
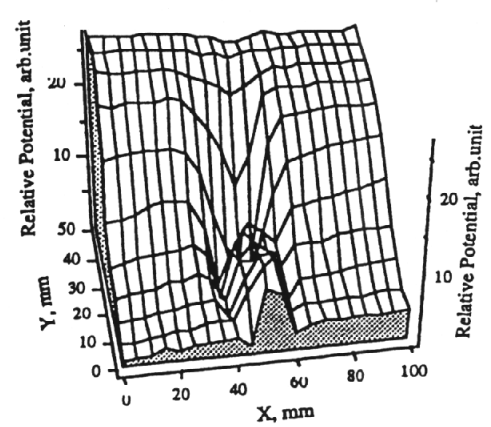


Fig.9 Area of potential mapping near neutralizer



(a) Neutralizer=58mA, heater=25mA



(b) Neutralizer=8mA, heater=76mA

Fig.10 Experimental results of potential mapping

Active current partition control of two neutralizers

As described previously, in most cases the operation of two neutralizers exhibits imbalanced so that the equal distribution necessitates an active current control of each device. In this reason, the maximum currents of each power supply were examined to control using the external current limitter circuits. The use of the current limitters corresponds to let the power supply have the function of the pendulous character shown in Fig.11. As examples of this simple method shown in Fig.4, the current partition can be successfully controlled.

Next, the current controllability was tested in whole the classified region in Fig.7. For mapping the controllability, the maximum current of each device is set to be equal, that is, the microwave neutralizer being 40 mA and the emission heater 40 mA, respectively. In Fig.12, the operation was improved and completely controlled in the region (IV) of the heater emission level over 1.0 and the region (I) of the heater emission level over 1.8. In the region (I) of between 1.0 to 1.8, it was observed that a little change of the current partition ratio made the operation stable. It is also noted that it is physically impossible to neutralize the ion beam below the heater emission level of 0.5. As mentioned above, it was shown that the use of the function of the pendulous character was very effective to avoid the current interference of the neutralizers.

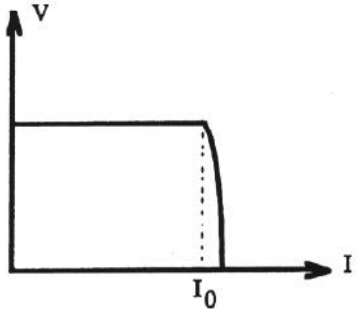


Fig.11 Pendulous character of the power supply for neutralizers

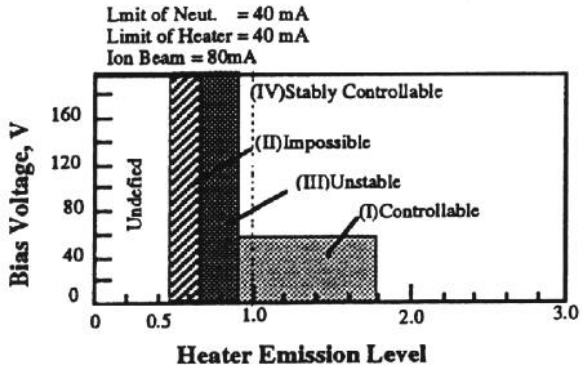


Fig.12 Mapping of controlled operation

Operational characteristics depending on the plasma contacting distance

The characteristics of a single microwave neutralizer was investigated using an electron collector. Fig.13 exhibits the typical trend of the electron emission versus the voltage. Fig.14 shows the plasma coupling characteristics dependent on the collector position which simulates the length of the plasma bridge between the ion beam and the neutralizer. The voltage that the mode transition begins depends on the distance. This suggests us an importance of the plume formation for the neutralization of the ion beam.

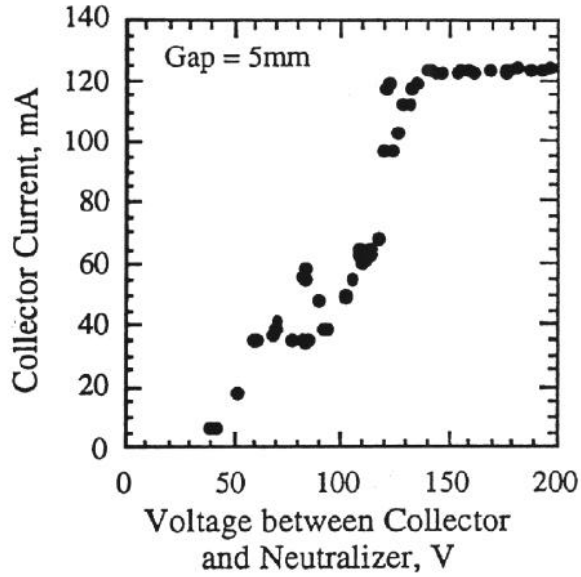


Fig.13 Typical I-V characteristics of the microwave neutralizer

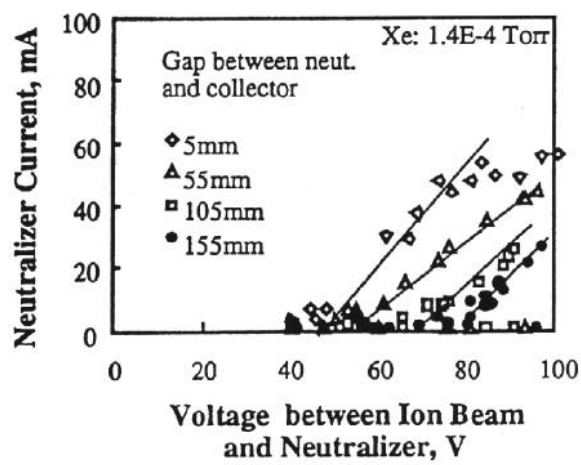


Fig.14 Dependence of I-V characteristics on distance

Effect of environmental pressure on plasma contacting voltage

For detail investigation of the mode transition, we define that the voltage V_S that begins to form the bridge transiting the low to high current emissions. The I-V characteristics on the the environmental pressure is represented in Fig.15. At the limitation of the electrodes gap being zero, the V_S seems to converge to 40 V tin spite of the pressure change.

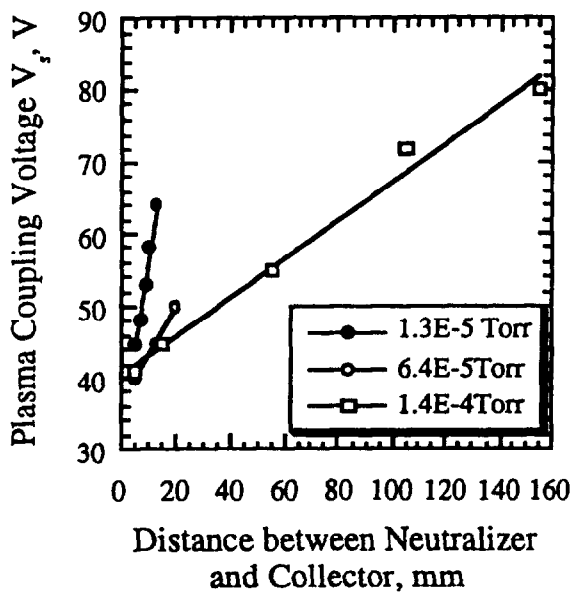


Fig.15 Dependence of the coupling voltage on the distance between the neutralizer and the collector.

Discussions

There exist two modes for the operation of the microwave neutralizer. The high mode is characterized the long plasma bridge and the the high emission current of the electron. The low mode the little electron emission and the plasma spot which is localized inside the discharge chamber. The formation of the plasma bridge is significant to the neutralization and also related to the plasma interaction using clusterlized neutralizers. The mode jump is initiated at the voltage, V_S that depends fairly on the environmental pressure, P and the distance, L between the neutralizer and the collector / ion beam positions as seen in Fig.14-15. At a given pressure, the V_S linearly increases. Dividing V_S by the distance L, the inclination of dV_S/dL is replotted in Fig.16 , giving a simple relation,

$$\frac{\partial V_s}{\partial L} = \frac{3.16 \times 10^{-5}}{P\ [\mathrm{Torr}]}\ [\mathrm{V/mm}]\ . \quad (1)$$

The condition of avoiding the interference is considered, supposing the arrangement of the ion thruster head and the neutralizers as depicted in Fig.17.

The suffix of "1" in Fig.17 means the paired neutralizer with the thruster head depicted and the suffix of "2" the other that causes the interference. The potential difference between the beam and the neutralizer is

$$\Delta V = V_{beam} - V_{bias}\ . \quad (2)$$

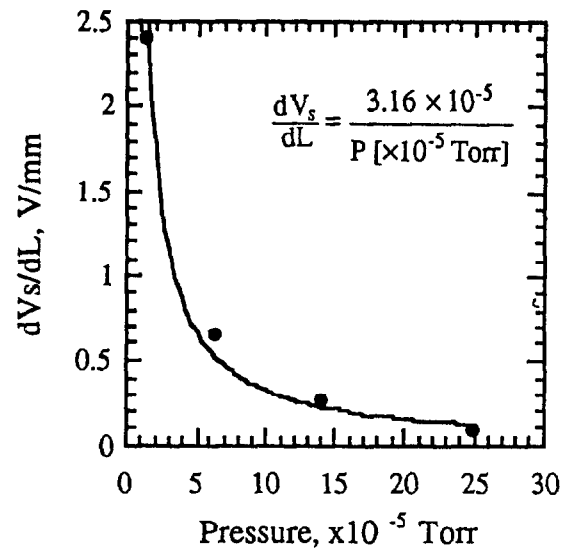


Fig.16 Derivative of coupling voltage

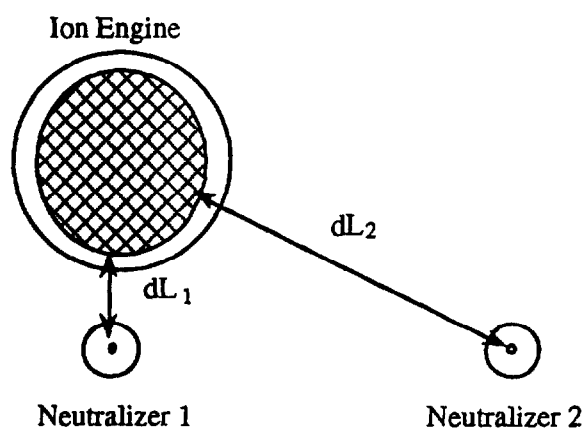


Fig.17 Arrangement of thruster head and neutralizers

The electron current can drain from the neutralizer when the ΔV is larger than V_S. For the purpose of emitting the current from the neutralizer "1" and at the same time for suppressing the outflow from the neutralizer "2", must be satisfied the inequality

$$V_{S1} < \Delta V << V_{S2}. \quad (3)$$

Using the relation of Eq.1, the V_S of each neutralizer is calculated by

$$V_{Si} = V_{S0} + \frac{\partial V_S}{\partial L} dL_i \quad (i = 1, 2) \quad (4)$$

where V_{S0} is 40 V. Seeing Fig.5, is estimated ΔV = 100 V. Supposing the environmental pressure P of 5 x 10^{-5} Torr and dL_1 of 50 mm, the V_{S1} is estimated

$$V_{Si} = 40 + \frac{3.16 \times 10^{-5}}{5 \times 10^{-5}} 50$$
$$= 71.6\ [V] < 100\ [V]\ , \qquad (5)$$

so that the inequality $V_{S1} < \Delta V$ is satisfied. Next, another inequality of Eq.3 gives the restriction against dL_2

$$100 << V_{S2} = 40 + \frac{3.16 \times 10^{-5}}{5 \times 10^{-5}} dL_2$$
$$dL_2 >> 95\ [mm]\ . \qquad (6)$$

From the result of Eq.6, one of recommended arrangements is shown in Fig.18.

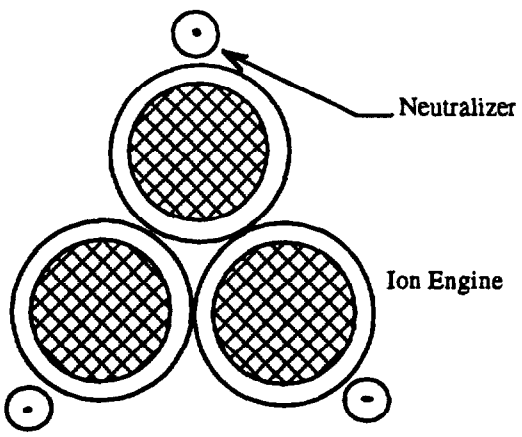


Fig.18 Recommended arrangement of ion engine clusterization

Conclusion

The interference phenomena caused by clusterization neutralizers is experimentally investigated. The voltage that the neutralizer initiates coupling with the plasma is expressed by the experimental relation

$$\frac{\partial V_s}{\partial L} = \frac{3.16 \times 10^{-5}}{P\ [Torr]}\ [V/mm]\ .$$

The function of the pendulous character to control the emission current is advisable for avoidance of this kind of plasma interference.

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