Research and Development on Inductively Coupled Plasma Cathode for Ion Engines

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Abstract: Hollow Cathode (H/C) is a common electron source for ion engines, because it achieves high electron emission current with relatively low consumption of gas and electric power. However, an oxide insert in H/C restricts its handling and lifetime. In order to liberate ion engines from these limits of H/C, inductively coupled plasma (ICP) was employed as the electron source in this study. A new cathode with ICP for ion engines was developed and then evaluated experimentally. This cathode enables instantaneous ignition and simple handling due to oxide-insert-less design. Moreover, it may permit ion engines longer lifetime compared with H/C. Through the experimental evaluations, the typical performance of the cathode was 2.1A of electron emission current at 100W of RF power with 13.56MHz, 2.0sccm of Xe mass flow rate and 40V of target voltage. Additionally, it was obtained that the cathode was operated normally as a neutralizer for RF ion thruster and a main cathode for DC cusped ion thruster.

Nomenclature

C_i = Ion production cost
D_b = Beam diameter
$D_{orifice}$ = Orifice diameter
I_{ac} = Accelerator current
I_b = Beam current
I_d = Discharge current
I_e = Emission electron current
I_i = Collection ion current
I_r = Return current
I_{sc} = Screen current
I_{sp} = Specific impulse
ID = Inner diameter of discharge vessel
ℓ = Length of discharge vessel
m = Xe mass flow rate at diode configuration
m_{mc} = Main cathode mass flow rate
m_{mpf} = Main propellant feed mass flow rate
m_n = Neutralizer mass flow rate
m_t = Thruster mass flow rate
n_{coil} = Total number of coils
n_e = Electron number density
P_{NRFG} = Net RF power input into neutralizer
P_t = Total power consumption
P_{TRFG} = Net RF power input into thruster
P_{RF} = Net RF power input into ICP/C
T = Thrust
T/P = Thrust-to-power ratio
V_{ac} = Accelerator voltage
V_d = Discharge voltage
V_{sc} = Screen voltage
V_t = Target voltage
V_{tran} = Transition voltage
η_u = Propellant utilization efficiency

*sccm : Standard cubic centimeters per minute
1.0sccm (Xe) = 9.77×10^{-5} g/s
at standard temperature and pressure

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I. Introduction

RECENTLY the applications of electric propulsion have been increasing in some space missions such as station keeping and solar system exploration[1]. An ion engine has the highest specific impulse and thrust efficiency among electric propulsion systems in practical use. Therefore, it can expand the area of exploration and human activity in space. However, in order to generate required velocity increment by the ion engine, long continuous operation of several years is required due to its low thrust.

Generally, ion engine has two main failure modes; grid structural failure due to its erosion, and cathode failure due to hollow cathode (H/C)[2]. Ion engine needs electron sources as a main cathode to produce ions to be accelerated or a neutralizer to keep the satellite potential neutral. H/C is employed as the electron sources, because of its high electron current density with the low consumption of gas and electric power. However, its lifetime is limited by degradation and depletion of an oxide insert. Additionally, the insert has to avoid contacting with active gas and H/C requires preheating by heater wire before ignition. As a result, ion engines with H/C have some difficulties for long-term operation, and they should be controlled strictly from prelaunch to end of life.

The microwave discharge ion engine "μ10", which was onboard Hayabusa asteroid explorer, is attractive ion engine that is oxide-insert-less design. The engine established 31,400 hours the total numbers of space operational time and proved its longer lifetime by not using H/C[3]. However, due to electron cyclotron resonance plasma (ECRP), the electron density is limited by cutoff frequency and the plasma of ion source is not uniform. Additionally, a microwave generator is low power efficiency that is below 50%. Consequently, microwave discharge ion engines are lower thrust performance than other ion engines.

Thus, in order to liberate ion engines from these limits of H/C without thrust performance degradation, inductively coupled plasma (ICP) was employed as an electron source for ion engine. The objectives of this study are (1) Design and construction of a new cathode with ICP, (2) Experimental evaluation of its electron emission characteristics, and (3) Demonstration of its applications as a main cathode and a neutralizer for ion engine.

II. Experimental Apparatus and Procedure

A. Apparatus and Facilities

All experiments are conducted in the vacuum chamber, whose diameter and length are 1.6m and 3.2m, respectively. The vacuum chamber reaches approximately 2×10^{-3}Pa by a turbo-molecular pump and a cryogenic pump, when the Xe mass flow rate is 8.0sccm. RF generator, impedance matching box, and DC power supply are attached at out of the vacuum chamber. The RF generator's frequency and rated power are 13.56MHz and 500W, respectively. The impedance matching circuit consists of two variable capacitors to reduce reflected power. Xe is employed as propellant, and the neutral Xe gas is fed via thermal sensing mass flow controller.

B. Inductively Coupled Plasma Cathode

Since ICP does not depend upon high voltage to drive displacement current through the powered RF sheath, the plasma achieves sufficiently high electron density without an oxide insert[4]. Moreover, the limitation of electron density, which is attributed to cutoff frequency, is not important to ICP like ECRP.

Figure 1 shows the ICP cathode (ICP/C) that is designed in this study. It consists of discharge vessel, orifice plate, induction coil and ion collector. The orifice plate, which is made of mica, covers the downstream of the vessel to keep inner pressure high. For electron emission, there is an orifice at the center of the plate. The induction copper coil is not cooled by water. The ion collector is necessary for ICP/C during steady operation in order to maintain quasineutrality at ICP. The collector, which is made of stainless steel, is inserted to the discharge vessel along its wall. When electron is extracted from ICP/C, ion that is equal to the extracted electron is collected at the ion collector. The ion collector also has an axial slit, which allows the axial *dB/dt* fields into the plasma, but suppresses the circumferential *dE/dt* field, effectively serving as a Faraday shield for the plasma within ICP/C[5,6].

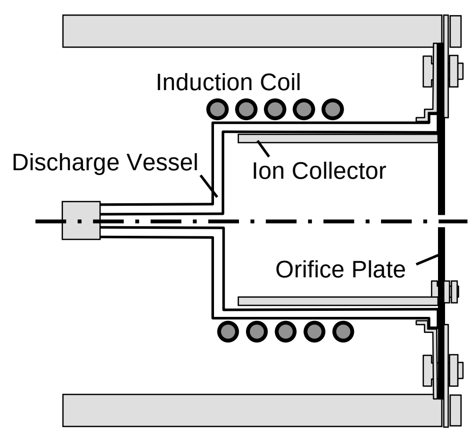


Figure 1. Schematic illustration of ICP/C.

Two scales of ICP/C, which are 4cm ICP/C and 1.5cm ICP/C, are constructed. At the 4cm ICP/C, its electron emission characteristics and its application as a main cathode are evaluated. On the other hand, the application as a neutralizer is evaluated at 1.5cm ICP/C. Table 1 shows the details of these cathodes.

Table 1. Details of the fabricated cathodes.

Items			4cm ICP/C	1.5cm ICP/C
Vessel material			Pyrex	Alumina
Vessel inner diameter	*ID*	mm	40	15
Vessel length	ℓ	mm	46	18
Orifice diameter	$D_{orifice}$	mm	2	1
Total No. of coils	n_{coil}	turns	5	10

C. Electron Emission Characteristics

Electron emission characteristics of 4cm ICP/C are evaluated at diode configuration. Figure 2 shows the electrical configuration in this experiment. The target, as an anode, is located at 50mm downstream of the orifice plate, and it is biased positively by DC power supply. The electrical potential difference between the grounded ion collector and the target simulates the potential difference between the neutralizer common and the ion beam in the normal operation of ion engine.

After the ICP is sustained stationary, Xe mass flow rate and RF power are set as follows: Xe mass flow rate of 1.0, 2.0, 3.0sccm and RF power of 20, 40, 60, 80, 100, 120W. When the target bias voltage is varied from 0V to 80V at intervals of 5V, the electron current emitted from the ICP/C and the ion current collected by the ion collector are measured.

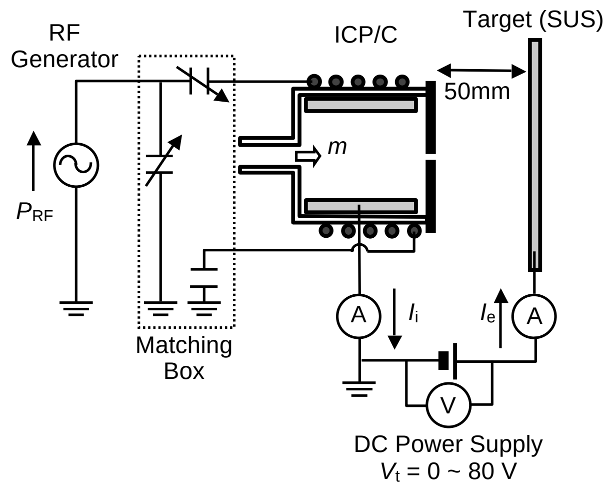


Figure 2. Diode configuration with ICP/C.

D. Application of ICP/C as a Main Cathode

At DC cusped ion thruster, steady magnetic field produced by permanent magnets is employed to confine the main DC plasma. On the other hand, ICP/C uses induced magnetic field to sustain the ICP. There is a fear that steady magnetic field and induced magnetic field interfere mutually, and then ICP/C will not work as a main cathode. Thus, it is necessary to prove whether ICP/C is operated as a main cathode of DC cusped ion thruster.

Figure 3 shows the electrical configuration of DC cusped ion thruster with ICP/C. The 4cm ICP/C is installed at center of the upper wall of the main discharge chamber. The chamber is made of iron and has three magnet rings for forming cusped-magnetic field. The ion extraction optics consists of two dished grids; whose beam diameter is 12cm and material is molybdenum. The power supplies consists of beam power supply (PS1), accelerator power supply (PS2), discharge power supply (PS3) and RF generator (RFG).

In order to investigate the difference of electron emission characteristics at thruster configuration and diode configuration, the discharge current is measured as the discharge voltage increased from 0V to 45V. The

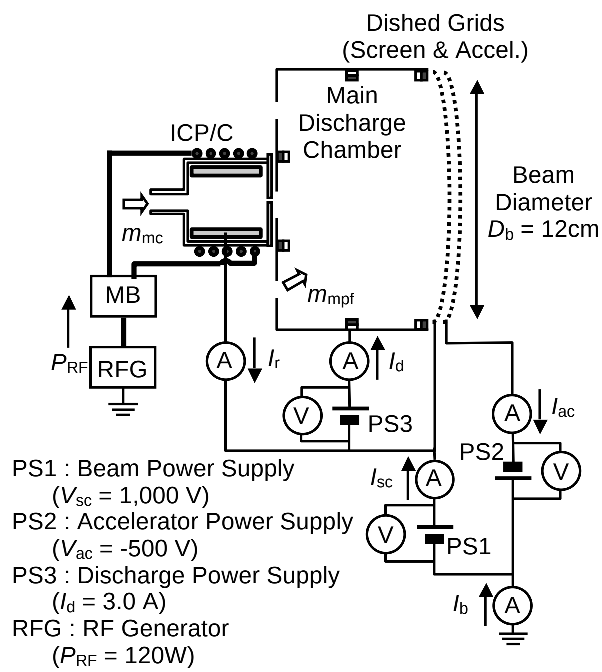


Figure 3. Electrical configuration of DC cusped ion thruster with ICP/C.

experimental conditions are 0.8sccm of main cathode mass flow rate, 7.2sccm of main propellant feed mass flow rate and 120W of RF power.

The ion engine is operated at the following conditions: 0.8sccm of main cathode mass flow rate, 7.2scccm of main propellant mass flow rate, 120W of RF power, 3.0A of discharge current, 1,000V of screen grid potential, and -500V of accelerator grid potential. Then the each current and voltage are measured to calculate the thrust performance.

E. Application of ICP/C as a Neutralizer

When ICP/C is applied as a neutralizer of RF ion thruster, there is a fear that induced magnetic fields at a thruster and a neutralizer interfere mutually, and then two ICPs will not be sustained. Thus, it is necessary to prove whether ICP/C is operated as a neutralizer of RF ion thruster.

Figure 4 shows the experimental conditions and electrical configuration of RF ion engine with 1.5cm ICP/C. Beam diameter of the RF ion thruster is 3.0cm, and the ion extraction optics consists of screen and accelerator grids. The power supplies consist of beam power supply (PS1), accelerator power supply (PS2), and two RF generators (TRFG and NRFG). In order to evaluate the current loop and calculate thrust performance, each current is measured.

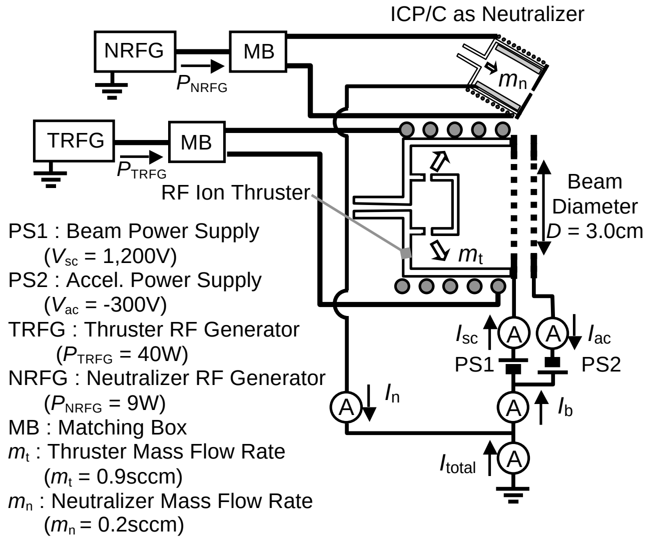


Figure 4. Electrical configuration of RF ion thruster with ICP/C.

III. Results and Discussions

A. Electron Emission Characteristics

Through the preliminary experiment, it was obtained that the electron current emitted from the ICP/C is nearly equal to the ion current collected by the ion collector[7]. This result demonstrates that the ICP/C works as an electron emission device.

Figure 5 shows current-voltage characteristics of 4cm ICP/C when RF power is 40W. It was obtained that there were two current modes. One is low current mode when the target voltage is from 0V to 15V, the other is high current mode beyond 25V of target voltage. At about 20V of target voltage, the emission electron current increases sharply and the plume between the orifice and the target is observed as shown in Fig. 6. At high current mode, the extracted electrons are accelerated to ionize Xe atoms, and they produce a plasma plume between the cathode and the target electrode. When this plasma plume supplies electrons to the target, the emission electron current rapidly increases as shown in Fig. 5. The similar *I-V* characteristics were obtained at 1.5cm ICP/C.

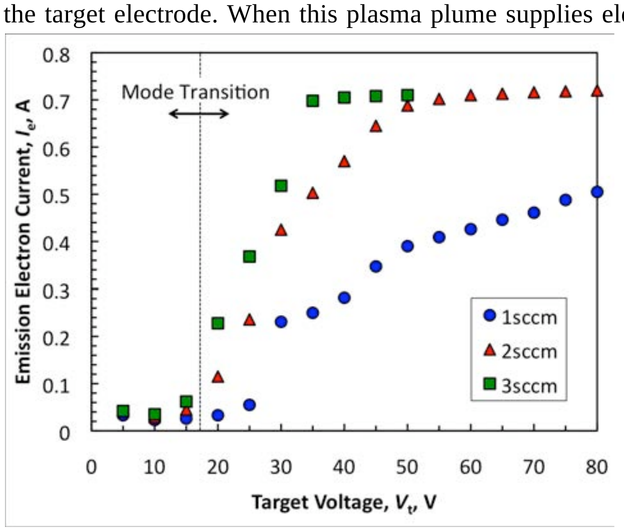
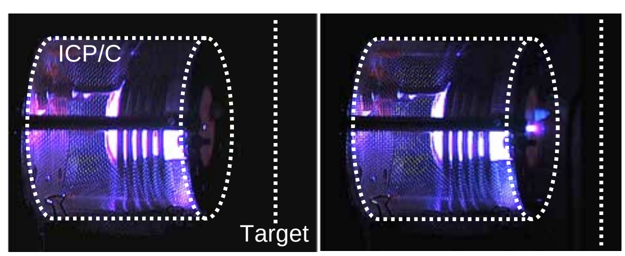


Figure 5. Current-voltage characteristics of ICP/C at 40W RF power.



(a) Low current mode (I_e = 0.08A) (b) High current mode (I_e = 1.6A)

Figure 6. Photos of ICP/C operation at 80W of RF power and 3.0sccm of Xe mass flow rate, (a) 5V of target voltage, (b) 40V of target voltage.

In higher Xe mass flow rate, the current increase is more obvious, and the upper limit of emission electron current is observed. Figure 7 shows the transition voltage as functions of RF power and Xe mass flow rate. When the target voltage is biased to transition voltage, the plume appears and the current mode transits from low current mode to high current mode. In Fig. 7, the transition voltage decreases with increasing Xe mass flow rate. On the other hand, the transition voltage reaches a minimum at 40W of RF power in same Xe mass flow rate.

The emission electron current as functions of RF power and Xe mass flow rate at constant target voltage (V_t = 40V) is shown in Fig. 8. The emission electron current has a proportional relation to RF power beyond 2.0sccm of Xe mass flow rate. Figure 9 shows the electron number density inside the discharge vessel as functions of RF power and Xe mass flow rate. Using double probe method, the density was measured. In Fig. 9, the density has a proportional relation to RF power at every Xe mass flow rate. Through these proportional relations, the emission electron current is limited by the ion current that is collected at the ion collector, because the ion current through the ion sheath is equal to Bohm current, which is proportional to electron number density[8]. Thus, the emission electron current has a proportional relation to RF power at sufficient high Xe mass flow rate, and the electron current also has the upper limit as shown in Fig. 5. On the other hand, it is assumed that the low emission electron current at 1.0sccm in Fig. 9 is attributed to the condition outside the cathode rather than the plasma production inside the cathode.

The data presented in Fig. 8 show that the 4cm ICP/C achieves approximately 2.1A of emission electron current with 100W of RF power, 2.0sccm of Xe mass flow rate and 40V of target voltage. The value of emission electron current is high enough to neutralize ion beam of large ion engines, which will be used in orbit transfer missions[9].

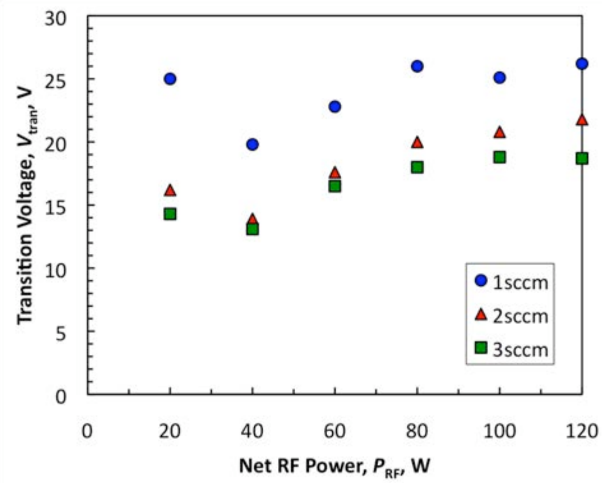


Figure 7. Transition voltage as functions of RF power and Xe mass flow rate.

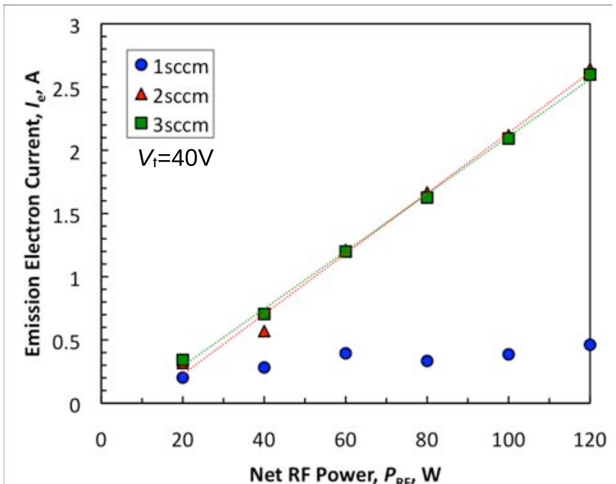


Figure 8. Emission electron current as functions of RF power and Xe mass flow rate.

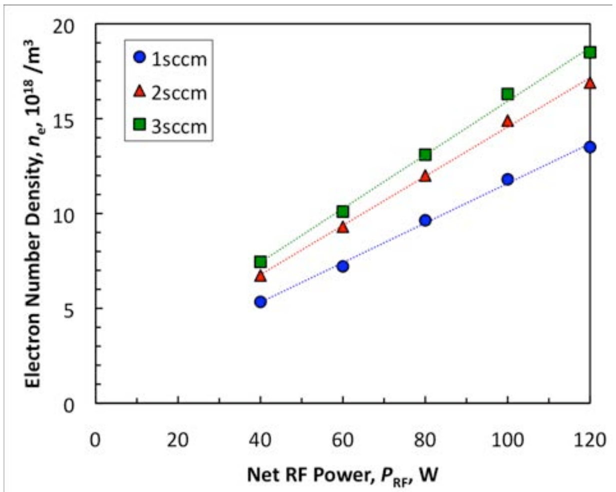


Figure 9. Electron number density as functions of RF power and Xe mass flow rate.

B. Application of ICP/C as a Main Cathode

Proper ion beam extraction of DC ion thruster with 4cm ICP/C is confirmed. Figure 10 shows current-voltage characteristics at thruster configuration and diode configuration. At each configuration, RF power and main cathode mass flow rate are same: P_{RF} = 120W and m_{mc} = 0.8sccm. There is additional propellant 7.2sccm fed to the main discharge chamber at thruster configuration. As shown in Fig. 10, the upper limit of discharge current is exited at thruster configuration. The discharge current increases dramatically at about 20V of discharge voltage, and then the main plasma is ignited inside the main chamber. Then, over 3.0A of discharge current is achieved. The comparison of *I-V* characteristics in Fig. 10 shows that the trend of electron current as voltage increases is attributed to the condition outside the cathode rather than the plasma production inside the cathode as mentions previously.

Table 2 is the comparison of the thrust performance with ICP/C and H/C at same conditions. The thrust performance of the ion thruster with ICP/C achieved thrust of 17mN, specific impulse of 2,200s, and thrust-to-power ratio of 31mN/kW. At each cathode the same values of thrust and specific impulse were obtained with same propellant consumption. However, the electric power of ICP/C for plasma production is much higher than the power of H/C, so thrust-to-power ratio of the ion thruster with ICP/C is lower. Therefore, as future work, the dimensions and materials of ICP/C should be investigated to improve its characteristics of electron emission. Additionally, a lifetime throughout the ion engine, including cathode degradation, grid erosion and so on, should be evaluated.

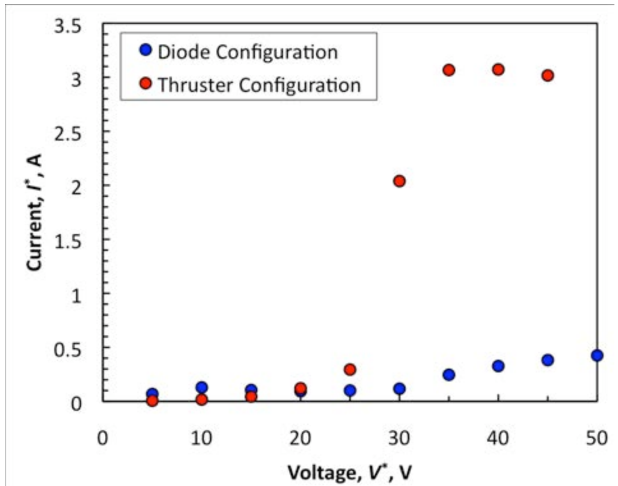


Figure 10. Comparison of emission electron current with diode configuration and thruster configuration.

Table 2. Comparison of thrust performance with ICP/C and H/C.

Items			ICP/C	H/C
Beam diameter	D_b	cm	12	
Screen voltage	V_{sc}	V	1000	
Accel. voltage	V_{ac}	V	-500	
Discharge current	I_d	A	3.0	
MPF mass flow rate	m_{mpf}	sccm	7.2	
MC mass flow rate	m_{mc}	sccm	0.8	
Discharge voltage	V_d	V	33.7	34.7
Beam current	I_b	mA	335	332
Thrust	T	mN	17.4	17.3
Specific impulse	I_{sp}	s	2280	2260
Propellant util. efficiency	η_u	%	58.2	58.2
Ion production cost	C_i	W/A	661	324
Total power consumption	P_t	kW	0.56	0.45
Thrust-to-power ratio	T/P	mN/kW	31.1	38.9

C. Application of ICP/C as a Neutralizer

Through the experiment of simultaneous operation, it was obtained that two ICPs were maintained stationary by each RF generator. The ignition sequence is as follows:

1) Neutralizer mass flow rate set: m_n = 1.5sccm.
2) Neutralizer RF generator on: P_{NRFG} = 25W.
3) Neutralizer (1.5cm ICP/C) ignition.
4) Thruster mass flow rate set: m_t = 3.0sccm.
5) Thruster RF generator on: P_{TRFG} = 40W.
6) Beam power supply on: V_{sc} = 100V.
7) RF ion thruster ignition.

Figure 11 shows the typical current loop with and without neutralization through the experiment. Without neutralization, extracted ions reach the vacuum chamber wall, and then ions exchange their charge with the grounded wall. Therefore, the current loop generated by PS1 is formed through the ground as shown in Fig. 11(a). On the other hand, with neutralization, Electrons are extracted from neutralizer by the potential deference between ion beam and the plasma potential of neutralizer. Ions extracted from the thruster and electrons emitted from the neutralizer are mixed, and then neutral beam plasma reaches the wall. Thus, the current loop is formed through the plasma of neutralizer as shown in Fig. 11(b). Therefore, it is considered that a neutralizer power supply, which supplies negative potential for the neutralizer to emit electrons, is not necessary for the RF ion engine to neutralize ion beam.

The thrust performance of the ion engine achieved thrust of 1.6mN, specific impulse of 1,500s, and thrust-to-power ratio of 18.9mN/kW as shown in Table 3. It is not sufficient for practical use at small satellite missions. Improvement of thrust performance and ignition capability will be required for actual use.

As a result, H/C less RF ion engine without neutralizer bias power supply was demonstrated. The engine achieves instantaneous ignition and simple handling. Moreover, the engine promises to achieve longer lifetime due to oxide-insert-less design.

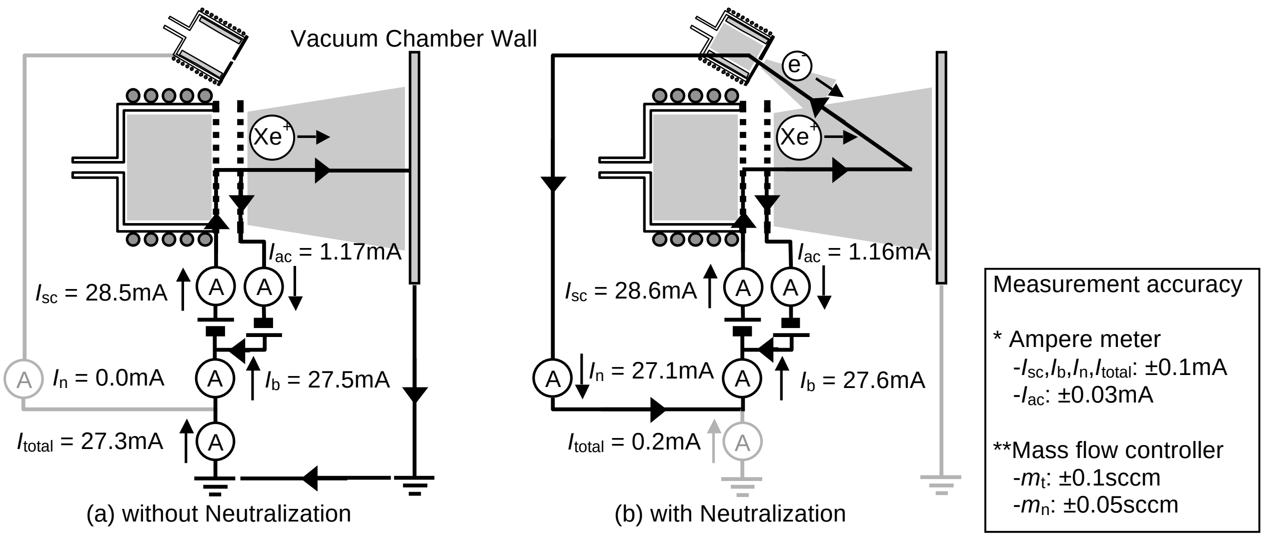


Figure 11. Current loop of RF ion engine with ICP/C at P_t=40W, P_n=9W, m_t=0.9sccm, m_n=0.2sccm, (a) without neutralization, (b) with neutralization.

Table 3. Thrust performance of RF ion thruster with ICP/C.

Beam diameter	D_b	cm	3.0
Thruster RF power	P_{TRFG}	W	40
Neutralizer RF power	P_{NRFG}	W	9
Thruster mass flow rate	m_t	sccm	0.9
Neutralizer mass flow rate	m_n	sccm	0.2
Screen voltage	V_{sc}	V	1200
Accel. voltage	V_{ac}	V	-300
Beam current	I_b	mA	27.6
Accel. current	I_{ac}	mA	1.16
Thrust	T	mN	1.58
Specific impulse	I_{sp}	s	1500
Ion production cost	C_i	W/A	1450
Propellant util. efficiency	η_u	%	35
Total power consumption	P_t	W	83.7
Thrust-to-power ratio	T/P	mN/kW	18.9

IV. Conclusion

Through the fabrication and experimental investigation of inductively coupled plasma cathode for ion engines, the following results have been obtained.

1) ICP/C has two current modes, which are low current mode and high current mode. The mode transition from low current mode to high current mode occurs as target voltage increases, and the transition voltage decreases with increasing Xe mass flow rate.
2) The emission electron current of ICP/C is limited by the ion current collected at the ion collector, and the electron current is proportional to input RF power at sufficient high Xe mass flow rate and target voltage.
3) Typical performance of 4cm ICP/C is 2.1A of emission electron current at 100W of RF power with 13.56MHz, 2.0sccm of Xe mass flow rate and 40V of target voltage. The value of emission electron current is high enough to neutralize ion beam of large ion engines, which will be used in orbit transfer missions.
4) ICP/C is operated normally as a main cathode of DC cusped ion thruster and a neutralizer of RF ion thruster. Additionally, the neutralizer bias power supply is not necessary for ICP/C to neutralize ion beam.
5) Improvement of electron emission characteristics and comprehensive study of ion engine with ICP/C will be required for actual use of ICP/C in space. Additionally, a lifetime throughout the ion engine, including cathode degradation, grid erosion and so on, should be evaluated.

Acknowledgments

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