Experiment of Parallel Field Emission Cathode Operation Preparing for On-orbit Demonstration of Electrodynamic Tether

IEPC-2015-440p／ISTS-2015-b-440p

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

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Abstract: Research of debris removal system using electrodynamic tether (EDT) system has been conducted in JAXA. The EDT system needs active electron emission device in order to drive large electric current through the tether for obtaining adequate de-orbit thrust. A field emission Cathode (FEC) can be a good option of the electron emitter because of its simplicity and potential performance. The FEC used in this study is composed of an emitter electrode with CNT coating and a gate electrode as extraction electrode. In the EDT systems, it is expected that several FEC units operates in parallel because of redundancy requirement. Since the interaction between the cathode units may cause instability or performance degradation, experiments of FEC parallel operation is required prior to practical on-orbit operation. We conducted experiments of FEC parallel and single operations in a vacuum and plasma environment. As a result, we found the following control method of the FEC was effective for obtaining the maximum emission current and minimizing the gate current; the gate voltage is controlled in response to the change of

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emitter potential with configuring the upper limit of the emission and gate currents. However, the emission currents during the FECs parallel operation were lower than those during FEC single operation. The electron current passed through the gate in plasma environment was lower than that in the vacuum because the positive potential of the gate attracts the electrons from plasma.

Nomenclature

B	=	earth's magnetic field
d	=	electrode spacing
d_{GA}	=	distance between the gate and the anode
e	=	electron charge
E	=	electric field between the electrodes
F_E	=	electric field of the tip
F_L	=	Lorentz force
h	=	Plank's constant
I_e	=	emitter current
I_g	=	gate current
I_{tether}	=	current flowing though the tether
J	=	current density
J_{SCL}	=	one-dimensional Child Langmuir law current density
J_{GA}	=	space charge limited current density (negative cathode potential)
L_{tether}	=	tether length
m_e	=	electron mass
n_0	=	electron density
r_{tip}	=	curvature radius of the emitter tip
s	=	thickness of plasma sheath
T_e	=	electron temperature
v_{orbit}	=	orbital velocity
V	=	voltage on the gate to emitter
V_0	=	potential difference between electrodes
V_a	=	anode voltage
V_{emf}	=	electromotive force
V_e	=	emitter voltage
V_s	=	potential difference between the plasma and emitter
β	=	field enhancement factor
ε_0	=	permittivity of free space
ϕ	=	work function
η	=	Extraction efficiency
λ_{DS}	=	electron Debye length at the sheath edge

I. Introduction

RESEARCH of debris removal system using electrodynamic tether (EDT) System has been conducted in JAXA. The EDT system is propelled by the interaction between the electric current through the tether and the geomagnetic field. To obtain the tether current, it is necessary to make a closed electrical circuit through surrounding plasma by collecting electrons at one end and emitting them at the other end of the tether. A field emission cathode (FEC) is suitable as the electron emission device because it possesses structural simplicity, and low electric power consumption without working gas and a heater. We selected Carbon Nanotube (CNT) as the emission material because they have very small tip diameters, moderate working function (approximately 5 eV), high mechanical strength, chemical stability and high electrical conductivity[1].

In the EDT system for debris removal, multiple FEC devices should be operated by multiple power sources in order to maintain the redundancy. In addition, it is desirable to maximize the total electron emission from all the FECs loaded. However, electron emission performances of the FECs have large individual differences because the FECs are susceptible to variations in CNT arrangement and electrode misalignment during assembly. This means that the required extraction voltages for obtaining a certain level of emission current are different in the each unit. Therefore, electrons emitted from a FEC would be drawn to another FEC which possesses higher electron voltage. Figure 1 shows the conceptual diagram of the electron flow during two simultaneous operations.

This paper describes the operation characteristics and the control method of the FECs based on the results of two unit simultaneous operation of FECs.

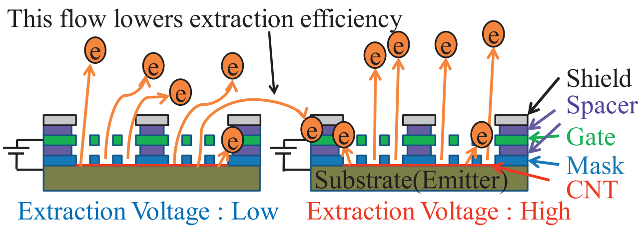

Figure 1. Electrode structure of FEC and flow of electrons in parallel operation of two FECs.

II. Electrodynamic tether system

A conceptual image of the EDT system is shown in Fig. 2. When a tether attached to an object such as the orbital debris is deployed in the radial direction of earth, its movement through the earth's magnetic field generates an electromotive force (EMF) across it is according to equation (1)[2]:

$$V_{emf} = (v_{orbit} \times B) \cdot L_{tether} \tag{1}$$

Where L_{tether} is the tether length, v_{orbit} is the orbital velocity and B is earth's magnetic field at an orbital altitude.

Due to this EMF, the zenith side of the tether (the upper side) acquires a positive electric potential and the nadir side of the tether (the lower side) becomes a negative electric potential with respect to the ambient plasma potential. Electrons are therefore collected from the ambient plasma by the upper side of the tether, while, an electron emitter such as an FEC attached at the lower end of the tether will emit electros to space due to its negative potential with respect to the ambient plasma. An electrical circuit is formed through the tether and the ambient plasma, which results in a current I_{tether} flowing though the tether. Lorentz force is generated by the interaction between this tether current and the earth's magnetic field. This Lorentz forth works to reduce the orbital velocity of the debris, causing it to re-enter the atmosphere. Lorentz force in the EDT system is given by equation (2).

$$F_L = (I_{tether} \times B) \cdot L_{tether} \tag{2}$$

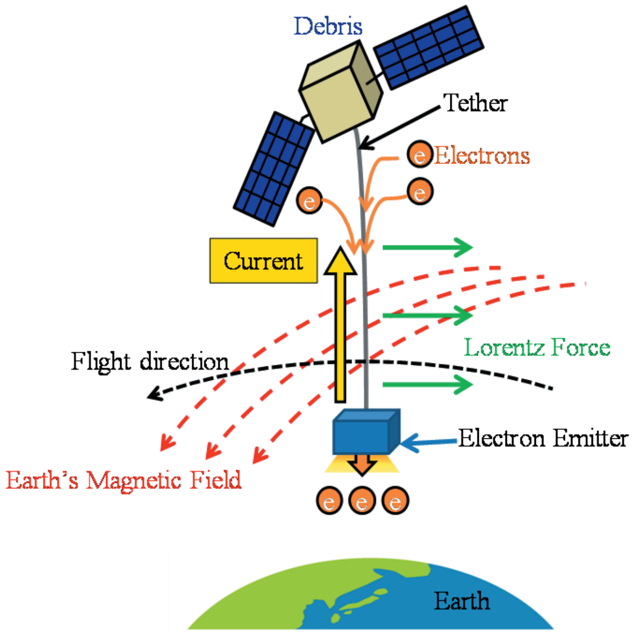

Figure 2. Conceptual image of EDT system.

III. Field Emission Cathode and Space Charge limit

A. Field Emission cathode

Figure 1 shows a schematic drawing of FEC. Electron emission occurs when a strong electric field of about 10^9-10^{11} V/m is generated by applying a voltage between the gate and the emitter. Potential barrier for electrons becomes thin by the high electric field, so that electrons are possible through the potential barrier by the wave nature of electrons. It is called the tunnel effect and electrons are emitted from the CNT by utilizing this phenomenon. The relationship between the current density J and local electric field F is described by the *Fowler-Noldheim* equation:

$$J = \frac{e^3 F_E^2}{8\pi h \phi} \exp\left(-\frac{8\pi \sqrt{2m_e}}{3heF_E} \phi^{\frac{3}{2}} \right) \tag{3}$$

Where e is the electron charge, h is Planck's constant, m_e is the electron mass, ϕ is the work function, and F_E is the electric field at emitter tip. When the emitter tip has paraboloidal surface, the electric field of the tip can be expressed as follows:

$$F_E = \beta E = \frac{2V}{r_{tip} \ln(4d / r_{tip})} \tag{4}$$

Where β is the field enhancement factor, E is potential difference between the electrodes, r_{tip} is the curvature radius of the emitter tip, d is electrode spacing, and V is voltage on the gate to emitter[3].

B. Space Charge limit

The FEC is quite an attractive emission device for an EDT system, but its maximum current (number of electrons) is limited by space charge effect at high emission current density levels. The maximum electron current density is determined by Child Langmuir law. The one-dimensional Child Langmuir law for current density J_{SCL} is given by equation (5)[4]

$$J_{SCL} = \frac{4\varepsilon_0}{9} \sqrt{\frac{2e}{m_e}} \frac{V_0^{3/2}}{d^2} \tag{5}$$

where ε_0 is the permittivity of free space, V_0 is voltage on the between electrodes, and d is the distance between the electrodes. The current density given by equation (5) is also called as the space charge limited current density.

IV. Potential Condition of an FEC in an EDT System

This section describes the electron potential condition of an FEC in an EDT system, as shown conceptually in Fig. 3.

As mentioned above, EMF occurs along the tether and the upper portion of the tether is at a positive potential while the lower portion of the tether is at a negative potential with respect to the potentials of the ambient plasma. If this negative potential is equal to the emitter potential of the FEC, electrons are emitted from the FEC to the space plasma by applying a positive voltage to the gate electrode. Most of the electrons from the FEC are emitted to the space plasma, while some electrons return to the gate electrode or the spacecraft by the space charge limited effect.

During the EDT operation, the electric potential of the FEC varies over time due to EMF fluctuations as the system travels in orbit around the earth because the plasma density and the geomagnetic filed strength change when the tether position at orbit changes. Figure 4 shows a sample simulation result of the emitter potential for a 700 m-long tether in the ISS orbit preparing for on-orbit demonstration. Orbital inclination angle in this case is 51.6 degrees. The Emitter potential varies from -10 to -60 V over time. For the operation of the FEC, it is important to know what proportion of the EMF can be used for biasing the FEC, in other words, what the negative electric potential of the FEC becomes with respect to the ambient plasma potential. This tether potential balance depends on the relationship between the electron collection ability of the conductive tether and the electron emission performance of the FEC[5].

In this study, the experiment was conducted at the emitter potential conditions simulating one rotation of the ISS-orbit. Smaller potential case was selected to consider worse case in the aspect of space charge effect.

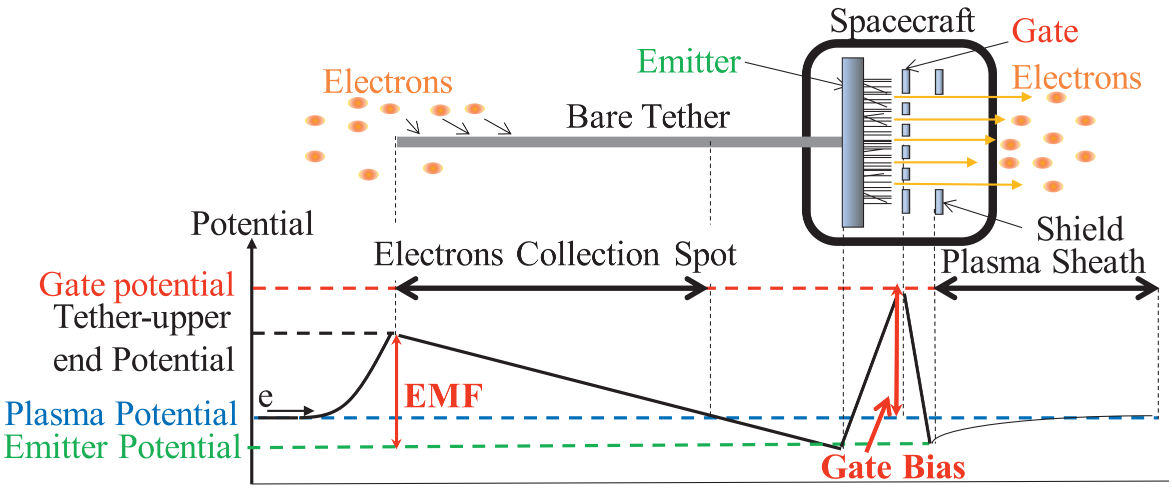

Figure 3. Potential condition of EDT system.

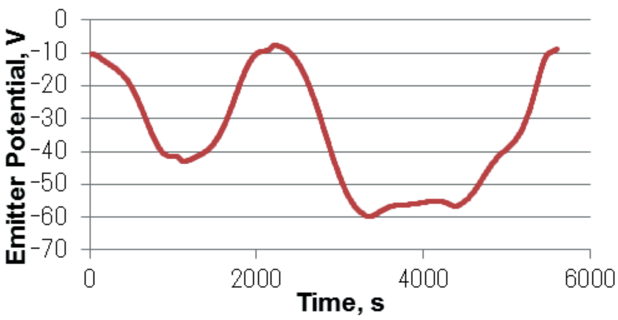

Figure 4. Sample simulation result of emitter potential for a 700-m-tether in ISS-orbit.

V. Experimental Setup

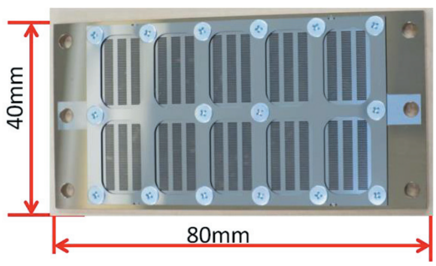

Figure 5. Appearance of the FEC.

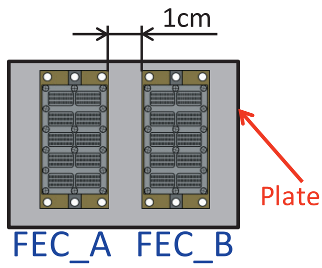

Figure 6. FECs on aluminum.

The FEC used in this study shown in Fig. 1 is composed of an emitter electrode with CNT coating, a gate electrode as extraction electrode, a mask electrode and a shield electrode. The Mask electrode attached to the emitter surface has the role to reduce the current flowing to the gate by bending the electron trajectories emitted from CNT. The shield electrode has a role to protect the emitter from ion sputtering and collisions of neutral particles. Photograph of the FEC used in the experiments is shown in Fig. 5. The FEC shown in Fig. 5 was assembled as the structure diagram shown in Fig. 1. Simultaneous operation experiments using two FECs were conducted by applying the positive voltage to the gate, while the emitter potential temporally varied. The FECs in two simultaneous operation experiments disposed on aluminum base plate so as to be adjacent (Fig. 6).

Circuit diagram for parallel FEC operation is shown in Fig. 7. In the single cathode operation, only on FEC (FEC_A) was operated using the same circuit. The anode potential was set to 0 V in order to simulate the plasma potential. The chamber pressure in experiments in the vacuum was 10^{-5}Pa order.

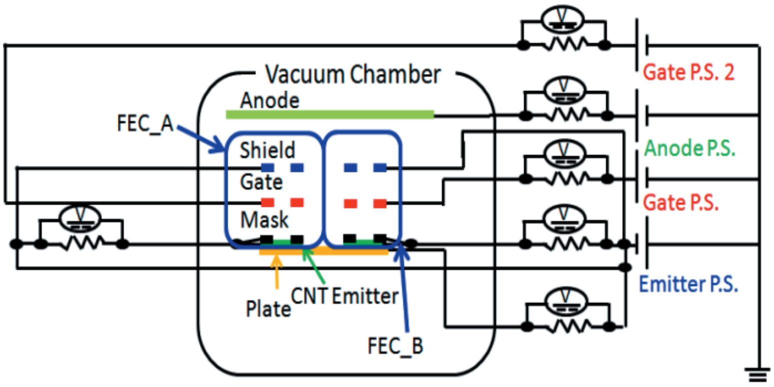

Figure 7. Circuit diagram for parallel FEC operation.

VI. Experimental Condition

This experiment was carried out at the condition expected in the EDT demonstration experiment planned in JAXA. Typical conditions are shown in Table 1.

Table 1. Expected condition of EDT experiment on HTV

Demonstration orbit	ISS orbit (altitude 350-440km)
Inclination	51.6°
Tether length	700m
Number of FEC unit	8
Maximum emission current per single FEC	2.2mA
Maximum power per single gate P.S.	0.5W（Maximum gate current 0.5mA）

The maximum electron current emitted from a single FEC is 2.2 mA, and the maximum current that can flow through the gate has became 0.5mA from specifications of the power supply used in experiments. Thus, the emission current and gate current per the single FEC should be controlled so that respectively below 2.2mA and 0.5mA. The EDT system is expected to release the maximum electrons from each of the eight FECs. Therefore, the control for minimizing the gate current and maximizing the electron emission from the FEC is needed. The emitter potential can not be controlled because it is allocated autonomously as indicated above. Inevitably the electron emission will be controlled by controlling the voltage applied to the gate electrode. Flow chart for realizing the electron emission control is shown in Fig. 8.

The time of 1 loop to update the current-voltage measurement is 1 s in the flow chart of Fig. 8. In this control, the gate voltage is lowered by 1 V / s until the emission or gate current becomes less than the limit value when the emission current exceeds 2.2mA or the gate current exceeds limit value. On the other hand, the gate voltage is raised by 1 V / s until the emission or gate current limit value when the emission is less than 2.2mA or the gate current becomes less than the limit value. If the emitter potential is close to the plasma potential, the electrons will not be able to reach the space plasma, and then, come back to the gate electrode. Therefore, unless the gate voltage is controlled appropriately, the gate current becomes excessive when the emitter potential and the plasma potential is close because the electron emitted from CNT flows to the gate electrode. The excessive gate current causes the power increase of EDT system and the thermal deformation of the gate electrode. Where the emission current is electron current emitted from CNT, the gate current is electron current flowing into the gate electrode, the electron current passed through the gate is the electron current minus the gate current from the

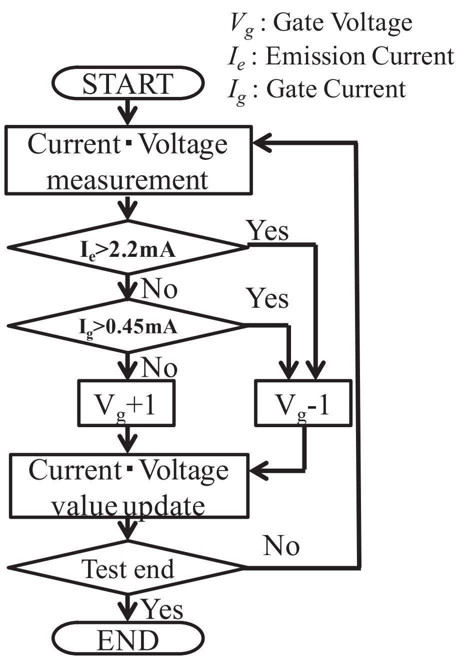

Figure 8. Flow chart of FEC control.

emission current. Therefore, this control method is expected to be optimal for maximizing the electron current passed through the gate as to emitter potential that varies with time.

In this study, the gate current upper limit of 0.45mA was configured because it consider deflection of the gate current by gate voltage fluctuation of 1 V / s. The upper limit value of the gate current in the demonstration experiment is 0.45mA. We performed the FEC of single operation and simultaneous operation for the purpose of evaluation of the validity of control and to obtain the electron emission performance. Extraction efficiency η is represented equation (6)

$$\eta = \left(1 - \frac{I_g}{I_e}\right) \times 100 \quad [\%] \tag{6}$$

where I_g is the gate current, I_e is the emission current.

VII. Experimental Results and Discussion

A. Effectiveness of electron emission control (single operation)

The experimental results obtained by the single operation of FEC_B under the conditions of the gate current limit 0.45 mA and time variation of the gate current is shown in Fig. 9 and 10, respectively. The time axes in both the figures correspond to the time axis of Fig. 4. From these figures, the gate current was maintained at about 0.45 mA throughout the experiment and, the gate voltage control for preventing an increase in the gate current was effective. The emission current was increased by the relaxation of the space charge limit effect when the emitter potential was deep enough (3000-4500 s). Figure 9 illustrates that the gate voltage was controlled so that the emission current does not exceed 2.2 mA. In addition, the gate voltage was controlled so that the emission current equal the gate current when the emitter potential was nearly equal to the earth potential because the electron could not go external to the FEC. Therefore, the control method was effective to obtain the maximum electron current passed through the gate and to suppress the gate current.

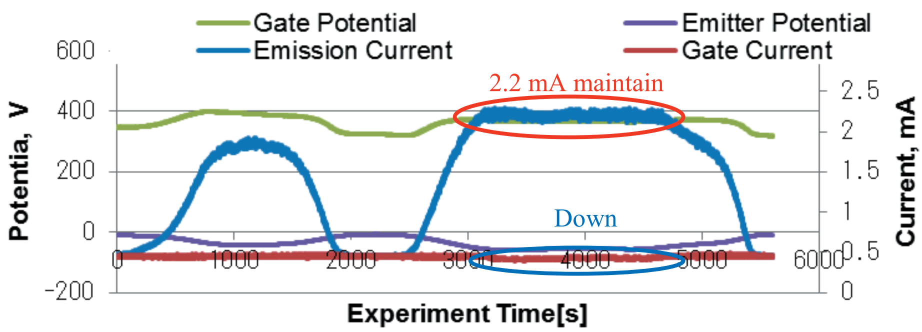

Figure 9. Currents and voltage variation in single FEC operation.

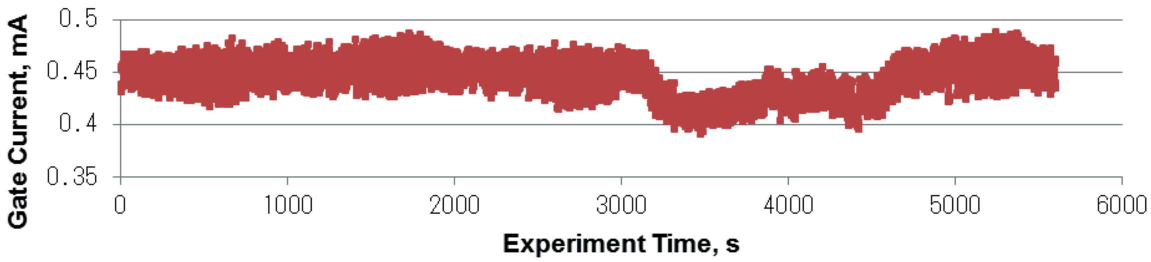

Figure 10. Gate current variation in single FEC operation.

B. Comparison of Single and Simultaneous Operation (In the case of Emitter-Anode Distance 17 cm)

The emission current and the gate voltage in the case of a single behavior of FECA and FEC B is shown in Fig. 11. Further, the extraction efficiency in the single operation and two simultaneous operation is shown in Fig. 12. As shown in Fig. 6, FEC_A and FEC_B are in close proximity.

Figure11 illustrates that the gate potential difference of FEC_A and FEC_B is about 150V. Figure 12 illustrates that the extraction efficiency in simultaneous operation was no significant degradation despite potential difference and distance between the FECs is respectively high and short.

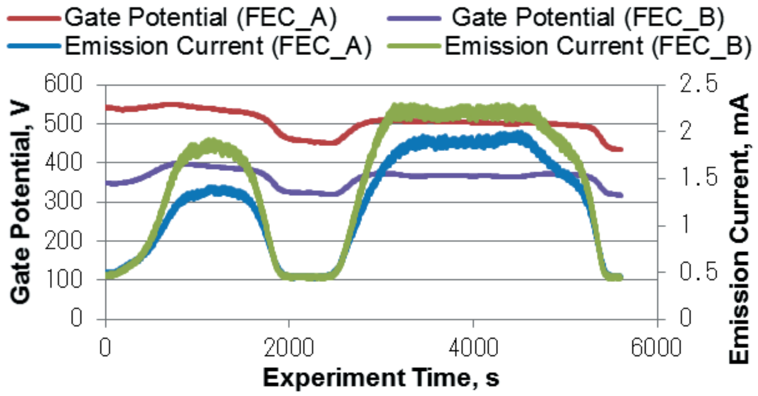

Figure 11. Gate voltage and emission current at the time of standalone operation (in the case of Emitter-Anode distance 17 cm).

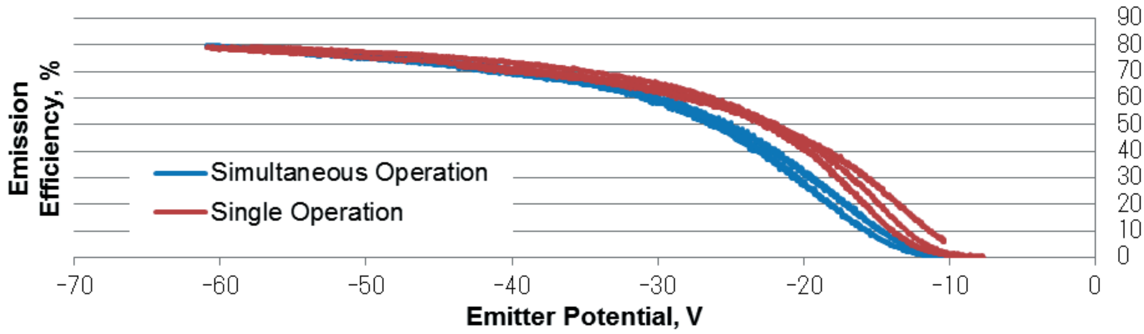

Figure 12. Average extraction efficiency in single operation and entirety extraction efficiency in simultaneous operation (in the case of Emitter-Anode distance 17 cm).

C. Comparison of Single and Simultaneous Operation (In the case of Emitter-Anode Distance 8 cm)

In the case of distance of 17 cm and 8 cm between the emitter and the anode, the extraction efficiency of the single and the simultaneous operations is shown in Fig. 13. Figure 13 illustrates that the extraction efficiency of the simultaneous operation in the case of distance of 8cm between the emitter and the anode was lower than that of the single operation.

In the case of short distance between the emitter and anode, as in results, the extraction efficiency was lower than long distance. However, According to above mentioned the space charge limited current, the shorter distance between the emitter and the anode is, the larger the space charge limited current is. We considered occasion of obtained the consequence adverse to theory.

The electron current of between the gate and the anode is dominated by the space charge limited current. In the case of a cathode has negative potential, the space charge limited current J_{GA} is expressed equation (7)[6]

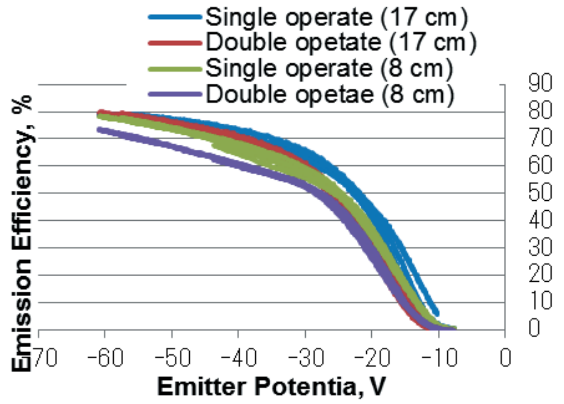

Figure 13. Average extraction efficiency in single operation and entirety extraction efficiency in simultaneous operation (in the case of Emitter-Anode distance 17 cm & 8 cm).

$$J_{GA} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m_e}}\frac{\left[V_e^{1/2} + (V_e + V_a)^{1/2}\right]^3}{d_{GA}^{\ 2}} \tag{7}$$

where V_e is the emitter potential, V_a is the anode potential, d_{GA} is the distance between the gate and the anode. Equation (7) illustrates that the shorter the distance between the gate and the anode is, the larger the space charge limited current is. In the case of the distance of 17 cm and 8 cm between the emitter and the anode, the space charge limited current and the anode current is shown in Figure 14. Further, the electron current passed through the gate is shown in Fig. 15.

Figure 14 illustrates that the space charge limited current and the anode current in the case of short distance between the emitter and anode was larger than that of in the case of long distance. On the other hand, figure 15 illustrates that the electron current passed through the gate in the case of long distance between the emitter and anode was larger than that of in the case of short distance. Where, the anode current is the current flowing through the anode electrode of the emitted electrons from the CNT. In the case of distance between the emitter and the anode is long, the emitted electrons from CNT fled toward the chamber wall from interspace between the emitter and the anode because the emitter potential had negative potential relative to the chamber wall by the chamber used the experiments was grounded. The longer distance between the emitter and the anode is, the more electrons back to the gate are reduced. Thus, the more the emission current is, the longer distance between the emitter and the anode is because the space charge limited effect is relaxed.

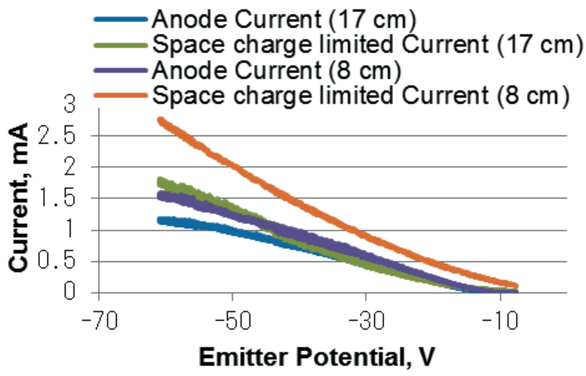

Figure 14. Anode current and space charge limited current of FEC_B single operation (in the case of Emitter-Anode distance 17 cm & 8 cm).

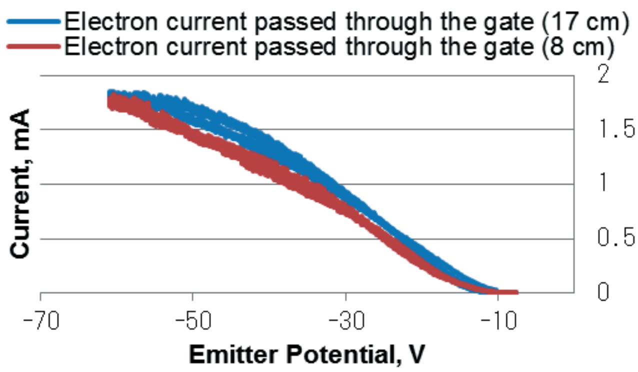

Figure 15. Electron current passed through the gate of FEC_B single operation (in the case of Emitter-Anode distance 17 cm & 8 cm).

Therefore, in the case of the distance between the emitter and the anode is close, and the potential difference and distance between the FECs is respectively high and close, the space charge limit effect of the simultaneous operation become more intense by the increasing electrons doing back and forth between the FECs. Further, in the case of the distance between the emitter and the anode is close, there is possibility that secondary electrons emitted from the anode electrode of the anode electrode neighborhood flow into the gate. We think that the extraction efficiency was increased in the case of the distance between the emitter and the anode because of each the point above.

D. Comparison of Single and Simultaneous Operation in Plasma Environment

The test of single and the simultaneous operations in plasma environment were conducted by using the argon plasma generated by using an ECR ion gun. The main parameters of plasma generated in these experiments and plasma parameters of on the ISS orbit are shown in Table 2. The experiments were conducted by removing the anode. Otherwise the same conditions as the experiment in the vacuum.

Table 2. Plasma parameter and experiment conditions

	This experiment	Demonstration experiment
Pressure of experiment environment, Pa	8.2×10^{-4}	10^{-9} order
Electron density, m^{-3}	7.1×10^{11}	Maximum 1×10^{-9}
Electron temperature, eV	9.8	0.1-0.2
Plasma potential, V	19	Reference potential (0V)

The extraction efficiency of the single and the simultaneous operations of FEC_A and FEC_B is shown in Fig. 16. The abscissa axis is the potential difference between the plasma and the emitter because of matching the test results of the experiments in vacuum.

Figure 16 illustrates that the extraction efficiency of the simultaneous operation in the region of the emitter potential 40-60 V was lower 5 % than that of single operation. The extraction efficiency of the simultaneous operation relative to the single operation was lowered more in the region of 0-40V. The larger absolute value of emitter potential is, the smaller the extraction efficiency is. This cause is explained by the thickness of the plasma sheath. The relationship between the thickness of the space plasma sheath s and the potential of the spacecraft V_s is described by equation (8) [7]

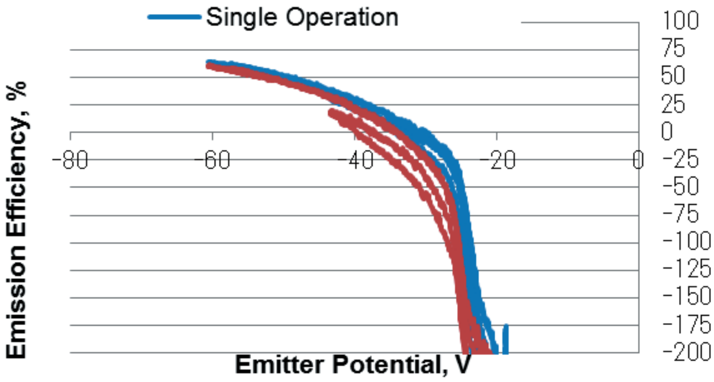

Figure 16. Average extraction efficiency in single operation and entirety extraction efficiency in simultaneous operation (in plasma).

$$s = \left(\frac{2\varepsilon_0 V_S}{en_0}\right)^{1/2} = \lambda_{DS}\left(\frac{2V_S}{T_e}\right)^{1/2} \quad (8)$$

where n_0 is the electron density, T_e is the electron temperature, and $\lambda_{DS}=(\varepsilon_0 T_e/en_0)^{1/2}$ is the electron Debye length at the sheath edge. The Vs in these experiments is the potential difference between the plasma and emitter.

The thickness of plasma sheath corresponds to the distance between the emitter and the anode in the experiments in vacuum. Thus, the larger absolute value of the emitter potential is, the thicker the thickness of the plasma sheath is. The electrons doing back and forth between the FECs were decreased because the electrons flowing through the chamber wall is increased. From the above, we think that the larger absolute value of emitter potential is, the smaller the extraction efficiency is.

The anode current and the electron current passed through the gate of in the plasma experiments is shown in Fig. 17. Figure 17 illustrates that electron current passed through the gate of in the plasma experiments was smaller than the anode current. We think the reason that the maximum emission current was not obtained because the gate current has reached in a short period of time to the 0.45 mA of upper limit value by the electrons in the plasma are attracted to the gate.

The emission current and the gate current variation of FEC_B of the single operation in the plasma is shown in Fig. 18. The emission current is controlled without significantly exceeding the upper limit value 2.2 mA. However, the gate current was detected current value of the maximum 0.49mA. This current value considerably exceeds the setting gate current upper limit value 0.45 mA. We think that control of the gate voltage of 1 Hz was unable to follow the increase in the gate current because influx of the electrons in the plasma and the emitted electrons from CNT were concurrently instantaneously increased. The control method of the FEC for electron emission in the plasma should be reviewed

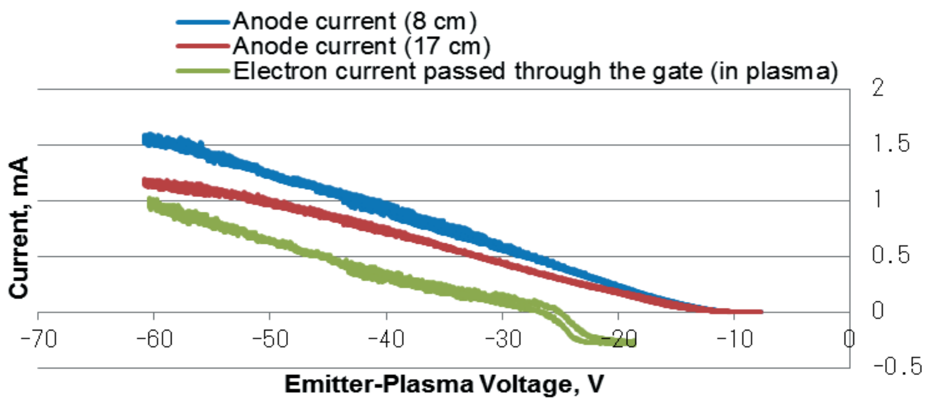

Figure 17. Anode current of FEC_B (in the case of emitter-anode distance 17 cm & 8 cm) and electron current passed through the gate in plasma (FEC_B single operation).

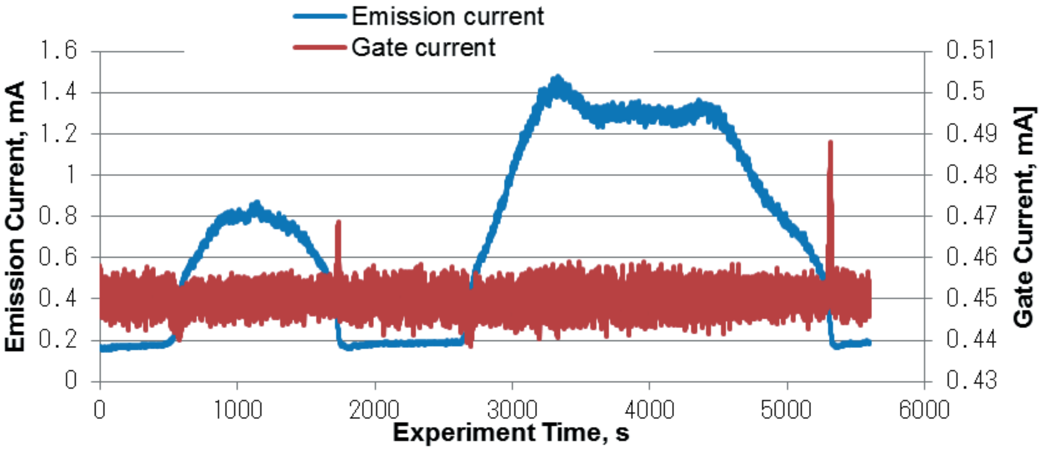

Figure 18. Emission current and gate current variation of FEC_B (in plasma).

VIII. Conclusion

In this study, the single and parallel operations of the FEC in the vacuum and the plasma environment simulated the emitter potential of the ISS orbit were conducted for estimating the performance of the FECs preparing for an on-orbit EDT demonstration.

As a result, we found the following control method of the FEC was effective for obtaining the maximum emission current and minimizing the gate current; the gate voltage is controlled in response to the change of emitter potential with configuring the upper limit of the emission and gate currents. The shorter the distance between the emitter and the anode is, the lower the emission current of each of FECs obtained by the simultaneous operation is. Therefore, the extraction efficiency of the simultaneous operation is lower than that of the single operation in the simple vacuum condition. This tendency was also observed in the FEC operations in the plasma environment and the extraction efficiency drop was larger than that in the operations in vacuum.

The electron current passed through the gate in plasma was lower than that in the vacuum because the positive potential of the gate attracts the electrons in the plasma to the gate electrode. Therefore, the gate current sometime exceeded its upper limit.

Acknowledgments

This work was supported by JAXA and Shizuoka University.

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