Parallel Operation of Field Emission Cathodes in Preparation for an On-Orbit Demonstration of an Electrodynamic Tether

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Research on a debris removal system that uses an electrodynamic tether (EDT) system has been conducted in JAXA. The EDT system requires an active electron emission device to drive a large electric current through the tether for obtaining adequate de-orbit thrust. A field emission cathode (FEC) is one good option for the electron emitter owing to its simplicity and potential performance. The FEC used in this study is comprised of an emitter electrode with a carbon nanotube (CNT) coating and a gate electrode as the extraction electrode. In these EDT systems, it is expected that several FEC units will operate in parallel to fulfill the redundancy requirement. Since interactions between cathode units may cause instability or performance degradation, parallel operation experiments must be performed on the FECs prior to practical on-orbit operation. We conducted experiments on FEC parallel and single operations in both vacuum and plasma environments. Consequently, we found that the following control method for the FEC is effective for obtaining a maximum emission current and minimizing the gate current; the gate voltage is controlled in response to the change in the emitter potential by configuring the upper limit of the emission and gate currents. However, the emission currents during parallel operations of the FECs were still lower than those during operations of single FECs. The electron current passing through the gate in the plasma environment was found to be lower than that in the vacuum as the positive potential of the gate attracts electrons from the plasma.

Key Words: Field Emission Cathode, Carbon Nanotube, Propulsion, Active Debris Removal

Nomenclature

- $B$: Earth’s magnetic field
- $d$: electrode spacing
- $d_{g,a}$: distance between the gate and the anode
- $e$: electron charge
- $E$: electric field between the electrodes
- $F_T$: electric field at the tip
- $F_L$: Lorentz force
- $h$: Plank’s constant
- $I_e$: emission current
- $I_g$: gate current
- $I_{tether}$: current flowing through the tether
- $J$: current density
- $J_{SC}$: space charge limited current density (negative cathode potential)
- $J_{1D}$: one-dimensional Child Langmuir law current density
- $L_{tether}$: tether length
- $m_e$: electron mass
- $n_e$: electron density
- $r_{tip}$: curvature radius of the emitter tip
- $s$: thickness of plasma sheath
- $T_e$: electron temperature
- $v_{orb}$: orbital velocity
- $V$: voltage on the gate to emitter
- $V_a$: potential difference between electrodes
- $V_a$: anode voltage
- $V_e$: emitter voltage
- $V_g$: gate voltage
- $V_{emf}$: electromotive force
- $V_p$: potential difference between the plasma and emitter
- $\beta$: field enhancement factor
- $\varepsilon_0$: permittivity of free space
- $\phi$: work function
- $\eta$: extraction efficiency
- $\lambda_{De}$: electron Debye length at the sheath edge

1. Introduction

Research on a debris removal system that uses an electrodynamic tether (EDT) system has been conducted in JAXA. The EDT system is propelled by interactions between the electric current passing through the tether and the geomagnetic field. To generate the tether current, creating a closed electrical circuit is necessary in the 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 an electron emission device in this setup because of its structural simplicity and low electric power consumption without working gas and/or a heater. We selected carbon...
nanotubes (CNTs) as the emission material because they possess very small tip diameters, a moderate work function (approximately 5 eV), high mechanical strength, chemical stability, and high electrical conductivity.\(^1\)

When using the EDT system for debris removal, multiple FEC devices should be operated by multiple power sources to maintain redundancy. It is also desirable to maximize the total electron emission from all of the FECs used. However, the electron emission performance values of FECs have large individual differences because the FECs are susceptible to variations in a CNT arrangement and electrode misalignment during assembly. This means that the required extraction voltages for obtaining a certain level of emission current are different for each unit. Therefore, electrons emitted from an FEC could be drawn to another FEC with a higher electron voltage. Figure 1 illustrates a conceptual diagram of this electron flow during the simultaneous operation of two FECs.

This study describes operational characteristics and control methods for such FECs based on results from the simultaneous operation of two FEC units.

### 2. Electrodynamic Tether System

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

\[
V_{\text{emf}} = (v_{\text{orbit}} \times B) \cdot \text{Lether}
\]  

(1)

where \(L_{\text{ether}}\) is the tether length, \(v_{\text{orbit}}\) is the orbital velocity, and \(B\) is the Earth's magnetic field at the orbital altitude.

### 2.1. Field emission cathode

When using the EDT system for debris removal, multiple FECs should be operated by multiple power sources to maintain redundancy. It is also desirable to maximize the total electron emission from all of the FECs used. However, the electron emission performance values of FECs have large individual differences because the FECs are susceptible to variations in a CNT arrangement and electrode misalignment during assembly. This means that the required extraction voltages for obtaining a certain level of emission current are different for each unit. Therefore, electrons emitted from an FEC could be drawn to another FEC with a higher electron voltage. Figure 1 illustrates a conceptual diagram of this electron flow during the simultaneous operation of two FECs.

This study describes operational characteristics and control methods for such FECs based on results from the simultaneous operation of two FEC units.

### 2.2. Space charge limit

The FEC is a rather attractive emission device for use in an EDT system, but its maximum current (number of electrons) is limited by the space charge effect at high emission current density levels. The maximum electron current density is determined by the Child-Langmuir law. The one-dimensional Child-Langmuir law for a current density \(J_{\text{SCL}}\) is given by Eq. (5):\(^4\)

\[
J_{\text{SCL}} = \frac{4e_0}{9} \sqrt{\frac{3e}{m_e}} \frac{V_0^{3/2}}{d^2}
\]

(5)

where \(e_0\) is the permittivity of free space, \(V_0\) is the voltage between the electrodes, and \(d\) is the distance between the...
electrodes. The current density given by Eq. (5) is also called the space charge limited current density.

2.3. Potential condition of an FEC in an EDT system

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

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

During the EDT operation, the electric potential of the FEC varies over time owing to EMF fluctuations as the system travels in an orbit around the Earth because the plasma density and the geomagnetic field strength change when the tether position in the 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. The orbital inclination angle in this case is 51.6°. The emitter potential varies from $-10$ to $-60$ V over time. For operating 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 emitter potential conditions simulating one rotation of the ISS orbit. A smaller potential case was used to consider the worst case scenario in terms of the space charge effect.

3. Experimental Setup

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

A circuit diagram for parallel FEC operation is shown in Fig. 7. In the case of single cathode operation, only one FEC (FEC_A) was operated using the same circuit. The anode potential was set to the ground potential. In this case, the ground potential simulates the space plasma potential on orbit and the emitter potential was controlled with reference to the ground potential as shown in Fig. 4. The chamber pressure of the vacuum was of the order of $10^{-5}$ Pa.

The tests for single and the simultaneous operation in the plasma environment were conducted using the argon plasma generated using an ECR ion source. The main parameters of the plasma generated in these experiments and the plasma parameters of the ISS orbit are shown in Table 1. The experiments were conducted by removing the anode. Otherwise, the conditions were the same as for the experiments in vacuum. Although low-Earth orbit (LEO) plasma mainly consists of oxygen, nitrogen, and argon, to use argon plasma is acceptable because the electron flow dominates the electric potential conditions of spacecraft, and ion species have negligible effects. On the other hand, the selection of ion species is important when the degradation of CNT is discussed.6)
3.1. Experimental conditions

This experiment was conducted at the conditions expected for the EDT demonstration experiment planned in JAXA. The typical conditions are shown in Table 2.

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

The time taken for 1 loop to update the current-voltage measurement is 1 s in the flow chart of Fig. 8. Under our controls, 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 2.2 mA or the gate current exceeds the limit value. In contrast, the gate voltage is raised by 1 V/s until it reaches the emission or gate current limit value when the emission is less than 2.2 mA or the gate current is 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 will then come back to the gate electrode. Therefore, unless the gate voltage is appropriately controlled, the gate current becomes excessive when the emitter potential and the plasma potential are close because the electrons emitted from the CNTs flow to the gate electrode. The excessive gate current causes a power increase in the EDT system and thermal deformation of the gate electrode.

The emission current is the electron current emitted from CNT; the gate current is the electron current flowing into the gate electrode; and the electron current passed through the gate is the difference of the electron current and the gate current from the emission current. Therefore, this control method is expected to be optimal for maximizing the electron current passed through the gate for an emitter potential that varies with time.

In this study, the gate current upper limit of 0.45 mA was decided upon by considering deflection of the gate current by a gate voltage fluctuation of 1 V/s. The upper limit value of the gate current in the demonstration experiment was 0.45 mA. We performed single operation and simultaneous operation experiments on the FECs for evaluating the validity of the controls and obtaining the electron emission performance. The extraction efficiency $\eta$ is represented by Eq. (6):

$$\eta = \left(1 - \frac{I_g}{I_e}\right)$$  \hspace{1cm} (6)

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

Table 2: The expected conditions for the EDT experiment on the HTV.

<table>
<thead>
<tr>
<th>Demonstration orbit</th>
<th>20 km (or more) below ISS orbit (altitude 300–400 km)</th>
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</thead>
<tbody>
<tr>
<td>Inclination</td>
<td>51.6°</td>
</tr>
<tr>
<td>Tether length</td>
<td>700 m</td>
</tr>
<tr>
<td>Number of FEC unit</td>
<td>8</td>
</tr>
<tr>
<td>Maximum emission current per single FEC</td>
<td>2.2 mA</td>
</tr>
<tr>
<td>Maximum power per single gate P.S.</td>
<td>0.5 W (Maximum gate current 0.5 mA)</td>
</tr>
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</table>

Fig. 8: A flow chart of the FEC control method.
4. Experimental Results and Discussion

4.1. Effectiveness of electron emission control (single operation)

The experimental results obtained for the single operation of FEC_B with the gate current limited to 0.45 mA and time variation of the gate current is shown in Figs. 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 approximately 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 through 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 did not exceed 2.2 mA. In addition, the gate voltage was controlled so that the emission current was equal to the gate current when the emitter potential was nearly equal to Earth’s potential, because the electrons could not go to the FEC externally. Therefore, the control method was effective for obtaining the maximum electron current passing through the gate and in suppressing the gate current.

For distances of 17 cm and 8 cm between the emitter and the anode, the extraction efficiency of the single and simultaneous operations is shown in Fig. 13. The results of the single operation indicate the average of FEC_A and FEC_B. The results possess multiple lines due to hysteresis. This figure illustrates that the extraction efficiency for the simultaneous operation in the case of a distance of 8 cm between the emitter and the anode was lower than that for the single operation.

In the case of a short distance between the emitter and the anode, as in these results, the extraction efficiency was lower than for a long distance. However, according to the above-mentioned space charge limiting of the current, the shorter the distance between the emitter and the anode, the larger the space charge limited current should be. We considered possible causes of this discrepancy between experiment and theory.

The electron current between the gate and the anode is dominated by the space charge limited current. In the case that a cathode has negative potential, the space charge limited current $J_{\text{GA}}$ is expressed by Eq. (7):8)
\[
J_{GA} = \frac{4e_0 \sqrt{\frac{\mu_e V_e}{m_e}} \left( V_e + V_a \right)^{1/2}}{d_{GA}^2}
\]

(7)

where \( V_e \) is the emitter potential, \( V_a \) is the anode potential and \( d_{GA} \) is the distance between the gate and the anode. Eq. (7) illustrates that the shorter the distance between the gate and the anode, the larger the space charge limited current. In the case of distances of 17 cm and 8 cm between the emitter and the anode, the space charge limited current and the anode current are shown in Fig. 14. Furthermore, the electron current passed through the gate is shown in Fig. 15. The results possess multiple lines due to hysteresis.

Figure 14 illustrates that the space charge limited current and the anode current in the case of a short distance between the emitter and anode was larger than that in the case of a large distance. In contrast, Fig. 15 illustrates that the electron current passed through the gate in the case of a large distance between the emitter and anode was larger than that in the case of a short distance. Here, the anode current is the current of emitted electrons from the CNTs flowing through the anode electrode. In the case when the distance between the emitter and the anode is large, the emitted electrons from the CNTs fled toward the chamber wall from the interspace between the emitter and the anode because the emitter had a negative potential relative to the chamber wall having the ground potential the chamber used in the experiments was grounded. The longer the distance between the emitter and the anode, the more the number of electrons going back to the gate is reduced. Thus, the higher the emission current, the longer the distance between the emitter and the anode, because the space charge limiting effect is relaxed.

Therefore, in the case of a smaller distance between the emitter and the anode, and a high potential difference and short distance between the FECs, the space charge limiting effect in simultaneous operation becomes more intense due to the increase in the number of electrons going back and forth between the FECs. Furthermore, in the case when the distance between the emitter and the anode is short, there is a possibility of secondary electrons emitted from the anode electrode neighborhood flowing into the gate. We think that the extraction efficiency was increased in the case of a larger distance between the emitter and the anode because of the points above.

As explained above, this result contradicts the simple Child-Langmuir law. The reason for this contradiction seems to be that when the distance between the emitter and the anode is larger, the emitter can view larger chamber-wall area, and the electrons from the emitter easily flow to the chamber wall. This situation relaxed the space charge limitation.

Since the FEC operations in the plasma environment incur the increase in cost and the experiment time, it is desirable to simulate the plasma environment using an anode plate. Moreover, deterioration of CNT by the artificial plasma environment should be avoided for long-term operation tests.

4.3. Comparison of single and simultaneous operation in plasma environment

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

Figure 16 illustrates that the extraction efficiency for simultaneous operation in the region of the emitter potential 40–60 V was lower by 5% than that for single operation. The extraction efficiency for the simultaneous operation relative to the single operation was lowered further in the region of 0–40 V. The larger the absolute value of the emitter potential, the smaller the extraction efficiency. This 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 Eq. (8): 

\[
S = \left( \frac{2eV_s}{n_0} \right)^{1/2} = \lambda DS \left( \frac{V_s}{T_e} \right)^{1/2}
\]  

(8)

where \( n_0 \) is the electron density, \( T_e \) is the electron temperature, and \( \lambda DS = (e \epsilon_0 T_e/n_0)^{1/2} \) is the electron Debye length at the sheath edge. The \( V_s \) in these experiments is the potential difference between the plasma and emitter.

The thickness of the plasma sheath corresponds to the distance between the emitter and the anode in the experiments in vacuum. Thus, the larger the absolute value of the emitter potential, the larger the thickness of the plasma sheath. The number of electrons going back and forth between the FECs was decreased because the number of electrons flowing through the chamber wall was increased. Therefore, the larger the absolute value of the emitter potential, the smaller the extraction efficiency. The results of the experiments in vacuum differ from those in the plasma, where plasma electrons exist. The reason for this difference is derived from the influence of the leak current to the chamber wall as discussed in section 4.2. In order to avoid this contradiction, improvements in the test environment such as the reconsidering of the anode shape and covering the chamber wall by insulation films as a future work.

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

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

5. Conclusion

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

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

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

References


