Ground-Based Experiment of Current Collection to Bare Tether in High-Speed Magnetized Plasma

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Abstract: Bare-tether systems are one of the greatest-efficiency electrodynamic tethered systems. The system with an uninsulated portion of the metallic tether itself to collect electrons from the space plasma is operated as a thruster or a power generator on a satellite. Ground-based experiments were carried out to understand phenomena of electron collection by a bare tether in space. Metallic tether samples were exposed to a simulating Low-Earth-Orbit plasma flow as varying tether sample diameter and length, and plasma velocity. A magnetic field was also applied. The normalized collection current increased with normalized tether sample potential. The tether sample diameter did not influence the normalized collection current characteristics although an increase in tether sample length decreased the normalized collection current in this experiment. The collection current characteristics were independent of plasma velocity under meso-thermal conditions. The existence of magnetic field raised the collection current because of the three-dimensional current collection effect at the edge of a tether sample under the magnetic field. Although the existence of magnetic field may raise the collection current, the effect will be small with a long tether. Accordingly, the dependence of tether diameter and length, plasma velocity and magnetic field on collection current characteristics of a bare tether in space might be small. The collection current may not exceed the OML current.

I. Introduction

Bare-tether systems are one of the greatest-efficiency electrodynamic tethered systems.[1-3] The system with an uninsulated portion of the metallic tether itself to collect electrons from the space plasma is operated as a thruster or a power generator on a satellite.[4-7] Bare-tether systems have advantages of simple structure, low cost and constant current against changing space plasma density. In a bare tether, the highest current density on the surface of the uninsulated portion of the metallic tether, i.e. on a raw metallic wire, is considered to be achieved under the orbital-motion-limited (OML) condition.[8] The OML current density is the highest current density on an electrically-positive electrode located in a steady-state, uniform and non-flowing plasma. The theoretical two-dimensional OML current is given as follows.

$$I_{OML} = eN_eA \times \frac{\sqrt{2}}{\pi} \times \sqrt{\frac{eV}{m_e}} \quad (1)$$

where I_{OML} is orbital-motion-limited (OML) current, e and m_e electron charge and mass, respectively, N_e plasma number density, A surface area of electrode, and V electrode potential. The OML condition is expected to be established with a smaller radius of a metallic wire than the Debye length of the space plasma. However, the OML

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condition may be modified in the magnetized space plasma relatively moving on a bare tether.[9] We need to understand phenomena of electron collection by a bare tether in space and to predict collected electron current.

In this study, ground-based experiments on a bare tether were carried out. Metallic tether samples were exposed to simulating space plasma flow as varying tether sample diameter and length, and plasma velocity with a magnetic field. The current flowing from plasma flow to a tether sample was measured with varying biased voltage to a tether sample.

II. Experimental Apparatus

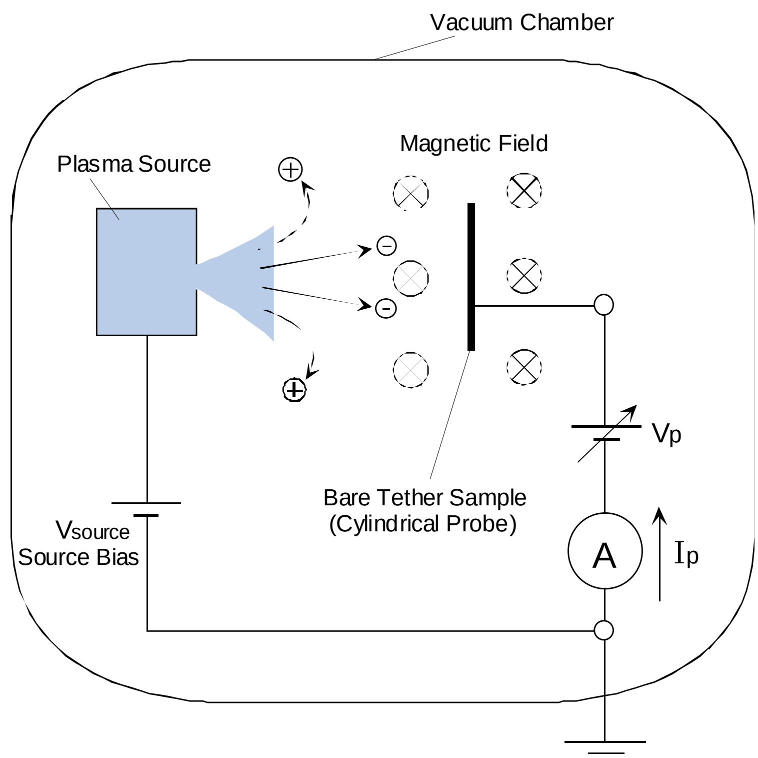
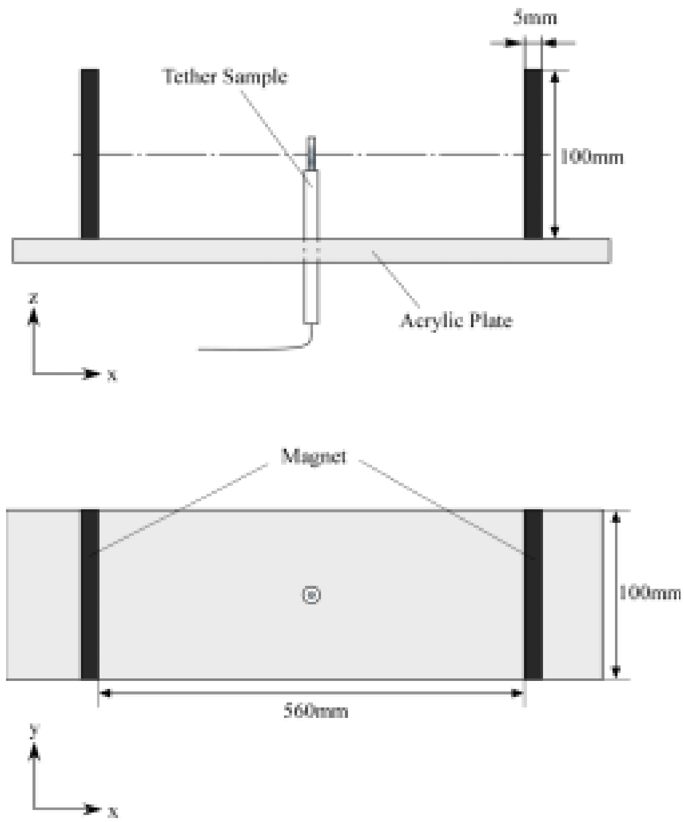


Figure 1. Ground-based experimental system of spacecraft bare tether.

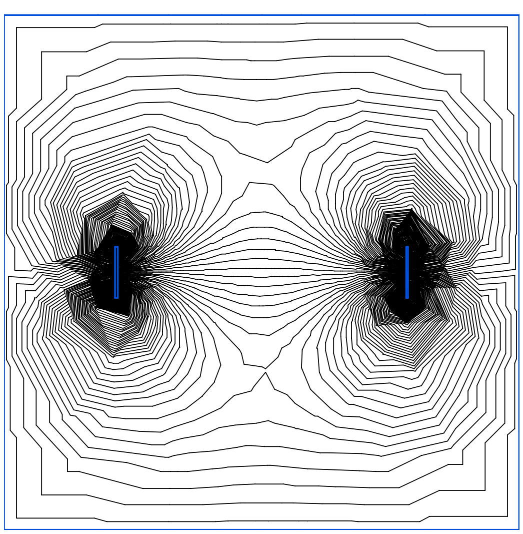
Figure 1 shows the experimental facility of a bare tether for this study. The experimental system mainly consists of a tether sample, a plasma source and permanent magnets. The tether sample is made of straight tungsten wire. The tether sample is installed perpendicular to plasma flow and magnetic field produced by the plasma source and the permanent magnets, respectively. The plasma flow is also perpendicular to the magnetic field. The plasma source is a type of cylindrical Hall accelerator, and it produces plasma flow simulating the Low-Earth-Orbit (LEO) plasma relatively moving on the bare tether. Xenon is used as the working gas. The plasma source is settled in a vacuum chamber 1.2 m in diameter x 2.25 m long, which is evacuated with turbo-molecular pumps. The vacuum chamber pressure is kept at 10^{-2}-10^{-3} Pa under experiments.

Figure 2 shows the arrangement of the Ferrite permanent magnets, and the magnetic field strength and shape. The magnetic field strength at the position of a tether sample is 1.8 mTesla, with which the magnetic field in the simulating plasma corresponds to that in the LEO plasma. The distribution of the magnetic field is very flat. A biased voltage, i.e., a positive voltage to a tether sample on the potential of the vacuum chamber, is applied, and then the tether sample collects electrons from the plasma flow.

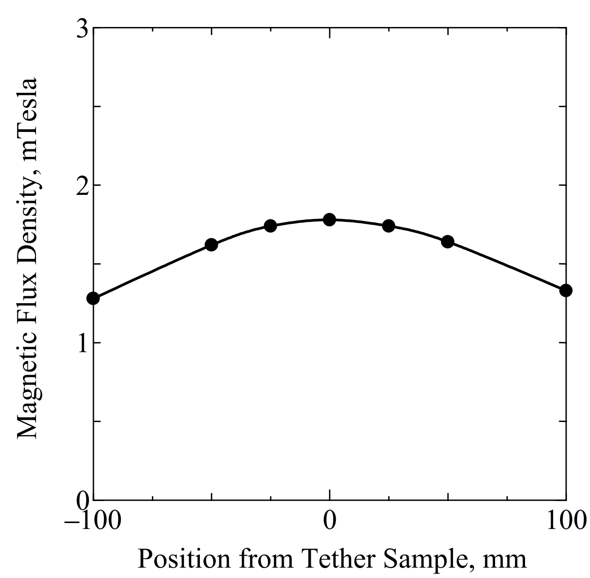
The cylindrical Hall accelerator named TCHT-3, as shown in Fig.3, is operated with a xenon mass flow rate of 0.3 mg/s. The plasma flow velocity, which is evaluated by the thrust measured, can be changed with the discharge



(a) Arrangement of Ferrite permanent magnets.

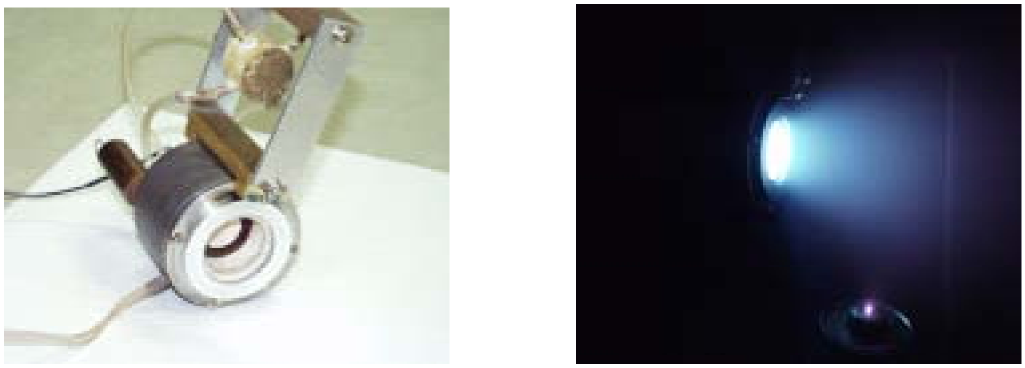


(b) Magnetic field lines.



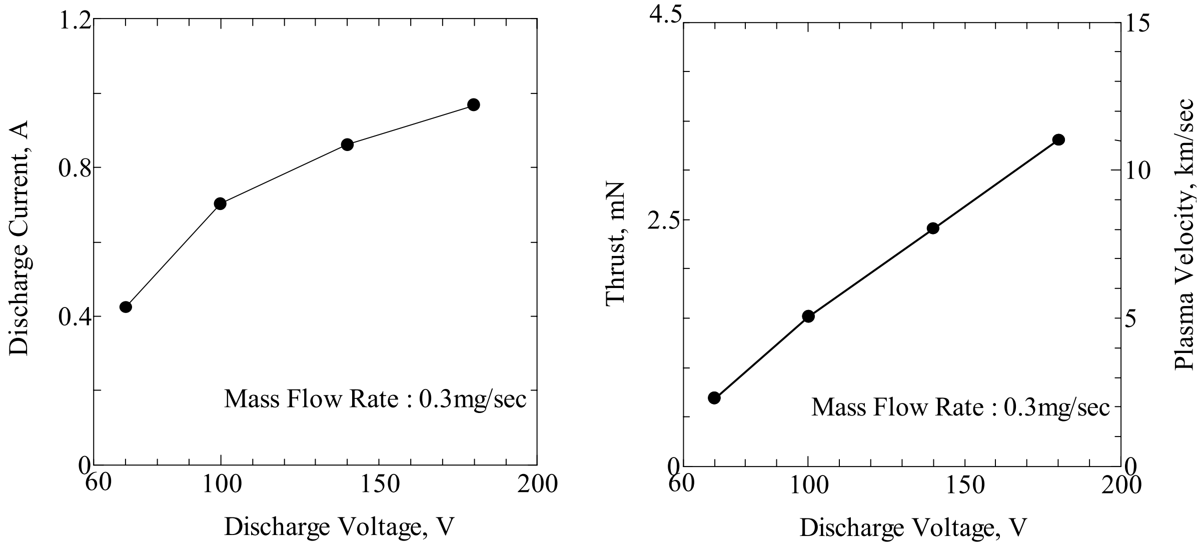
(c) Distribution of magnetic flux density.

Figure 2. Arrangement of magnets, and magnetic field strength and profile applied to tether sample. The magnetic field strength was measured with a Hall sensor.



(a) THHT-3 Hall accelerator. (b) Feature of plasma plume.

Figure 3. Configuration of Hall plasma accelerator for bare-tether ground-based experiments.



(a) Discharge current. **(b) Thrust and plasma velocity.**

Figure 4. Operational characteristics of Hall plasma accelerator.

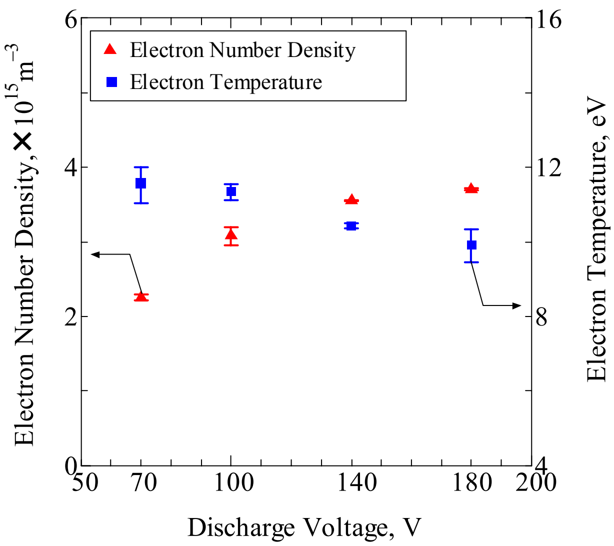
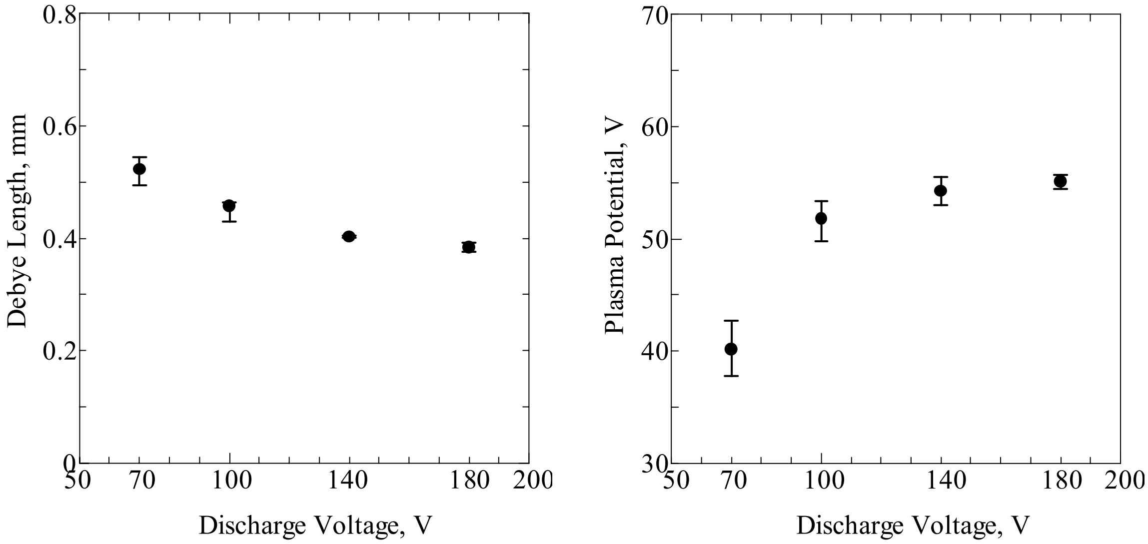


Figure 5. Plasma parameters of plasma flow at tether sample location.



(a) Debye length. **(b) plasma potential.**

Figure 6. Debye length and plasma potential of plasma flow at tether sample location.

Table 1. Experimental conditions.

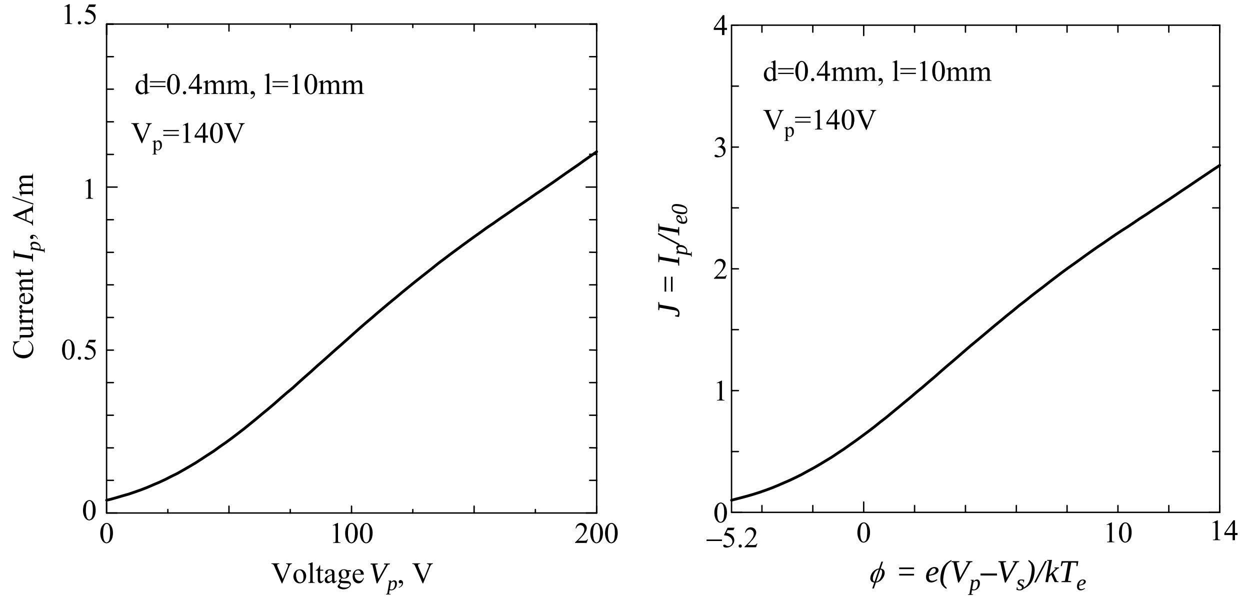
Tether Sample Material	**Tungsten**
Discharge Voltage, V	**70, 100, 140, 180**
Tether Sample Diameter, mm	**0.2, 0.4, 1.6**
Tether Sample Length, mm	**5, 10, 25**
Thruster-Tether Sample Distance, mm	**300**

voltage. Figure 4 shows the operational characteristics of the Hall accelerator. The discharge current increases with increasing discharge voltage, and the thrust also increases linearly; the evaluated plasma velocity increases from 2 to 11 km/s. The plasma parameters of plasma potential, electron number density, electron temperature at 300 mm from the exit of the Hall accelerator, i.e., at the axial position of the tether sample, are measured with a Langmuir probe. As shown in Figs. 5 and 6, both the electron density and the plasma potential increase with increasing discharge voltage although the electron temperature decreases. The estimated Debye length gradually decreases from 0.5 to 0.4 mm.

The experimental conditions are summarized in Table 1.

III. Experimental Results and Discussion

In this experiment, the current flowing from plasma flow to a tether sample is measured with varying biased



(a) Raw current vs voltage. **(b) Normalized current vs voltage.**

Figure 7. Typical collection current vs biased voltage characteristics.

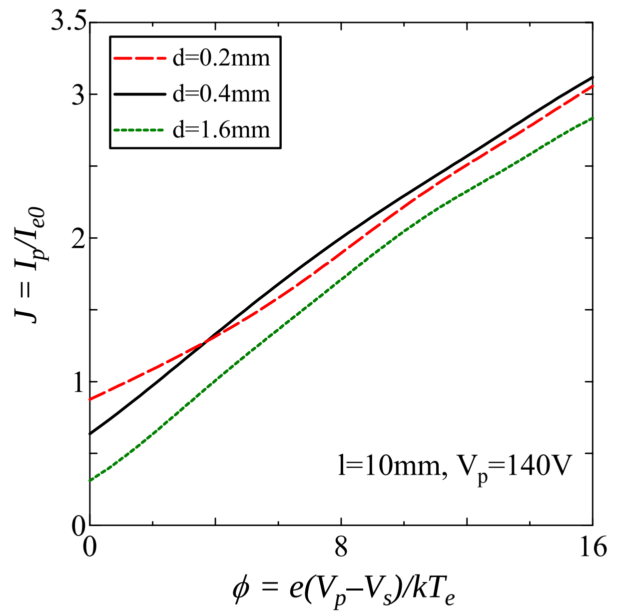


Figure 8. Normalized collection current vs normalized plasma potential characteristics dependent on tether sample diameter with tether sample length of 10 mm at accelerator discharge voltage of 140 V.

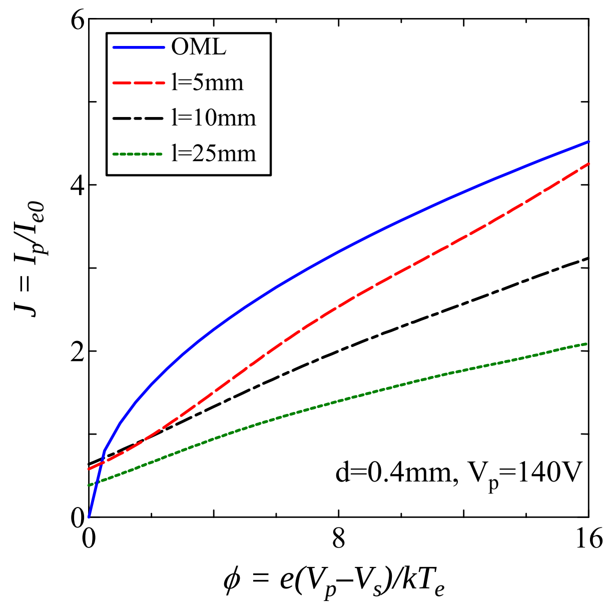


Figure 9. Normalized collection current vs normalized plasma potential characteristics dependent on tether sample length with tether sample diameter of 0.4 mm at accelerator discharge voltage of 140 V.

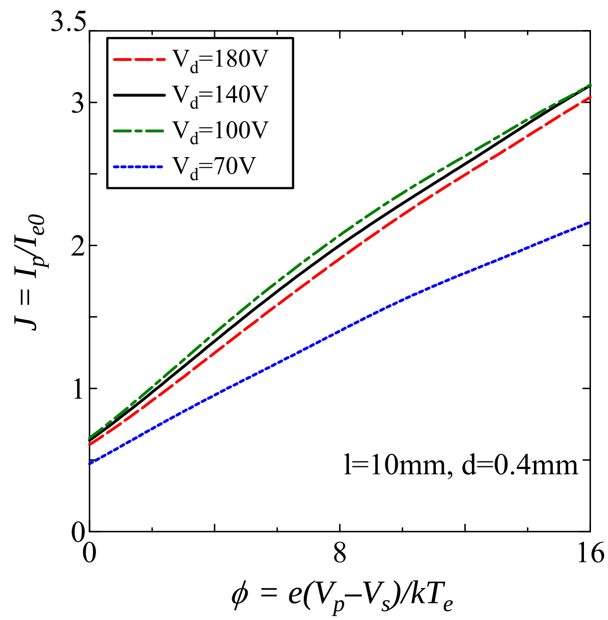


Figure 10. Normalized collection current vs Normalized plasma potential characteristics dependent on accelerator discharge voltage with tether sample length and diameter of 10 mm and 0.4 mm, respectively.

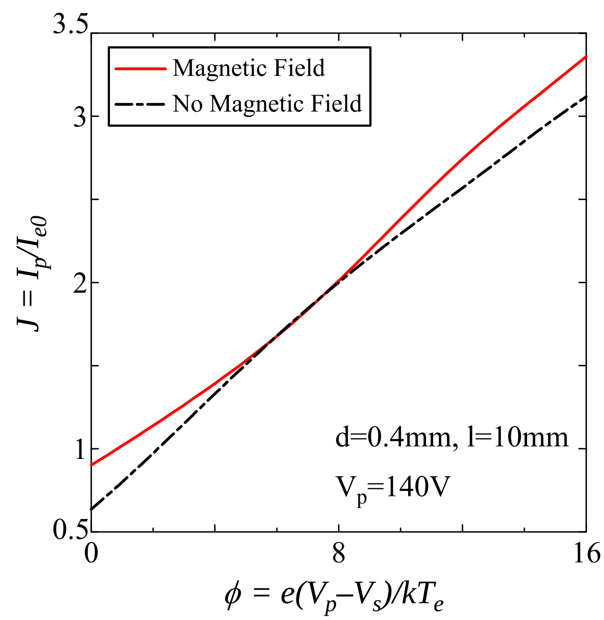


Figure 11. Normalized collection current vs normalized plasma potential characteristics under magnetic field with tether sample length and diameter of 10 mm and 0.4 mm, respectively, at accelerator discharge voltage of 140 V.

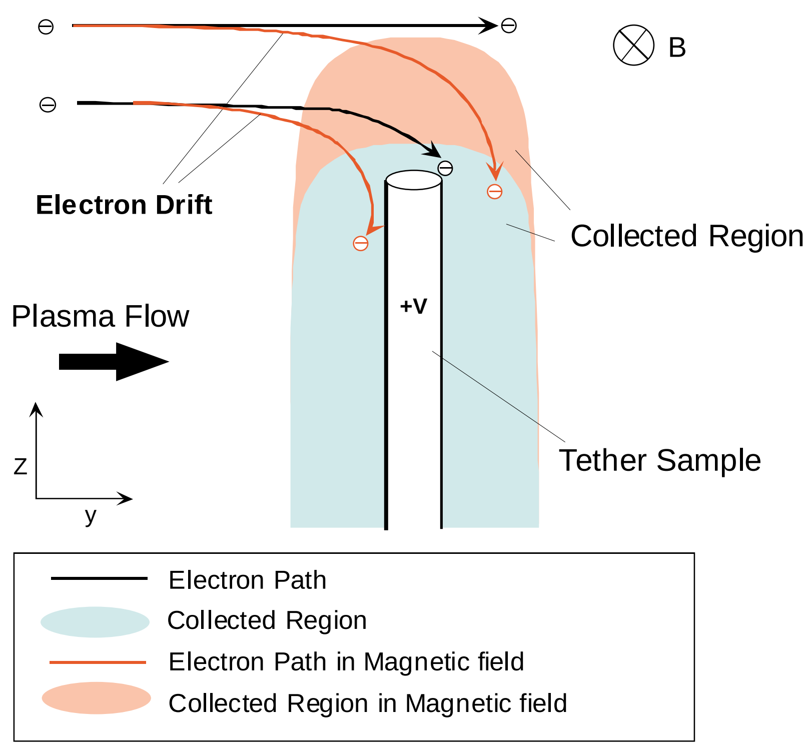


Figure 12. Feature of current collection under magnetic field near edge of tether sample.

voltage to a tether sample. The potential of a tether sample on the plasma potential is normalized with voltage corresponding to electron temperature, and the measured collection current with thermal diffusion current as follows:

$$\phi = \frac{e\left(V_p - V_s\right)}{kT_e}, \quad J = \frac{I_p}{J_{th}}, \quad J_{th} = eN_e v_{th} A_p \tag{2}$$

where Φ is normalized tether sample potential, J normalized collection current, J_p measured collection current, J_{th} thermal diffusion current, e electron charge, V_p biased voltage, V_s plasma potential, k Boltzmann constant, T_e electron temperature, N_e plasma number density, v_{th} electron thermal velocity and A_p surface area of tether sample. The plasma parameters shown in Figs. 5 and 6 are used for normalization. Typical current vs voltage characteristics are shown in Fig.7. The normalized current gradually increases with the normalized potential.

A. Effects of Tether Sample Diameter and Length

Figures 8 and 9 show the normalized collection current vs normalized tether sample potential characteristics dependent on tether sample diameter and length, respectively, with a discharge voltage of the Hall accelerator of 140 V, i.e., at a constant plasma velocity of about 8 km/s without magnetic fields. In general, the normalized collection current increases with normalized tether sample potential. The current with a 0.2-mm-diameter tether sample, as shown in Fig.8, almost equals to that with a 0.4-mm-diameter tether sample at high potentials although the current with a diameter of 1.6 mm is smaller than those. Accordingly, the normalized collection current characteristics with a small diameter are independent of tether sample diameter. This is considered because the Debye length is larger than the tether sample diameter; that is, the OML condition is established. With a large diameter of 1.6 mm, the OML condition is not established. In tether sample length, the normalized collection current decreases with increasing tether sample length at a constant tether sample potential. The current with a length of 5 mm approaches the OML current with increasing sample potential. However, this is considered because of the three-dimensional current collection effect at the edge of the tether sample. As a result, too short tether sample is not acceptable for this experiment.

B. Effects of Plasma Velocity and Magnetic Field

Figure 10 shows the normalized collection current vs normalized tether sample potential characteristics dependent on plasma velocity, corresponding to the discharge voltage shown in Fig.4(b), at tether sample diameter and length of 0.4 and 10 mm, respectively, without magnetic fields. The normalized collection current is almost independent of plasma velocity at a constant tether sample potential without the smallest plasma velocity at a discharge voltage of 70 V. Because the plasma flow velocity is smaller than the ion sonic velocity at a discharge voltage of 70 V; i.e., the ion subsonic flow condition is established; the meso-thermal condition is broken, it may cause decrease in collection current.

When the magnetic field is applied perpendicular to a tether sample, the normalized collection current, as shown in Fig.11, increases at a constant tether sample potential. As shown in Fig.12, this is also considered due to the three-dimensional current collection effect at the edge of the tether sample under the magnetic field; that is, because electrons drifting far from the edge of a tether sample are pulled into the collected region near the tether sample by rotating motion with a large Larmor radius.[10] Accordingly, although the existence of magnetic field may raise the collection current, the effect will be small with a long tether.

IV. Conclusions

Ground-based experiments were carried out to understand phenomena of electron collection by a bare tether in space. Metallic tether samples were exposed to the simulating LEO plasma flow as varying tether sample diameter and length, and plasma velocity. A magnetic field was also applied. The current flowing from the plasma flow to a tether sample was measured with varying biased voltage to a tether sample. The potential of a tether sample on the plasma potential was normalized with voltage corresponding to electron temperature, and the collection current with thermal diffusion current.

1) The normalized collection current increased with normalized tether sample potential.

2) The tether sample diameter did not influence the collection current characteristics although an increase in tether sample length decreased the collection current in this experiment.

3) The normalized collection current characteristics were independent of plasma velocity under meso-thermal conditions.

4) The existence of magnetic field raised the collection current because of the three-dimensional current collection effect at the edge of a tether sample under the magnetic field. Although the existence of magnetic field may raise the collection current, the effect will be small with a long tether.

Accordingly, the dependence of tether diameter and length, plasma velocity and surrounding magnetic field on collection current characteristics of a bare tether in space might be small. The collection current may not exceed the OML current.

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