GROUND-BASED EXPERIMENT OF ELECTRON COLLECTION BY AN ELECTRODYNAMIC BARE TETHER

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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 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 plasma velocity. The existence of magnetic field raised the normalized collection current because of the edge effect of a tether sample or the three-dimensional effect. A high collection current above the orbital-motion-limited current could be achieved with a magnetic field. The current characteristics of a bare tether strongly depended on plasma velocity and surrounding magnetic field.

1. 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.

$$I_{OML} = eN_e A \times \frac{\sqrt{2}}{\pi} \times \sqrt{\frac{eV}{m_e}} \qquad (1)$$

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 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 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.

2. Experimental Apparatus

Figure 1 shows the experimental facility of a bare tether for this study. The experimental system mainly consists of a metallic tether sample, a plasma source and a solenoidal coil. 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 solenoidal coil, respectively. The plasma flow is also perpendicular to the magnetic field. The plasma source is a type of electron cyclotron resonance (ECR) plasma accelerator, and it produces plasma flow simulating the Low-Earth-Orbit (LEO) plasma relatively moving on the bare tether. Argon is used as the working gas. The plasma source is settled on a flange of a vacuum chamber 0.7 m in diameter x 1.5 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 axial distribution of magnetic field strength on the central axis of the plasma source. The magnetic field strength at an axial position of 657 mm is 4.54 Gauss, with which the magnetic field in the simulating

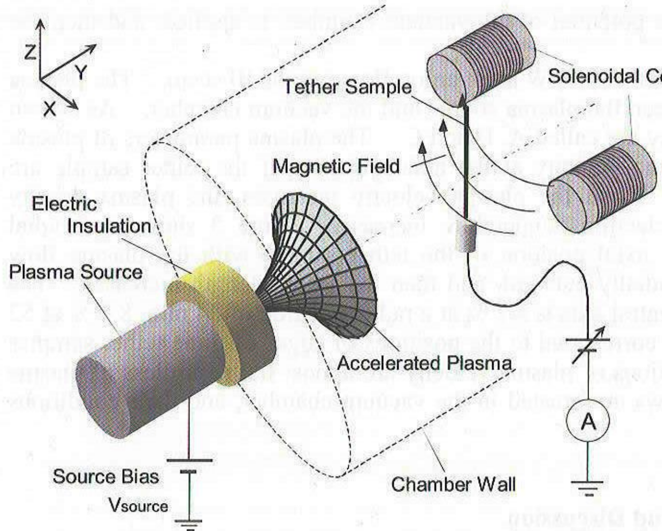

Fig.1 Ground experimental system of spacecraft bare tether.

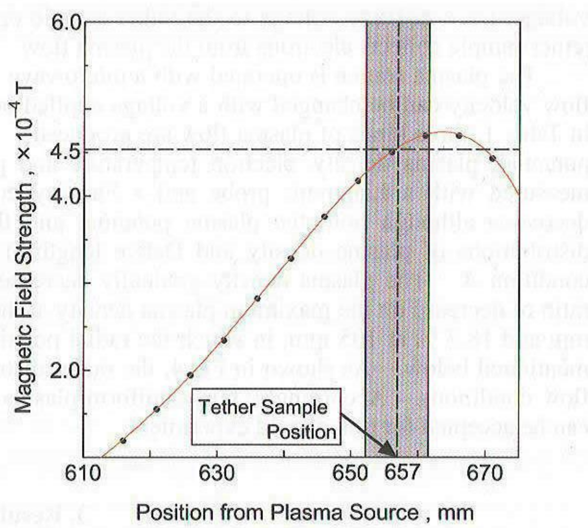

Fig.2 Axial distribution of magnetic field strength on central axis of plasma source. The magnetic field strength was measured with a Hall sensor.

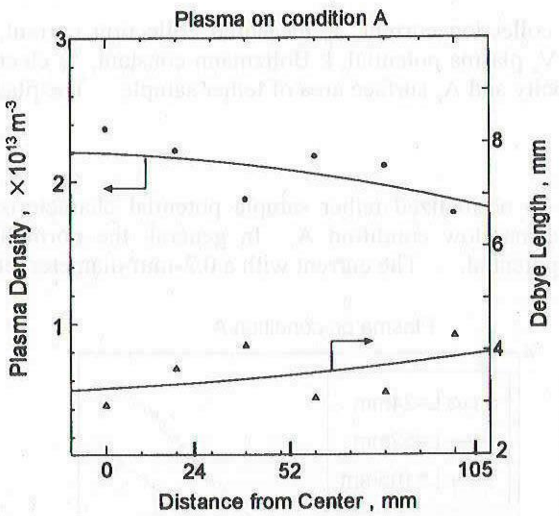

Fig.3 Radial distributions of plasma number density and Debye length at plasma flow condition A without magnetic field.

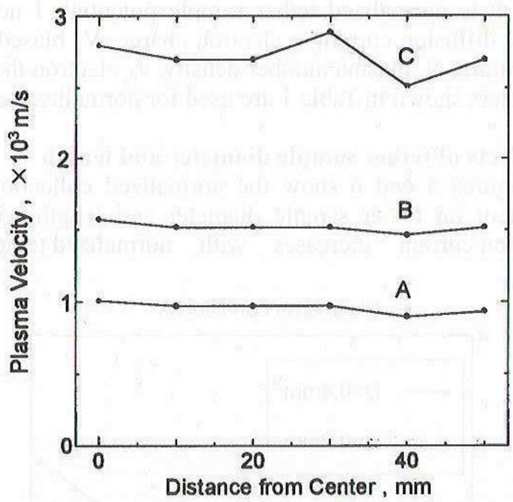

Fig.4 Radial distributions of axial plasma velocity at plasma flow conditions A, B and C without magnetic field.

Table 1 Plasma parameters for plasma flow conditions A, B and C.

	A	B	C
Plasma Potential (V)	0.4	86	128
Plasma Density (m^{-3})	2.37×10^{13}	1.63×10^{13}	0.95×10^{13}
Electron Temperature (eV)	3.7	10	20.6
Debye Length (mm)	2.9	5.8	10.9
Plasma Axial Velocity (m/s)	1008	1570	2802

plasma corresponds to that in the LEO plasma. The change of magnetic field strength is within 6 % in an axial distance range of -10 mm and +10 mm from 657 mm. As a result, the tether sample is located at 657 mm. A biased voltage, i.e. a positive voltage to the tether sample on the potential of the vacuum chamber, is applied, and then the tether sample collects electrons from the plasma flow.

The plasma source is operated with a microwave power of 300 W at an argon flow rate of 10 sccm. The plasma flow velocity can be changed with a voltage applied between the plasma source and the vacuum chamber. As shown in Table 1, three kinds of plasma flow are produced. They are called A, B and C. The plasma parameters of plasma potential, plasma density, electron temperature and plasma velocity at the axial position of the tether sample are measured with a Langmuir probe and a Faraday cup. When the plasma velocity increases, the plasma density decreases although both the plasma potential and the electron temperature increase. Figure 3 shows the radial distributions of plasma density and Debye length at the axial position of the tether sample with the plasma flow condition A. The plasma density gradually decreases radially-outward, and then the Debye length increases. The ratio of decrease on the maximum plasma density at the central axis is 4.7 % at a radial position of 24 mm, 8.2 % at 52 mm and 18.7 % at 105 mm, in which the radial positions correspond to the positions of edges of three tether samples mentioned below. As shown in Fig.4, the radial distributions of plasma velocity are almost flat regardless of plasma flow conditions. Accordingly, fairly uniform plasma flows are created in the vacuum chamber, and their conditions can be accepted for this ground experiment.

3. Results and Discussion

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

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

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 Table 1 are used for normalization.

3.1 Effects of tether sample diameter and length

Figures 5 and 6 show the normalized collection current vs normalized tether sample potential characteristics dependent on tether sample diameter and length with the plasma flow condition A. In general, the normalized collection current increases with normalized tether sample potential. The current with a 0.2-mm-diameter tether

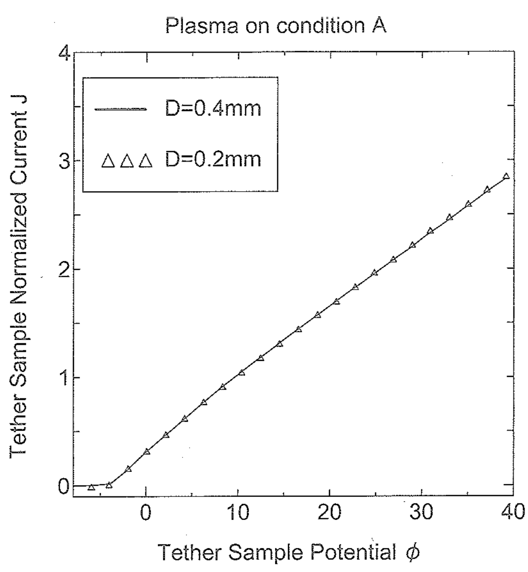

Fig.5 Normalized collection current vs normalized tether sample potential characteristics varying tether sample diameter at constant tether sample length of 52 mm for plasma flow condition A without magnetic field.

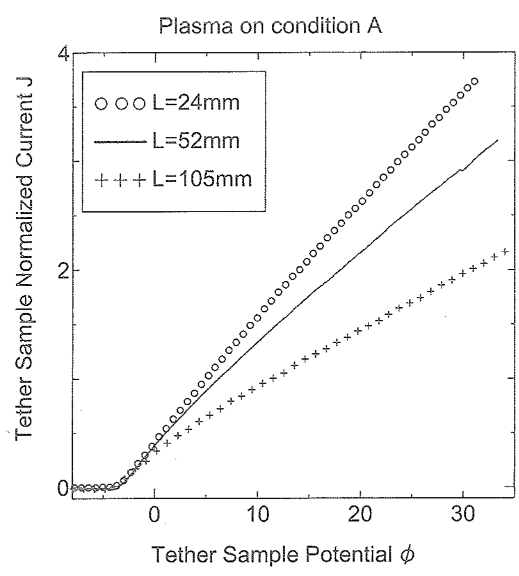

Fig.6 Normalized collection current vs normalized tether sample potential characteristics varying tether sample length at constant tether sample diameter of 0.4 mm for plasma flow condition A without magnetic field.

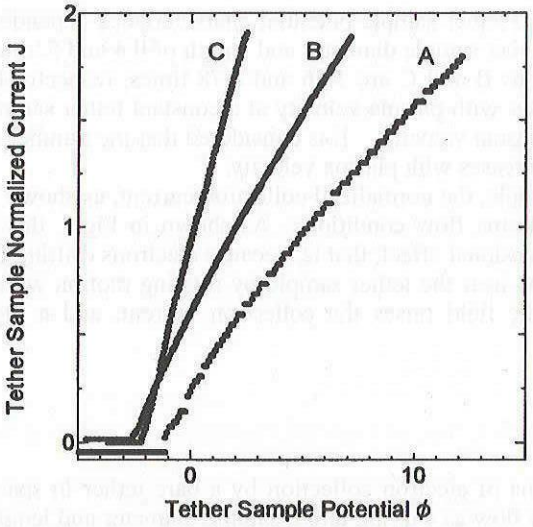

Fig.7 Normalized collection current vs normalized tether sample potential characteristics varying plasma velocity (for plasma flow conditions A, B and C) at tether sample diameter and length of 0.4 and 52 mm, respectively, without magnetic field.

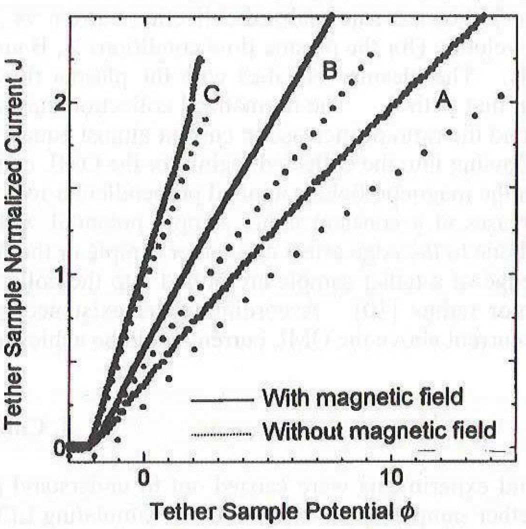

Fig.8 Normalized collection current vs normalized tether sample potential characteristics varying plasma velocity (for plasma flow conditions A, B and C) at tether sample diameter and length of 0.4 and 52 mm, respectively, with magnetic field.

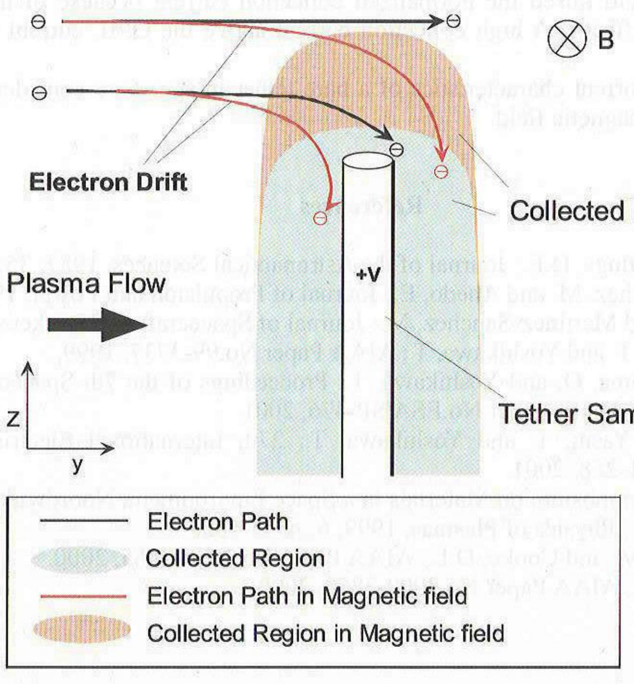

Fig.9 Feature of electron collection for bare tether with magnetic field.

sample, as shown in Fig.5, equals to that with a 0.4-mm-diameter tether sample. Accordingly, the normalized collection current is independent of tether sample diameter. This is considered because the Debye length with the plasma flow condition A, as shown in Table 1, is much larger than the tether sample diameters; that is, the OML condition is established. In tether sample length, the normalized collection current decreases with increasing tether sample length at a constant normalized tether sample potential. This is expected because the plasma density, as shown in Fig.3, becomes low as increasing distance from the center. As a result, too long tether sample is not acceptable for this experiment.

3.2 Effects of plasma velocity and magnetic field

Figure 7 shows the normalized collection current vs normalized tether sample potential characteristics dependent on plasma velocity (for the plasma flow conditions A, B and C) at tether sample diameter and length of 0.4 and 52 mm, respectively. The plasma velocities with the plasma flow conditions B and C are 1.56 and 2.78 times, respectively, higher than that with A. The normalized collection current increases with plasma velocity at a constant tether sample potential, and the ratio of increase in current almost equals that in plasma velocity. It is considered that the number of electrons flowing into the collected region for the OML condition increases with plasma velocity.

When the magnetic field is applied perpendicular to a tether sample, the normalized collection current, as shown in Fig.8, increases at a constant tether sample potential with each plasma flow condition. As shown in Fig.9, this is considered due to the edge effect of a tether sample or the three-dimensional effect; 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, the existence of magnetic field raises the collection current, and a high collection current above the OML current could be achieved.

4. Conclusions

Ground 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 normalized collection current characteristics although an increase in tether sample length decreased the normalized collection current in this experiment.
3) The normalized collection current increased with plasma velocity.
4) The existence of magnetic field raised the normalized collection current because of the edge effect of a tether sample or the three-dimensional effect. A high collection current above the OML current could be achieved with a magnetic field.

Accordingly, the collection current characteristics of a bare tether in space are considered to strongly depend on plasma velocity and surrounding magnetic field.

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