Ion Engine Combining Positive and Negative Ions

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We have proposed a negative fullerene ion thruster. The negative ion thruster which emits negative charge substituted for neutralizer has the potential to improve thrust efficiency. We conducted basic experiments of a negative ion thruster using a magnet filter and an electron collector. The electron collector was able to decrease electron density in fullerene plasma. The measurements of an E×B probe indicated the accelerated negative fullerene ion. We succeeded to combine a positive Xe ion thruster and the negative fullerene ion thruster.

Nomenclature

η	=	thrust efficiency
η_{div}	=	beam divergence efficiency
η_{multi}	=	multiply charged ions efficiency
η_{U}	=	mass utilization efficiency
η_{V}	=	electrical efficiency
η_{I}	=	current efficiency
η_{bi}	=	negative ion beam current efficiency
F	=	total thrust (N)
$\dot{m}_{ex}$	=	exhaust mass flow rate (kg/s)
$\dot{m}_{i}$	=	ion thruster mass flow rate (kg/s)
$\dot{m}_{n}$	=	neutralizer mass flow rate (kg/s)
P	=	total input power (W)
V_S	=	screen voltage (V)
C_i	=	electrical cost of producing ions (W/A)
C_n	=	electrical cost of neutralize (W/A)
M	=	propellant molecular weight (kg)
v_{ex}	=	propellant exhaust velocity (m/s)

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g	=	acceleration of gravity (m/s^2)
I_{sp}	=	specific impulse (s)
e	=	elementary charge constant (1.6×10^{-19} C)
Z	=	ion valence
E	=	electric field (V/m)
$V_{ebprobe}$	=	E×B probe voltage (V)
d	=	E×B electrode separation (m)

I. Introduction

An ion thruster[1] is a device which electrostatically accelerates a beam of positively charged ions to high velocities, thereby producing thrust. The current-day ion thruster consists of a positive ion thruster head which emits positive ions to provide a thrust, and a neutralizer which emits electrons to keep spacecraft charge neutrality. The negative ion thruster is substituted for neutralizer (Fig. 1) and has potential to increase the total thrust efficiency. The purpose of this study is to examine the possibility of the negative ion thruster using fullerene propellant.

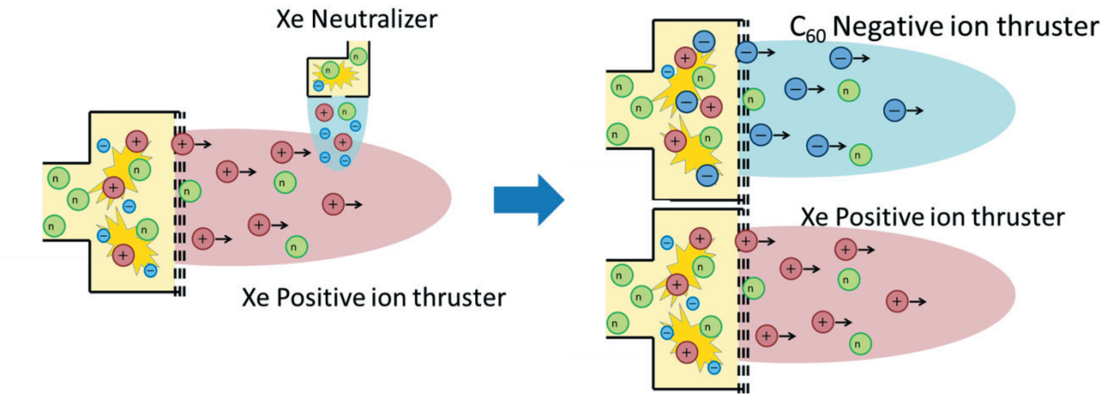


Figure 1. Concept of the negative ion thruster

II. Theory

A. Benefits of Negative Ion Thruster

The thrust efficiency[2] η given by

$$\eta = \frac{F^2}{2\dot{m}P} = \eta_{div}^2 \eta_{multi}^2 \eta_U \eta_V \eta_I$$

The mass utilization efficiency η_U and the electrical efficiency η_V is given[2] by

$$\eta_U = \frac{\dot{m}_{ex}}{\dot{m}_i + \dot{m}_n}$$

$$\eta_V = \frac{V_S}{V_S + C_i + C_n}$$

These equation indicate that the neutralizer doesn't generate a thrust but consume propellant ($\dot{m}_n$) and electricity (C_n). Thus the negative ion thruster which emits negative charge substituted for the neutralizer has a potential to improve the thrust efficiency. Moreover, by using fullerene propellant which is 5.5times more massive than xenon, electrical efficiency will increase in same specific impulse[3] because the screen voltage V_S is given by

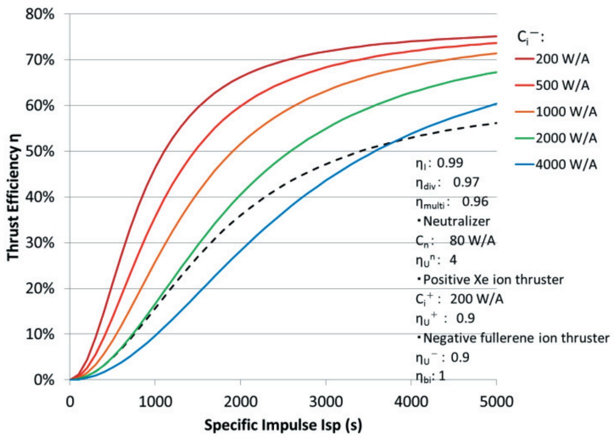


Figure 2. Thrust efficiency using negative ion thruster substituted for neutralizer

$$V_S = \frac{Mg^2}{2e} I_{sp}^2$$

Fig.2 shows the relation of thrust efficiency and specific impulse combined a negative ion thruster and a positive ion thruster. The figure shows that if the thrust efficiency of the negative ion thruster head achieved the same thrust efficiency of positive ion thruster head, the total thrust efficiency would increase about 25% at 3000 sec Isp.

B. A Problem of Negative Ion Thruster

Negative ion thruster has the potential problem that electrons are accelerated too. As electrons are much lighter than ions, the energy to accelerate electrons is loss (Fig. 3). The thrust efficiency of the negative ion thruster head is given by

$$\eta = \eta_{div}^2 \eta_{multi}^2 \eta_U \eta_V \eta_I \eta_{bi}$$

Thus it is necessary to generate electron free plasma in the vicinity of the screen grid.

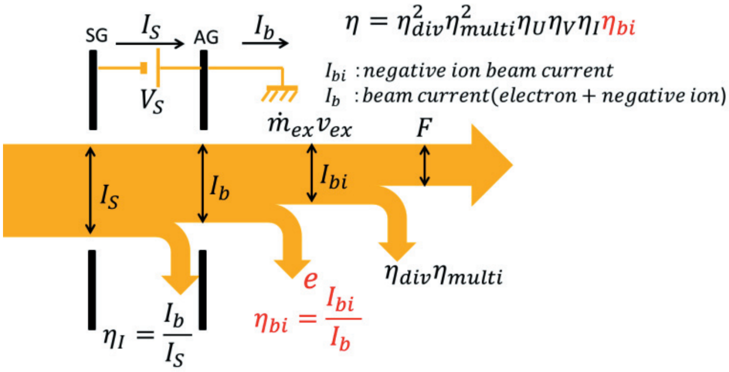


Figure 3. Current and power distribution of negative ion thruster

III. Experiment

The electrical connections of the ion thruster is shown in Fig.4. The thruster is a quadrangular prism stainless steel (7×7 cm, 14 cm long). The electron bombardment ionization method is adopted because electron sources is necessary to keep fullerene plasma[4]. The cathode is 0.27-mm dia. tantalum tungsten filament. Discharge voltage V_A is 40 V fixed. The filament cathode current is 7 A and filament cathode voltage is about 7 V. To supply fullerene gas into the ion source, fullerene vaporizer was constructed. The fullerene mass flow rate (≈0.5 mg/s) is measured in real-time by using electric balance. In order to decrease electron mobility, the magnetic filter (B_{max} ≈24 mT) generated by permanent magnet is located 3.5 cm from the screen grid. Differently from hydrogen or SF_6, the maximum electron attachment cross-section for C60 molecule is not near zero electron temperature[5]. The electron collector is installed in the magnetic field to collect electrons when the electrode voltage is upper than plasma potential (≈45 V). The screen voltage is +700 V and the accel grid voltage is -200V when positive charged particles (positive ions) is extracted. On the other hand, the screen voltage is -700V and the accel grid voltage is +200 V when negative charged particles (negative ions, electrons) is extracted. The screen bias voltage is +25 V.

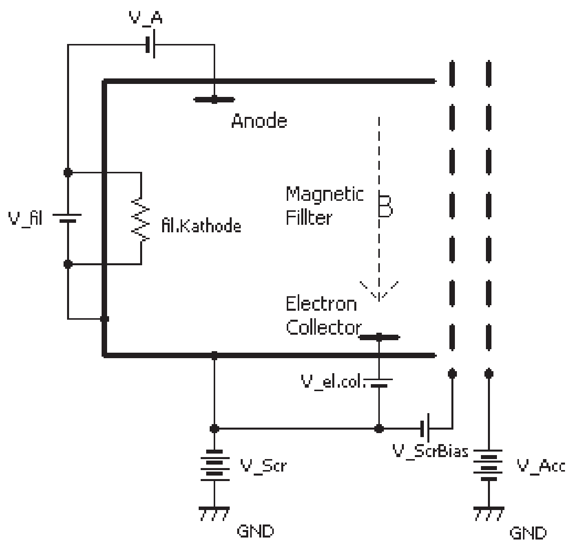


Figure 4. Electrical connections of the ion thruster

A. **Langmuir Probe – Plasma Measurement in the Thruster**

For this study, a cylindrical Langmuir probe was used. The probe tip is made of tungsten with a radius of 50 μ m and a length of 8 mm. The probe location is 5 mm from the screen grid where the magnetic field strength is 8 mT.

The result of Langmuir probe measurement in pure fullerene plasma is shown in Fig.5. When the electron collector voltage is less than the plasma potential (≈45 V), the electron saturation current is much larger than the ion saturation current. On the other hand, if the voltage is larger than plasma potential, the electron saturation current is decreased although the ionization saturation current is almost unchanged. The result shows that the electron collector was available to suppress electron density only but it is necessary to decrease electron density much more.

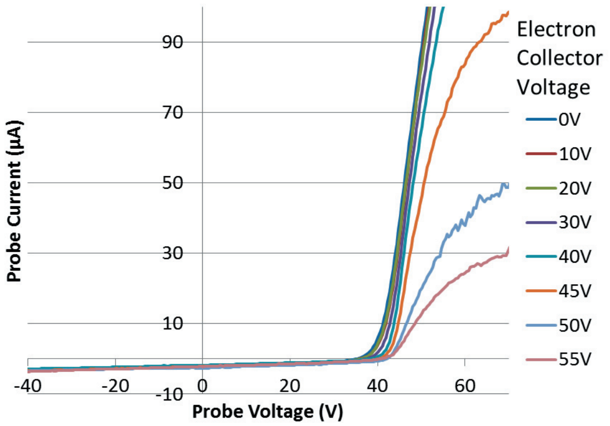


Figure 5. Langmuir probe measurement in fullerene plasma nearby screen grid

B. **E×B Probe - Ion Species Measurement in the Thruster Beam**

An E×B probe is a band-pass ion filter that selects ions according to their velocities through the application of crossed electric and magnetic fields[6-7]. The velocity v of the ion accelerated by the screen grid applied V_S is given by

$$v = \sqrt{\frac{2eZV_s}{M}}$$

The motion of ions in an electric and magnetc fields (Fig.6) is described by the Lorenz force F_z;

$$\mathrm{F_z} = \mathrm{eZ}(\mathrm{E_z} - \mathrm{v}B_y)$$

where eZ is the ion elementary charge, E_z and B_y the electric and magnetic field, respectively. When the particles undergo no force, previous equation becomes,

$$E_z = B_y\sqrt{\frac{2eZV_s}{M}}$$

Thus the mass of the ion is given by

$$\mathrm{M} = \frac{2eZV_S \mathrm{B_y}^{2} d^2}{V_{ebprob}^2}$$

where V_{ebprob} is E×B probe voltage and d is electrode separation. In this paper, d is 4.0×10^{-3} m, B_y is 176 mT and the absolute value of V_S is 700 V.

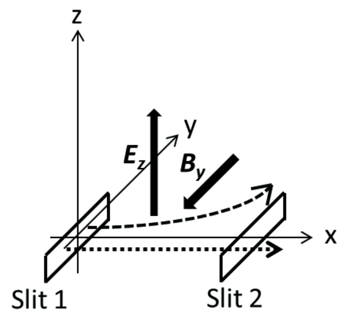


Figure 6. Electric and magnetic fields of the E×B prob

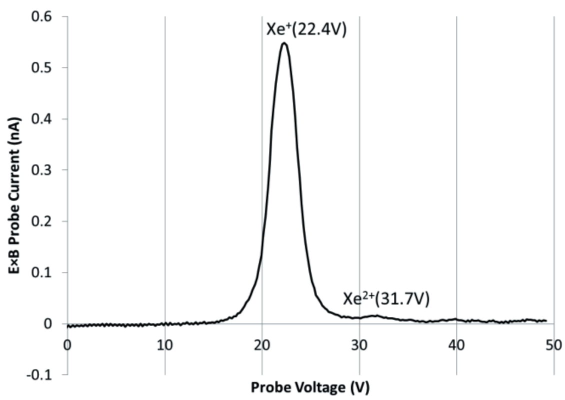


Figure 7. Measurement with the E×B probe at +700 V acceleration from pure Xe plasma.

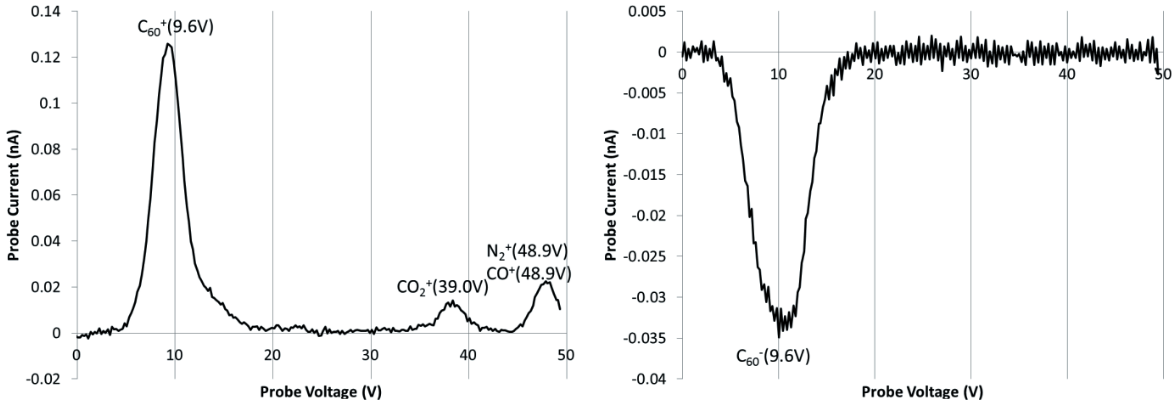
1. The positive charge beam measurement accelerated from the pure Xe plasma

The result of E×B probe positive Xe ion beam measurement is shown in Fig.5. The Xe^+ and Xe^{2+} peaks should occur at the probe voltage of 22.4 V and 31.7 V respectively which are in good agreement with the measurement result.

2. The positive and negative charge beam measurement accelerated from the pure fullerene plasma

The result of positive fullerene ion beam measurement with the E×B probe is shown in Fig.8 (a). The $C60^+$ peak occurs at near 9.6 V. Two peaks are shown at around 38 V and 48 V. An ion accurate mass measurement with quadrupole mass spectrometer (QMS) indicated that there were 44 m/z ion and 28 m/z ion. It is most likely that the ion species of the 44 m/z molecule is CO_2^+. Thus it is considered that the ion species of 28 m/z ion is CO^+. It is shown that there is oxygen in fullerene propellant because C_{60} has a possibility to absorb oxygen as molecule at room temperature[8]. CO_2^+ and CO^+ should be shown at 39.0V and 48.9V respectively in E×B probe measurement. Thus the two peaks in Fig.8 (a) are these spices.

The result of negative fullerene ion beam measurement is Fig.8 (b). There is a peak of which the probe current is opposite to the C_{60}^+ beam. This indicates that the peak is the C_{60}^- beam.



(a) (b)

Figure 8. Measurement with the E×B probe. Accelerated from pure fullerene plasma. (a) shows at +700 V acceleration. (b) shows at -700 V acceleration.

C. **Magnetically Filtered Faraday Probe – Electron Beam Measurement in the Negative Charged Beam**

In order to analyze the existence of the electron beam in the negative charged beam, a magnetically filtered faraday probe (MFFP) was used (Fig.9). The MFFP is able to separate the electron beam from the negative ion beam, because the electron beam are only filtered by magnetic field when the electric current flows through the coil of the MFFP. Fig.10 shows the electron beam measurement extracted from pure Xe plasma. The result indicates that the electron beam exists and magnetically filter of the MFFP ran properly when the electric current flowed through the coil.

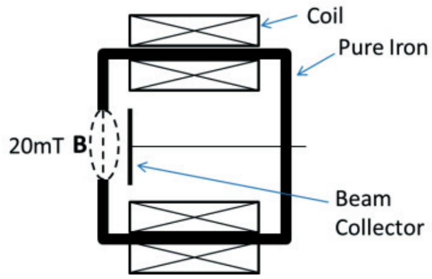
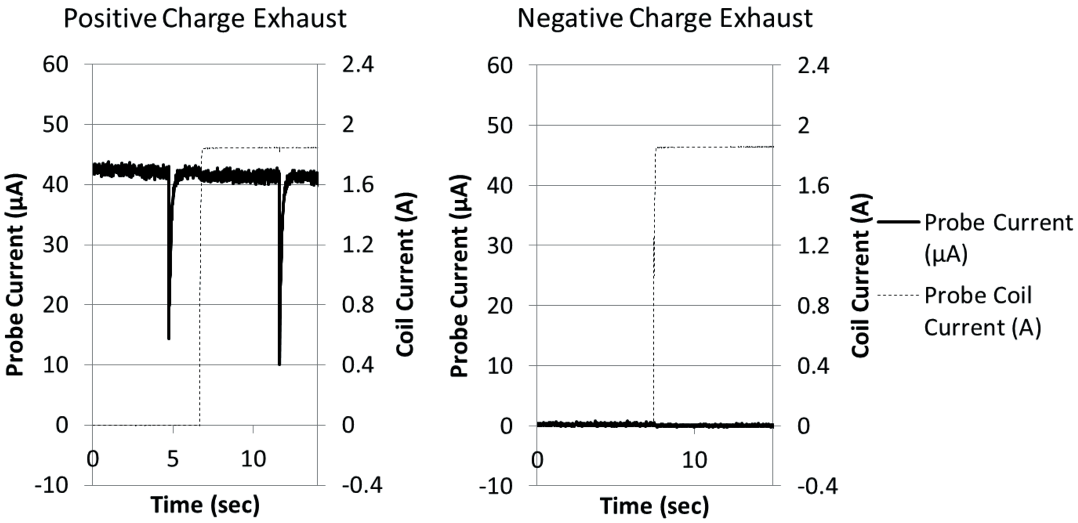


Figure 9. Schematic drawing of MFFP

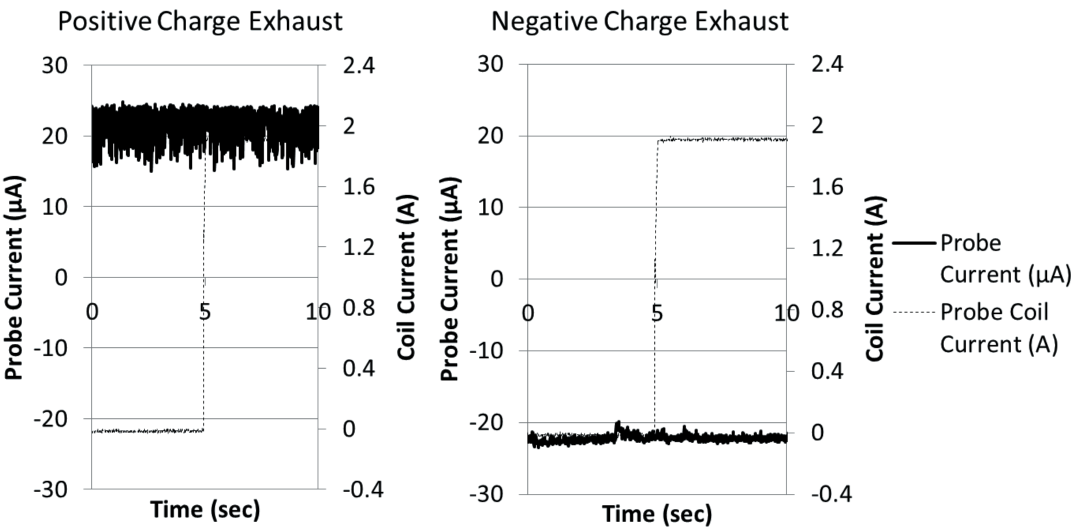
To suppress the electron beam, a magnetic filter is located on the downstream of the accel grid. The filter is connected to the accel grid electrically. This method is not worth to increase thrust efficiency but worth to simulate the negative ion thruster operation without electrons. Fig.11 (a) shows the MFFP measurement of the positive charged beam, and Fig.11 (b) shows the measurement of the negative charged beam extracted from the pure Xe plasma. The positive charged beam consists of ion. Accordingly, the probe current does not change whenever the magnetic filter of the MFFP runs. Fig.11 (b) shows that the negative charged beam (electron beam) does not exist.

Fig.12 (a) shows the measurement of positive charged beam, and Fig.12 (b) shows the measurement of negative charged beam extracted from pure fullerene plasma. Fig 12 (b) shows that negative ion beam (negative fullerene) exists but electron beam dose not exist.



(a) (b)

Figure 10. The beam accelerated from pure Xe plasma measurement with the MFFP. (a) shows positive charge beam. (b) shows negative charge beam.



(a) (b)

Figure 11. The beam extracted from pure fullerene plasma measurement with the MFFP. (a) shows positive charge beam. Screen grid current is 0.51 mA and accel grid current is 0.01 mA. (b) shows negative charge beam. Screen grid current is 1.88 mA and accel grid current is 1.37 mA.

D. C_{60}^{-} **Thruster and** Xe^{+} **Thruster Combination Operation**

To demonstrate the operating of the negative ion thruster, we combined the negative fullerene thruster and a Xe^{+} thruster. The Xe^{+} thruster is a miniature ECR(Electron Cyclotron Resonance) discharge ion engine named as μ 1, due to the 1-cm-class beam diameter and 1-W-class microwave power[9]. The μ 1 beam current is variable by regulating microwave power. Fig.13 shows the electrical connections of combination operation. Ion thrusters were isolated from the ground line and those are connected only by a 100 Ω resistance to measure net current. The distance from the center of the μ 1 to the center of the negative ion thruster is 7 cm. Fig.14 shows the measurements of the beam current and the net current. The combination operation starts from 160 sec. From 268 sec to the end of time, the absolute value of net current is under 0.01 mA. This means negative ion beam current is nearly equal to positive ion beam current.

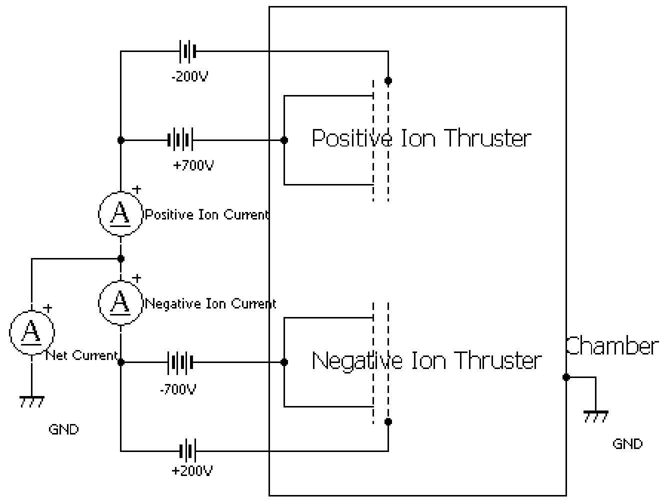


Figure 12 Electrical connections of the negative ion thruster and the positive ion thruster(μ 1).

The E × B probe measurement of the combination operation is shown in Fig. 15. This result shows that the beam consists of both C_{60}^{-} and Xe^{+}. These results show that we succeed in a demonstration of the combination operation without neutralizer.

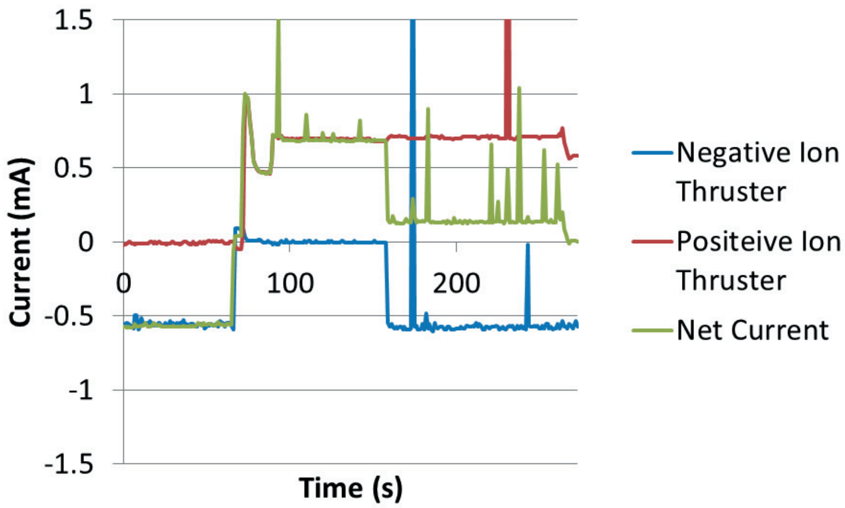


Figure 13. Combination operation of the negative ion thruster and the positive ion thruster.

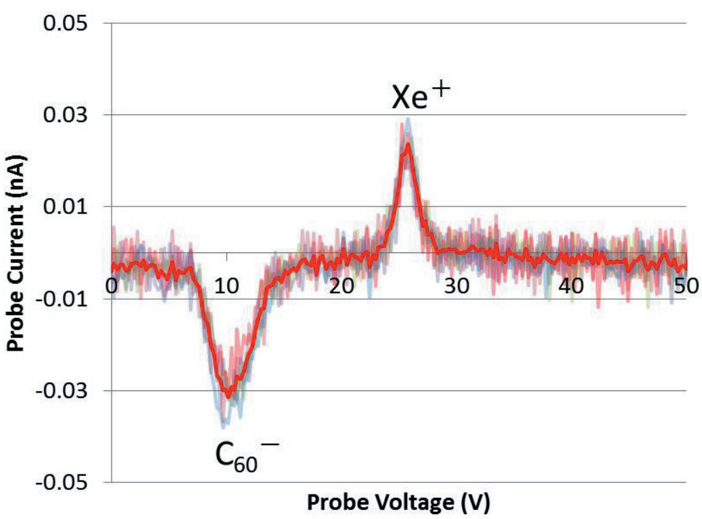


Figure 14. E×B probe measurement in the combination operation

IV. Conclusion

The authors have developed a negative ion thruster using fullerene propellant. The negative ion thruster is purposed to be combined with a positive ion thruster instead of neutralizer in order to increase total thrust efficiency. In order to decrease electron density in the vicinity of the screen grid, a magnetic filter and an electron collector were installed in the negative ion thruster. The electron collector was able to decrease the electron density but it is necessary to decrease much more. The measurement with E×B probe shew that the negative fullerene was extracted from pure fullerene plasma. The combination operation of the negative ion and the positive ion thruster without neutralizer was successful. The beam consisted of negative fullerene and positive Xenon.

References

[1]Goebel, D.M. and Katz, I., Fundamentals of Electric Propulsion, Wiley, New Jersey, 2008.

[2]Hitoshi K., Kaztaka N., and Yoshinori N., Ion Enjin ni okeru douryoku koukou, ISBN-10 4339012289

[3]John R. Anderson, Dennis Fitzgerald, Stephanie Leifer, and Juergen Mueller, "Design and Testing of a Fullerene RF Ion Engine", AIAA-95-2664

[4]John Steven Snyder, "Investigation of the Feasibility of Fullerene Propellant for Ion Thrusters", 1998

[5]Thomas J.,Eugen I., Mathias L., Stefan M., David S., Tilmann D. M.,"Formation of C60- and C70- by free electron capture. Activation energy and effect of the internal enelgy on liftime", Chemical Phy. Letters 226(1994)213-218

[6]Shastry, R., Hofer, R. R., Reid B. M. and Gallimore A. D., "Mehod for Analyzing E×B Probe Spectra from Hall Truster Plumes", Rev. Sci. Instrum, Vol. 80, pp. 063502, 2009.

[7]Gerst D., Renaud D. and Mazouffre S., "E×B probe investigation of the PEGASES thruster ion beam in Xe and SF6," IEPC-2013-130.

[8]Pan C., Chandrasekharaiah, M. S., Agan D., Hauge R. H. and Margrave, J. L., "Determination of Sublimation Pressures of C60/C70 Solid Solution," Journal of Physical Chemistry, 96, 6752-6755, 1992.

[9]Hiroyuki K. and Hitoshi K., "Performance of the Miniature and Low Power Microwave Discharge Ion Engine μ 1", 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 25-28 July 2010.