Overview of Electric Propulsion Research Activities in Japan

Conference Paper · July 2015

Overview of Electric Propulsion Research Activities in Japan

IEPC-2015-01 /ISTS-2015-b-01

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

Haruki Takegahara[1], Hitoshi Kuninaka[2], Ikkoh Funaki[3], Akira Ando[4], Kimiya Komurasaki[5], Hiroyuki Koizumi[6], Tony Schönherr[7], Shunjiro Shinohara[8], Takao Tanikawa[9], Masakatsu Nakano[10], Yoshinori Nakayama[11], Akihiro Sasoh[12], Takeshi Miyasaka[13] , Hirokazu Tahara[14], Naoji Yamamoto[15], and Akira Kakami[16]

[1] Tokyo Metropolitan University, Hino, Tokyo, 191-0065, Japan

[2,3] Institute of Space and Astronautical Science / JAXA, Sagamihara, Kanagawa, 252-5210, Japan

[4] Tohoku University, Sendai, Miyagi, 980-8579, Japan

[5,6,7] The University of Tokyo, Bunkyo-ku, Tokyo, 113-8654, Japan

[8] Tokyo University of Agriculture and Technology, Koganei, Tokyo, 184-8588, Japan

[9] Tokai University, Hiratsuka, Kanagawa, 259-1292, Japan

[10] Tokyo Metropolitan College of Industrial Technology, Arakawa-ku, Tokyo, 116-8523, Japan

[11] National Defense Academy, Yokosuka, Kanagawa, 239-8686, Japan

[12] Nagoya University, Nagoya, Aichi, 464-8601, Japan

[13] Gifu University, Gifu, 501-1193, Japan

[14] Osaka Institute of Technology, Asahi-ku, Osaka, 535-8585, Japan

[15] Kyushu University, Kasuga, Fukuoka, 816-8580, Japan

[16] Miyazaki University, Miyazaki, 889-2192, Japan

In Japan, many research activities on electric propulsion and its accompanying science / technology have been executing for the near / far future space propulsion

[1] Professor, Department of Aerospace Engineering, hal@astak3.sd.tmu.ac.jp.
[2] Professor, Department of Space Flight Systems, kuninaka@isas.jaxa.jp.
[3] Associate Professor, Department of Space Flight Systems, funaki@isas.jaxa.jp.
[4] Professor, Department of Electrical Energy System, akira@ecei.tohoku.ac.jp.
[5] Professor, Department of Aeronautics and Astronautics, komurasaki@al.t.u-tokyo.ac.jp
[6] Associate Professor, Department of Aeronautics and Astronautics, koizumi@al.t.u-tokyo.ac.jp.
[7] Assistant Professor, Department of Aeronautics and Astronautics, schoenherr@al.t.u-tokyo.ac.jp.
[8] Professor, Division of Advanced Mechanical Systems Engineering, sshinoha@cc.tuat.ac.jp.
[9] Professor, Research Institute of Science and Technology, tnth@keyaki.cc.u-tokai.ac.jp.
[10] Associate Professor, Aerospace Engineering Course, mnakano@acp.metro-cit.ac.jp.
[11] Associate Professor, Department of Aerospace Engineering, ynakayam@nda.ac.jp.
[12] Professor, Department of Aerospace Engineering, sasoh@nuae.nagoya-u.ac.jp.
[13] Associate Professor, Department of Mechanical Engineering, miyasaka@gifu-u.ac.jp.
[14] Professor, Department of Mechanical Engineering, tahara@med.oit.ac.jp.
[15] Associate Professor, Department of Advanced Energy Engineering Science, yamamoto@aees.kyushu-u.ac.jp.
[16] Associate Professor, Department of Mechanical Design System Engineering, kakami@cc.miyazaki-u.ac.jp.

system by universities, institutes, manufacturers and JAXA. After the impressive and emotional return of "HAYABUSA" to earth, many studies on next generation of electric / plasma propulsion are, now, going on. In this paper, we'd like to summarize our studies including ion thruster, hall thruster (magnetic layer type / anode layer type), MPD arc jet, Pulsed Plasma Thruster, Helicon Plasma Thruster, another thrusters and its electron sources, with / without applied magnetic / electric field for both large spacecraft and small satellite. Their fundamental concepts and state-of-the-arts are to be introduced and addressed.

I. Introduction

AFter the impressive and emotional return (2010.06.13) of "HAYABUSA" to earth, new space exploration programs such as "HAYABUSA2" (launch at 2014.12.03) are carrying on in Japan. On the other hand, there are the great demands of the near earth project for earth observation, commercial communication, and other missions. Following the present electric propulsion system, in Japan, electric / plasma propulsion concepts for new generation are, now, taken up for discussion and analytically / experimentally estimated and evaluated.

II. Electric Propulsion Research Activities in Japan

In this chapter, research activities of many universities, institutes, manufacturers and JAXA are described for each organization. Furthermore, joint researches of many universities, institutes, manufacturers with JAXA are in progress.

A. Electric Propulsion Laboratory at ISAS/JAXA

Optical Fiber Probes for Microwave Discharge Plasma Source

Optical diagnostics using fibers in the microwave discharge plasma sources has been developed. The conventional Langmuir probe seriously interferes with microwave electric field. Application of the optical fiber has advantages as follows:

1) little disturbance to microwave electric field due to dielectric material
2) durability under high temperature plasma because of glass
3) easy electrical isolation due to insulator
4) high spatial resolution

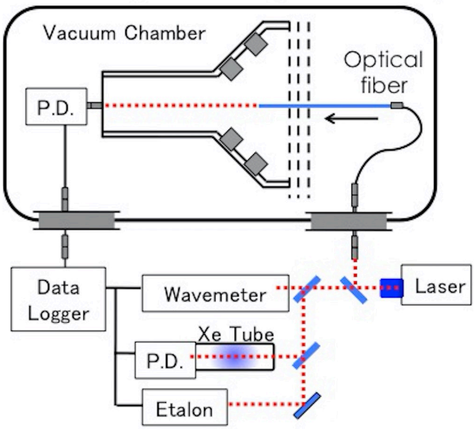


Figure 1. Laser absorption spectroscopy using an optical fiber in the microwave discharge plasma source.

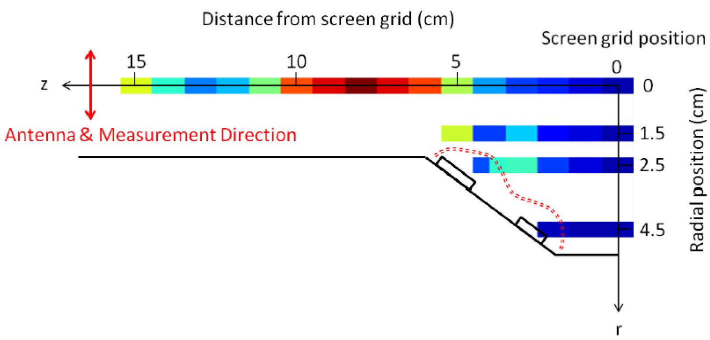


Figure 2. Microwave electric field measurement using an optical fiber with electro-optical device in the microwave discharge plasma source.

Figure 1 presents the diagnostic configuration of the laser absorption spectroscopic (LAS) using an optical fiber of 1mm diameter under ion beam acceleration[1]. The laser light emits from the optical fiber and runs through the microwave plasma source and is detected by a photo diode at the end. It is absorbed by targeted excited-particles depending on their density and length of light path, which is variable by insertion of the optical fiber through a grid hole. Difference of LAS signal by changing the length of light path means local density of the excited-particles. The proposed diagnostic has high spatial resolution instead of Abel inversion. Density profile of the excited-neutral Xe I 828nm of short life was revealed along the center line of the plasma source.

The optical fiber diagnostic is applicable to measure microwave electric field. An Electro-Optics (EO) device changes its polarization dependent on the external electric field. It is attached at the tip of optical fiber and inserted at an appropriate location in the microwave discharge plasma source. A 1.5micron laser is reflected through EO and the fiber and analyzed to identify microwave electric field. One of the experimental results is shown in Fig.2[2]. The electric field at the electron-cyclotron resonance region above the permanent magnet was about 2kV/m.

These internal diagnostics contribute well to understand physical processes and to improve performance of the microwave discharge plasma source.

Microwave Discharge Neutralizer onboard DubaiSat-2

The microwave discharge neutralizer of the ion engines for Hayabusa asteroid explorer can emit electron current around 150mA. In order to progress its technology and open new application fields a 500mA-class neutralizer was developed and applied to a cathode for 300W Hall thruster instead of a conventional hollow cathode. The combined system is seen in Fig.3[3]. The integrated thruster was installed onboard DubaiSat-2 satellite and launched in November 2013. The thruster system is devoted to keep the satellite in an appropriate sun-synchronous orbit. This satellite project was cooperated among Emirate Institution of Advanced Science and Technology (EIAST), Satrec-Initiative and JAXA

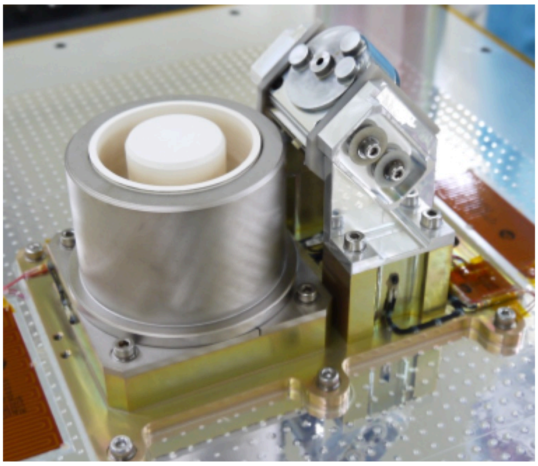


Figure 3. Microwave discharge neutralizer combined with 300W Hall effect thruster for DubaiSat-2.

Figure 4. Four microwave discharge ion engines onboard Hayabusa2 asteroid explorer on PAF of H2A rocket.

Hayabusa-2 Asteroid Explorer powered by Microwave Discharge Ion Engines

On the achievement of round-trip space voyage between Earth and Itokawa asteroid by Hayabusa asteroid explorer, Hayabusa-2 sample return project was initiated on 2011. Four microwave discharge ion engines were developed as main propulsion. They are improved in 10mN thrust force from the original 8mN. Whole of system was assembled at Tanegashima Space Center as seen in Fig.4 and launched by H2A rocket No.26 on December 3, 2014. Each ion engine was turned on one by one after two weeks and then all of ion engine system was identified in good health condition. It completed the first delta-V maneuver toward the Earth swing-by corridor in March. Hayabusa-2 spacecraft will arrive at 1999JU3 asteroid in 2018, and return to Earth in 2020.

B. Research Activities at ISAS/JAXA

Numerical Simulation Tool for EP Design

Numerical simulation tools are important to design and characterize a new thruster. Following successful release of the JIEDI tool[4,5], which is capable of predicting the performance and lifetime of ion thrusters' ion optics, JAXA is preparing several numerical design tools for other types of EP such as hall thruster, MPD arcjet, and cathode. Full particle method, which deals with all the particle motions as well as electric fields, is selected for simulating a plasma flow in Hall thrusters[6-8] since electron transport property is vitally important and it is difficult to estimate without dealing with electron particle motions (collisions and its Larmor motions). So far, a two-dimensional axi-symmetric code was successfully produced, and it is currently used for understanding electron transport properties, as shown in Fig.5, and are also used for designing middle-class hall thrusters that are under development among JAXA, IHI Aerospace, IHI, and Tokyo Metropolitan University).

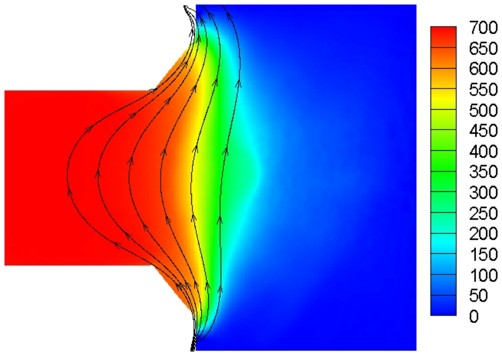


Figure 5. Preliminary simulation result of a 2 kW-class magnetic layer type Hall thruster. Acceleration voltage of 700V was applied to the anode and the displayed plasma potential distribution is time-averaged. The black stream traces denotes the lines of magnetic force.[8]

Particle-bases numerical simulation requires very heavy resources because simulation has to resolve the fine structure for a high-density plasma flow in the case of MPD arcjet or cathode. To overcome this issue, a hybrid simulation tool is under development that can deal with a high-density plasma flow inside and outside cathode[9]. Also, for MPD arcjet, a magnetohydrodynamic code, MAPS, is used to evaluate a plasma flow of MPD arcjet[10]. So far, the MAPS code was updated to include a sheath model so as to conduct both plasma flow simulation in combination with thermal simulation of arcjet body (thruster head)[11,12]. Preliminary fluid-thermal coupled simulation suggested that a larger anode and cathode radius is preferred to provide enough cooling capability for Mega-watt-class MPD arcjets.

Advanced Propulsion Concept, Magnetoplasma Sail

Mini-Magnetospheric Plasma Propulsion (M2P2) or Magnetoplasma sail (MPS) is a future spacecraft propulsion concept utilizing the energy of the solar wind[13,14]. When an MPS sail is launched into interplanetary space, an onboard hoop coil produces an artificial magnetic cavity (or magnetosphere) to reflect solar wind particles approaching the coil. In this case, a thrust force is produced due to the solar wind to magnetosphere interaction to accelerate the spacecraft in the direction leaving the sun. This concept of MPS and its applicability to future deep space missions is currently studied by JAXA in collaboration with Japanese universities. It is numerically shown that releasing a low-velocity plasma from an MPS spacecraft excites an equatorial ring-current, which makes a larger magnetosphere and correspondingly a larger thrust level becomes possible[15-17]. This "ring-current inflation" method of MPS is demonstrated in laboratory using scale-models[18]. The study of MPS is still in proof-of-concept status, but in addition to numerical and experimental investigations of plasma to magnetic field interactions[19-21], but also spacecraft system, in particular electric magnets design[22], is pursuit.

C. Research Activities at Tohoku University

Plasma dynamics in a magnetic nozzle include many aspects of physics relating to electric propulsion performance (see Fig. 6). In Tohoku University, plasma flow and expansion physics in the magnetic nozzles are experimentally investigated for wide range of plasma parameters by using various type of plasma thrusters, e.g., an applied-field magnetoplasmadynamic (AF-MPD) thruster, a helicon plasma thruster (HPT), and a helicon MPD thruster. The AF-MPD can be operated at the electric power of P ~1 MW and the propellant mass flow rate of m_{dot} ~ 50-500 mg/s in quasi steady-state of 1 msec; then a large thrust of T ~7 N can be obtained by applying de Laval nozzle[23]. The HPT is an electrodeless thrusters operated continuously at $P < 10$ kW in steady state and $m_{\mathrm{dot}} < 5$ mg/s; the thrust arising from the magnetic nozzle effects are individually measured[24]. A new loss mechanism of the axial plasma momentum to the wall is discovered in experiment[25], while the performance is recently improved up to 18 mN/kW based on the scientific insight[26]. The helicon MPD thruster is more advanced and recently developed concept of the plasma thruster operated at P ~ 500 kW and m_{dot} ~ 1-10 mg/s[27]. The linear and nonlinear interactions between the plasma and the magnetic nozzle will be experimentally investigated for the wide range of parameters, e.g., the plasma density over $10^{10} - 10^{15}$ cm^{-3}and the ion/electron temperature over 0.2-50 eV. The experimental devices are now ready for laboratory test and will provide interesting and universal features of the plasma dynamics and electric propulsion technology in near future. Furthermore, the engineering development is also ongoing such as the solenoid-free permanent magnet plasma thruster, which reduces the size and consumed electricity[28].

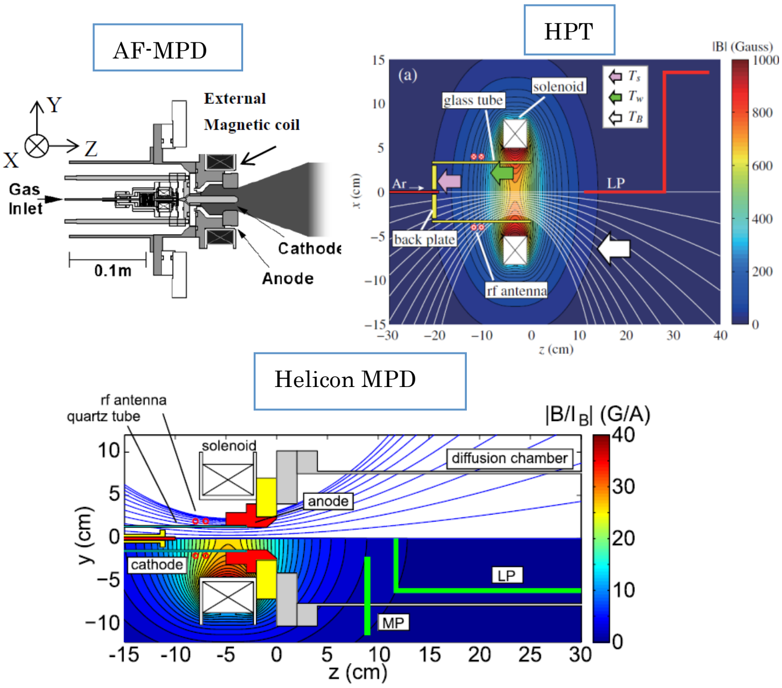


Figure 6. Schematic diagrams of various magnetic nozzle plasma thrusters at Tohoku University.

D. Research Activities at The University of Tokyo

Hall thruster

The University of Tokyo has focused research activities on thrusters with anode layer (TAL). UT-58, a 2-kW class thruster (see Fig. 7), was designed and tested with respect to thrust performance and discharge oscillations[29], and showed good performance compared to thrusters in the same power class.

Variations of channel and magnetic field geometries were experimentally tested, and thrust performance and guard ring currents as an indicator for erosion were evaluated to deduce an optimum configuration. As expected, thrust performance and guard ring current decreased concurrently, but unlike SPT erosion could not be completely avoided without a significant loss in thrust[30]. These results were confirmed by a fully kinetic PIC numerical code that was modified to handle computations of TALs and magnetic shielding configurations. To characterize the plasma and the effects of the change in magnetic field, a single Langmuir probe and an emissive probe were used to derive the distribution of the potential and of the electron temperature in the ionization region.

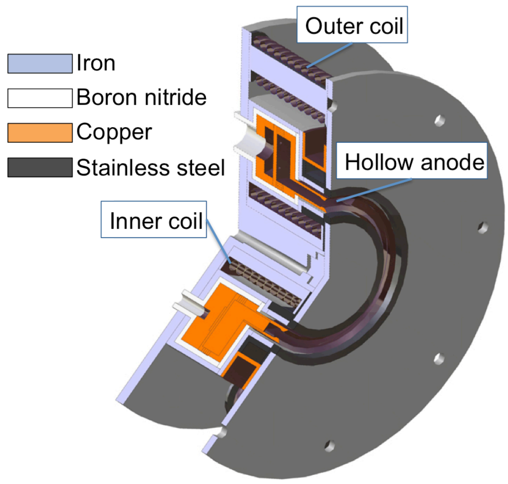


Figure 7. UT-58 thruster with anode layer.

With the aim for higher power in electric propulsion, the question regarding propellant was looked upon, and analyses made to estimate the costs of high-power missions like the establishment of an SPS structure. Consequently, alternative propellants like argon and iodine were and are tested to cope with the acquisition issue of xenon[31].

Pulsed plasma thruster

In collaboration with the University of Stuttgart, Germany, the University of Tokyo has achieved a substantial progress in the understanding of the working principle of ablative pulsed plasma thruster. By means of high-speed imaging, optical emission spectroscopy, Mach-Zehnder interferometry, and induction probes, the plasma resulting from the discharge of a 68 J parallel-type PPT was analyzed in time and space and distributions of electron temperature, electron density, and discharge current were derived[32,33]. The results confirmed the theory of a non-moving discharge current with continuous ablation. With emphasis on the plasma creation area, it was possible to observe the changes in ion charge state with variation of discharge current, and obtain a temperature profile in the high-current layer close to the propellant surface[34].With PTFE being the predominant propellant in PPT, other propellant choices are under investigation including variations of the solid propellant, application of liquid propellant[35], and application of gaseous propellant with the aim of an atmosphere-breathing PPT.

Microwave Rocket

Microwave Rocket is one of the Beamed Energy Propulsion thrusters and a candidate for use as a future launch system. A millimeter-wave beam drives a detonation wave in a thruster tube, and the vehicle acquires impulsive thrust. It can fly in air-breathing mode, which enables no-fuel consumption flight, so that launch cost will be drastically reduced by downsizing and weight saving of the launcher[36]. Passive and periodical air-intake through reed-valves is under development.

Demonstrative launch was conducted at Japan Atomic Energy Agency. A 1-MW Gyrotron (millimeter-wave oscillator) was used as a ground-based power source and a metallic rocket model of 126 g weight was successfully lifted up as shown in Fig. 8. The rocket model was continuously propelled for 1.2 m vertical distance using a repetitive pulse beam without any onboard propellant consumption.

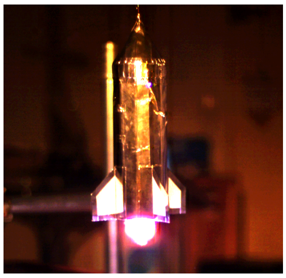


Figure 8. Demonstrative launch of Microwave Rocket.

Ion thruster

The University of Tokyo has successfully developed and operated miniature propulsion systems using ion thrusters on two small satellites: HODOYOSHI-4 and PROCYON. HODOYOSHI-4 is a 65 kg LEO satellite that was launched in June 2014 by a Dnepr rocket. It is equipped with a miniature ion propulsion system, named MIPS, and the first ion thruster operation was successfully conducted on December 28th that year. PROCYON is a 67 kg space probe that was inserted into an orbit around the Sun in December 2014 by a H-IIA rocket. PROCYON is equipped with a micropropulsion system, named I-COUPS, which unifies eight cold-gas thruster heads for RCS and an ion thruster for high Δv maneuver. The cold gas thrusters are operated since December 6th and the ion thruster has accomplished 223 hours operation since December 28th.

MIPS (Miniature Ion Propulsion System) was developed by the University of Tokyo[37] together with Next Generation Space Technology Research Association (NESTRA) in Japan, which developed HODOYOSHI-4. The satellite's primary mission was to demonstrate innovative small satellite technologies, and MIPS was one of the selected technologies. Development of the MIPS started from its EM in September 2011 to its final FM in March 2014. The FM has a total mass of 8.1 kg (dry mass: 7.1 kg), a volume of 34×26×16 cm^3, a power consumption of 39 W, and produces a thrust of 300 μN with a specific impulse of 1200 s (see Fig. 9).

I-COUPS (Ion thruster and COld-gas thruster Unified Propulsion System) was developed by the University of Tokyo as a propulsion system for the small space probe PROCYON[38]. PROCYON was launched as a small secondary payload by an H-IIA launch vehicle along with the main payload HAYABUSA-2 and it will be the first small space probe to explore deep space in the class of less than 100 kg. Components and structure of I-COUPS were based on MIPS and development of I-COUPS was finished within one year. Total mass of I-COUPS FM is 9.5 kg including 2.5 kg xenon propellant. The ion thruster produces a thrust of 350 μN and a specific impulse of 1000 s at 38 W of power consumption (see Fig. 10), and the cold-gas thruster yields a thrust of 22 mN and a specific impulse of 24 s at 8 W of power.

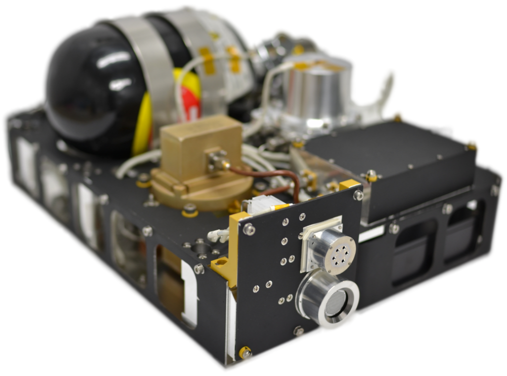


Figure 9. Flight model of the MIPS.

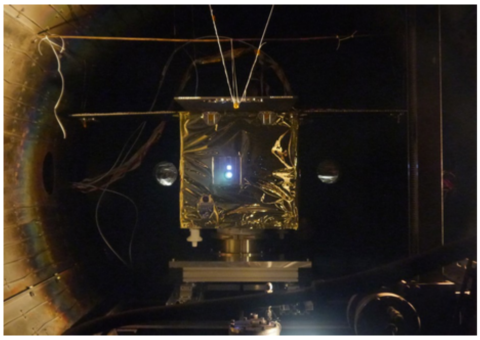


Figure 10. Firing of the ion thruster on the flight model PROCYON.

E. Research Activities at Tokyo University of Agriculture and Technology

Development of Electrodeless Plasma Thrusters with High-Density Helicon Plasma Sources

Many of conventional electric thrusters suffer from a problem of finite life time due to the electrode wastage. In order to solve this problem, we have been promoting the Helicon Electrodeless Advanced Thruster (HEAT) projec[39,40] to develop completely electrodeless advanced-concept electric thrusters. The entire process, i.e., a high electron density n_e (up to 10^{13} cm^{-3}) plasma production by helicon waves and its electromagnetic acceleration by novel proposed methods, can be achieved without any eroding electrodes.

First, we will show our developed helicon plasma sources. In the case of a long cylinder plasma with a small diameter and the weak magnetic field, N_e/P_{inp} is expected to be proportional to a^2 (a: plasma radius) from the classical (radial) diffusion, where P_{inp} (N_e) is the rf power (a total number of electrons in a plasma). As shown in Fig. 11, this scaling, close to a theoretical upper limit of a plasma production, holds good in a wide range of the plasma radius (from the largest diamete of 37 cm to the smalest one of 0.5 cm[40]. Recently, we have succeed in the plasma generation down to 0.3 cm in diameter. High-density discharges with a short axial plasma length and various antenna structures were also tried along with the combined use of electromagnets and permanent magnets.

Next, in addition to helicon source alone, some experimental and theoretical approaches of proposed acceleration schemes[39,40] were tried: 1) Rotating Magnetic

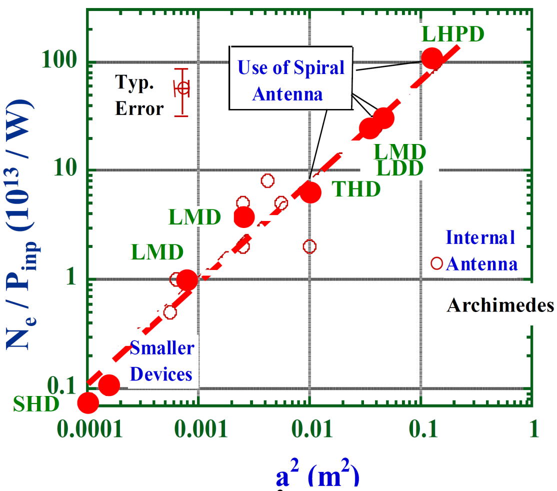


Figure 11. N_e/P_{inp} vs a^2 for different helicon sources. Here, red closed circles show the data taken by our group.

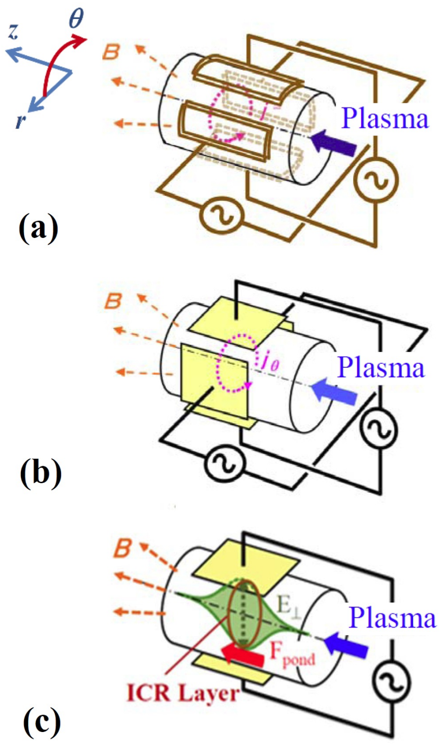


Figure 12. Proposed acceleration schemes: (a) Rotating Magnetic Field (RMF), (b) Rotating Electric Field (REF), and (c) ion cyclotron resonance (ICR) acceleration with a ponderomotive force acceleration (PA).

Field (RMF) acceleration, based on the Field Reversed Configuration (FRC) concept in a fusion field, 2) Rotating Electric Field (REF) or Lissajous acceleration, and 3) the ion cyclotron resonance (ICR) acceleration with a ponderomotive force acceleration (PA). (see Fig. 12)

Concerning the simple helicon sources alone, argon plasma thrust F up to 22 mN was obtained with P_{inp} less than 3 kW (Fig. 13), leading to the specific impulse I_{sp} of < 2,100 s (Fig. 14: plasma diameter was 15 cm). For Xe discharges, F was < 41 mN, as shown in Fig. 15. For the case of small diameter of 2.5 cm, higher I_{sp} was obtained with the lighter ions, e.g., < 4,000 s in hydrogen discharges. Concerning acceleration methods, e.g., the RMF method, show the increase of the ion velocity with the increase of the electron density, as shown in Fig. 16 (in an acceleration phase condition). Other schemes were also tried with developed diagnostics e.g., a diode laser for laser induced fluorescence method, a high-resolution monochromator, and a high-speed camera with optical filters).

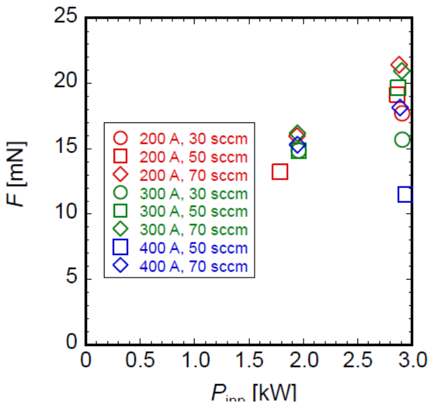


Figure 13. Argon plasma thrust as a function of rf power, changing the magnetic field coil current and gas flow rate.

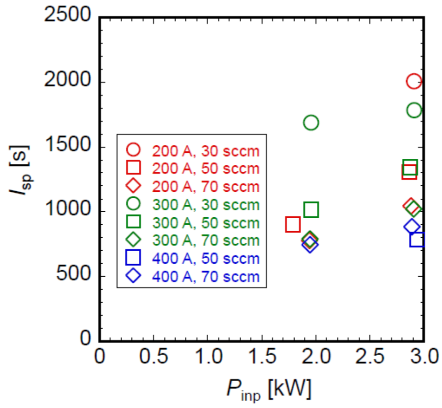


Figure 14. Specific impulse (argon plasma) as a function of rf power, changing the magnetic field coil current and gas flow rate.

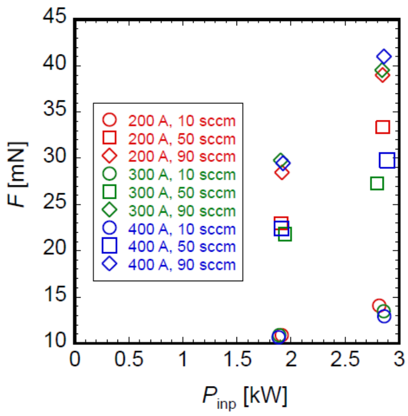


Figure 15. Xenon plasma thrust as a function of rf power, changing the magnetic field coil current and gas flow rate.

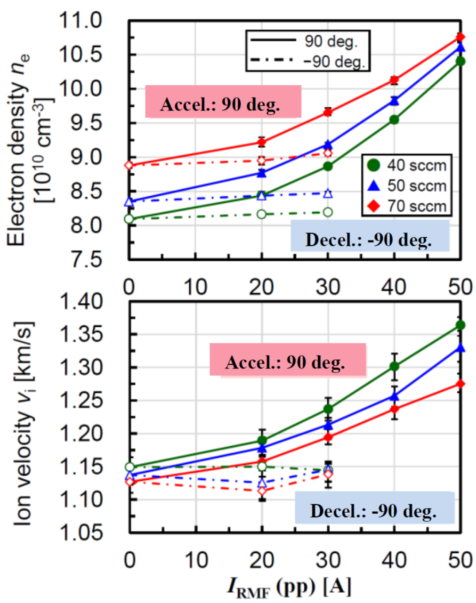


Figure 16. Electron density and argon ion velocity, changing the RMF coil current, gas flow rate, and the phase between two sets of RMF coils.

A working committee of sixteen members organized by Tokai University on "basic research and development of advanced electrodeless plasma thrusters (AEPTs)" has been established in the Japan Society of Plasma Science and Nuclear Fusion Research. The main objectives of the committee are to identify critical physics problems to be solved in order to develop AEPTs and to enhance interactions between researchers working on electric (or plasma) thrusters and those of various other plasma science and engineering fields so as to increase capabilities of solving the identified problems. It is hoped that the activities promoted by the committee can accelerate the development of AEPTs.

F. Research Activities at Tokyo Metropolitan University

RF Plasma Cathode for Electric Propulsion

To liberate Hall thrusters from the drawbacks associated with dispenser hollow cathodes[41-43], an outer coil-type radio frequency (RF) plasma cathode (Fig. 17) and an inner coil-type RF plasma cathode (Fig. 18) were constructed and experimentally evaluated. The influence of the coil configuration on the electron-emission characteristics of the RF plasma cathodes[44] is significant. Although a plasma cathode requires additional discharge power to produce electrons, it does not have the drawbacks associated with a thermionic emitter, and may achieve high robustness and a long lifetime. Electron cyclotron resonance (ECR) plasma[45-47], capacitively coupled plasma (CCP)[48], inductively coupled plasma (ICP)[49-51], and helicon wave plasma[52] have been investigated for cathode applications in electric propulsion. The microwave discharge ion thruster "µ10", which was installed in the Hayabusa asteroid explorer, is an attractive thruster that employs a thermionic-emitter-less design; it employed a microwave ECR discharge to ionize the propellant and a microwave ECR plasma cathode to neutralize the extracted ions.

Compared with the inner coil-type RF plasma cathode, the outer coil-type RF plasma cathode achieved higher electron-emission performance with low RF power[53]. For the outer coil-type RF plasma cathode, we obtained an anode current of 3.3 A at an RF power of 140 W, a xenon mass flow rate of 0.3 mg/s, and an anode voltage 58 V, as shown in Fig. 19. The anode current is sufficiently high to operate a 1-kW class Hall thruster. The gas utilization factor for the outer coil-type RF plasma cathode is comparable to that for a conventional dispenser hollow cathode. On the other hand, the electron production cost with the outer coil-type RF plasma cathode is four times higher than that with the hollow cathode. Thus, the reduction of the power consumption is necessary for the application of RF plasma cathodes to Hall thrusters.

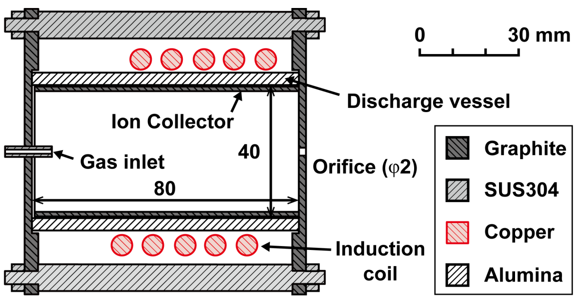


Figure 17. Cross Section of Outer Coil-type RF Plasma Cathode.

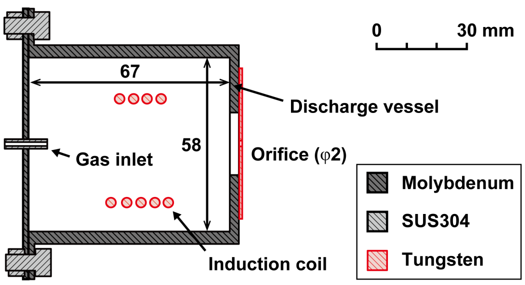


Figure 18. Cross Section of Outer Coil-type RF Plasma Cathode.

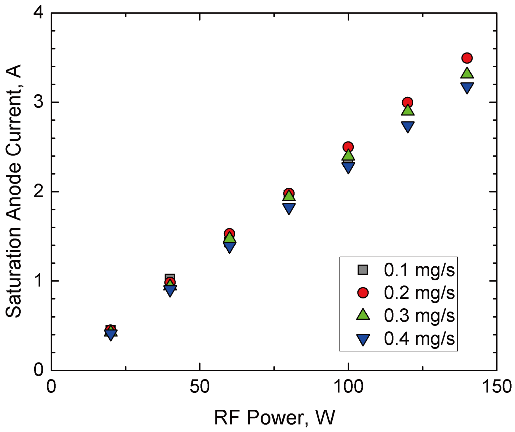


Figure 19. Anode Current from Outer Coil-type RF Plasma Cathode as a function of RF Power.

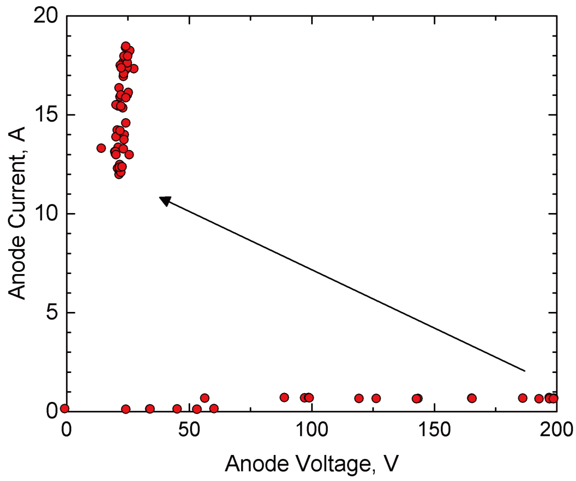


Figure 20. Anode Current with Inner Coil-type RF Plasma Cathode at 200 W RF Power and 2.0 mg/s Xe Mass Flow.

Figure 20 shows the anode current of the inner coil-type RF plasma cathode as a function of the anode voltage at an RF power of 200 W and xenon mass flow rate 2.0 mg/s. At the high RF power / high xenon mass flow rate, the transition phenomena for an anode current ranging from less than 1 A to over 12 A was observed as the applied anode voltage increased, as shown in Fig. 4. A high current operation over 12 A is indispensable for high-power Hall thruster operation. However, the transition phenomena and the high current operation were unstable. Thus, the further experimental evaluations to clarify the transition phenomena and the high current operation.

Performance Evaluation of TAL-type Hall Thruster with RF Plasma Cathode

Normal ion beam extraction and neutralization were experimentally confirmed with the combination of the TAL-type Hall thruster and the outer coil-type RF plasma cathode[54]. Figure 21 shows photographs of the thruster firing under the same conditions as that of the hollow cathode and the outer coil-type RF plasma cathode. The visual observation reveals that the discharge phenomenon does not depend on the types of cathode.

Figures 22 show the thrust performance for the two cathodes as a function of the discharge voltage at various anode mass flow rates, respectively. As shown in these figures, RF plasma cathode has the same capability for the TAL type hall thruster operation.

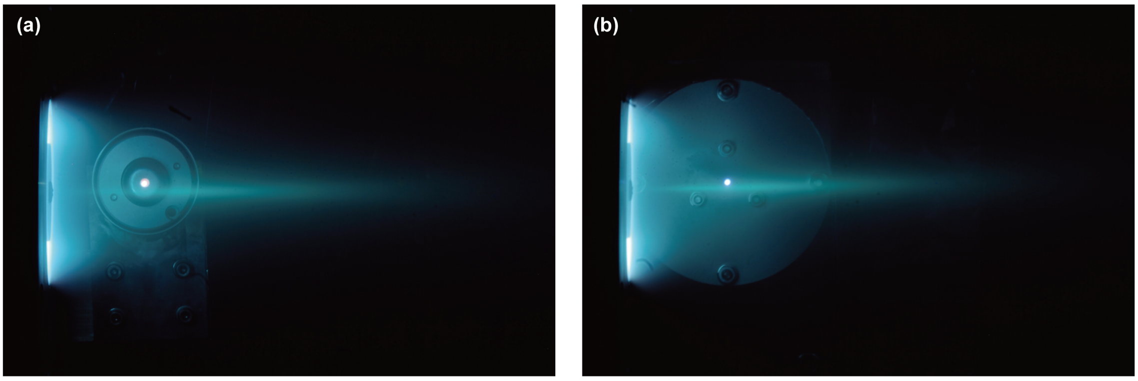


Figure 21. Photos of Thruster Firing at 300V Discharge Votage, 2.9 mg/s Anode Mass Flow Rate and 0.3 mg/s with (a) Hollow Cathode and (b) Outer Coil-type RF Plasma Cathode.

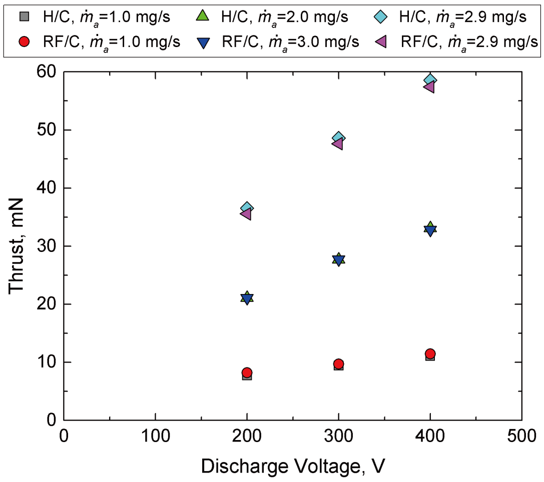


Figure 22. Thrust Comparison between H/C and Outer Coil-type RF/C.

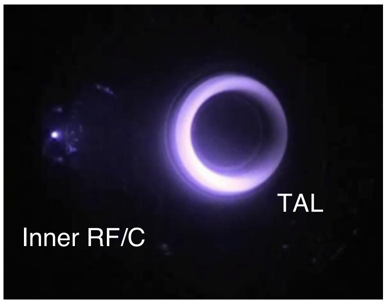


Figure 23. Coupling Phenomena at Inner RF/C Ignition Phase with TAL.

On the other hand, in the case of inner type RF plasma cathode application, when the inner type RF plasma cathode ignition was achieved, "*doughnut-like ring light*" was observed at the discharge chamber of Hall thruster (see Fig. 23). This coupling phenomena at inner RF/C ignition phase were observed only when inner RF/C is used as electron source. However, it never occurred, when hollow cathode is used as electron source.

Moreover, electron plume reversal by the direction of applied Hall magnetic field shows the interaction between TAL-type Hall thruster with inner type RF plasma cathode by the charged particle (i.e. electron). Nevertheless discharge power supply connected to the Hall thruster anode does not output the electrical power, induced current / voltage waveform (*f*:13.56 MHz) at TAL anode was observed, especially in voltage waveform. In the case of the conventional discharge oscillation in Hall thruster, the current oscillation of the discharge current is dominant. This voltage oscillation suggests the electric field interaction with the RF source, so capacitive coupling with the inner type RF plasma cathode may cause these unique phenomena. Some preliminary operation of TAL-type Hall thruster with inner type RF plasma cathode showed the sufficient steady-state operation and the reduction of discharge oscillation. Detailed evaluation of the thruster performance and the investigations of these interesting phenomena are planned for the understanding of physical process.

G. Research Activities at Tokyo Metropolitan College of Industrial Technology

Grid Wear Analysis

The grid wear analysis for a miniature ion engine[55] is conducted using the extended version of the JIEDI tool because the miniaturization of the ion engines introduces technical problems that have been settled for ordinary-sized ion engines: a shorter grid lifetime caused by erosion, due to the low plasma-production efficiency, and the lack of a gimballing device to countermeasure against the thrust-vector movement during flight. The complete three-dimensional lifetime analysis including the change in extraction ion beam performance (Figs. 24 and 25) is the first as well as predicting the erosion-induced change in the thrust-vector direction.

In addition to the grid wear analysis, the angular and energy dependence of the sputtering yield of a carbon-carbon composite due to xenon ion bombardment is investigated. The proposed model provided fairly good estimates of the angular and energy dependence of the sputtering yield for the carbon-carbon composite.

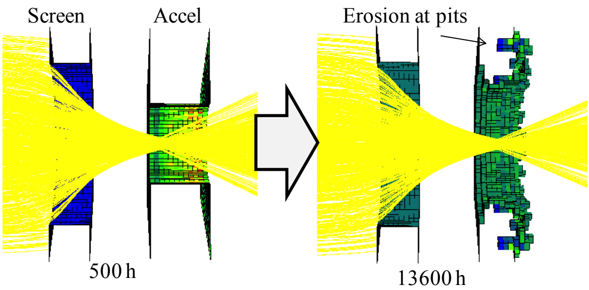


Figure 24. Ion beam trajectories and grid surfaces.

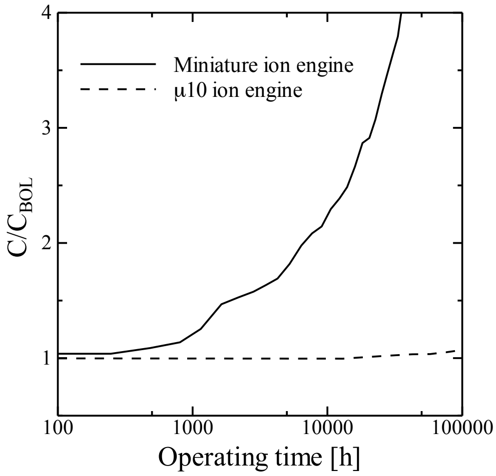


Figure 25. Comparison of change in grid conductance ratio.

Mission Analysis

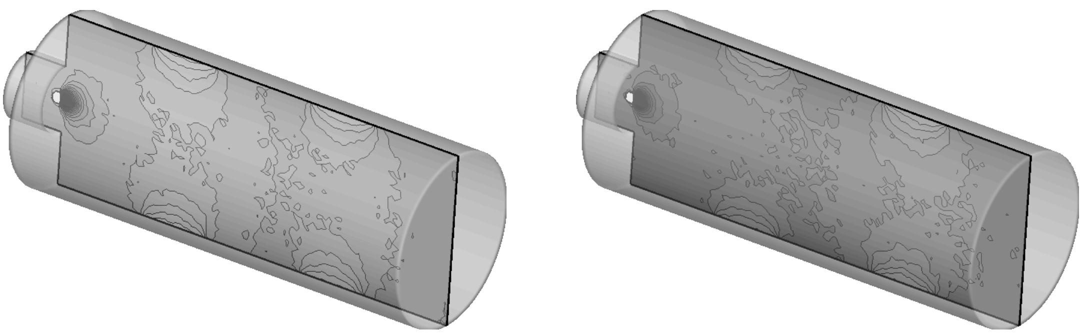
For RAIJIN project, feasibility studies of in-space transportation using a high-power thruster are in progress for tandem, triple or quad satellite insertions to high altitude orbits within several months.

H. Research Activities in National Defense Academy

The researches focused on the propellant flow and the neutralization phenomena of electrostatic thrusters are conducted in this laboratory[56,57]. This is because the both researches are closely related to the improvement of performance and durability.

The thrusters are performed in vacuum chambers in the development and durability estimation; ground test. Since the propellant reflects on the chamber wall until the propellant is pumped out, the back pressure in the ground test operation is higher than that in space operation. The back pressure affects the plasma production, the neutralization, and the erosion by the charge-exchange ion. Accordingly, the performance and durability may be over/under-estimated. Moreover, as shown in Fig. 26, the propellant distribution in the chamber is not uniform. Through the numerical analysis in this laboratory, it becomes clear that the distribution is influenced by the number and location of the vacuum pumps, the chamber shape, and the thruster location.

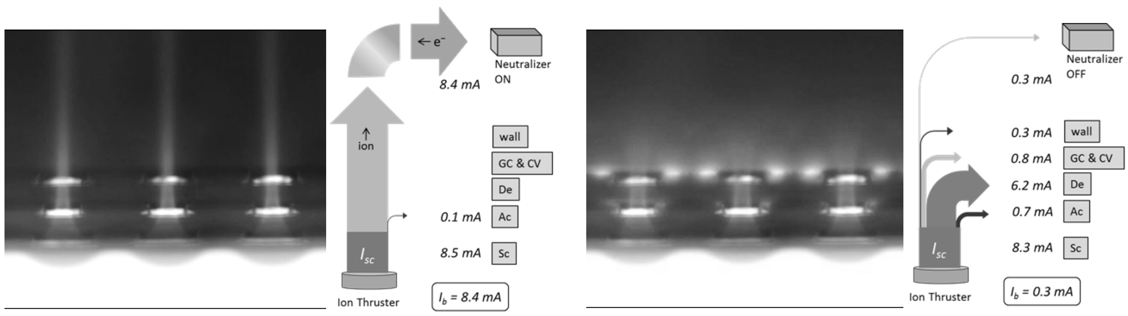
Figure 27 shows the photographs and the current flow charts in both the almost perfect neutralization case and the little neutralization case, with a two-dimensional visualized ion thruster. As shown in this figure, the neutralization phenomena in the both cases can be observed and evaluated. In this laboratory, the neutralization phenomena are researched for the improvement and the cause of neutralizer failure.



(a) Gridded ion thruster
(25 mN-class, 3000 s, Xe, with a neutralizer)

(b)Hall-effect ion thruster
(80 mN-class, 1500 s, Xe, with a neutralizer)

Figure 26. Pressure distribution within a vacuum chamber (2 m in diameter, 5 m in length, 4 pumps)



(a) almost perfect neutralization case (b) little neutralization case

Figure 27. Neutralization phenomena (with visualized ion thruster, 3 grid system)

I. Research Activities in Nagoya University

Magneto-plasma-dynamic Thruster

Two types of applied-field magneto-plasma-dynamic thruster (AF-MPDT) have been developed in Nagoya University[58]. Schematic illustrations of coaxial AF-MPDT and rectangular AF-MPDT are shown in Figs. 28 and 29.

Thrust performance of coaxial AF-MPDT of various discharge chamber diameter was obtained and the thrust was scaled by the operating characteristics and the chamber configuration. Scaling results of thrust was well agree with swirl thrust, as shown in Fig. 30.

Thrust performance of rectangular AF-MPDT of various anode-cathode distance is shown in Fig. 31. The thrust achieved about 60% of ideal electro-magnetic thrust, Lorentz force.

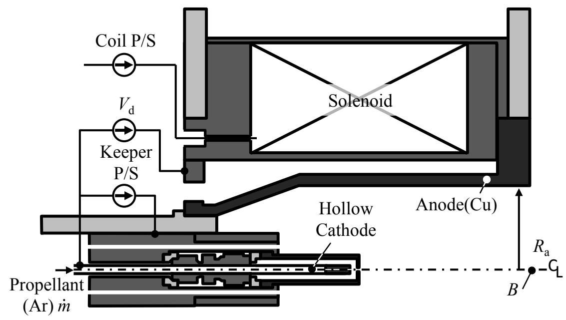


Figure 28. Schematic of coaxial AF-MPDT.

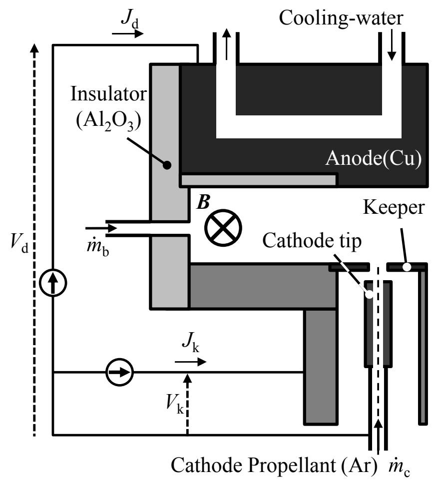


Figure 29. Schematic of rectangular AF-MPDT.

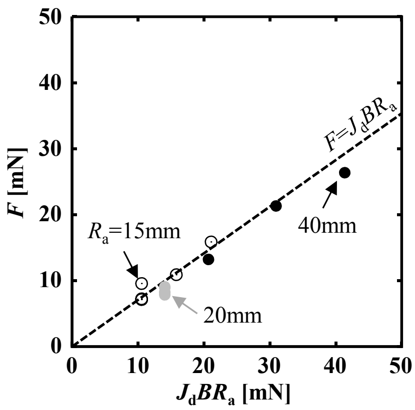


Figure 30. Thrust performance of coaxial AF-MPDT.

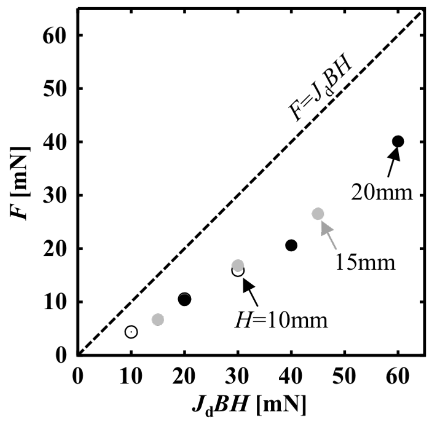


Figure 31. Thrust performance of rectangular AF-MPDT.

Helicon Electrostatic Thruster

Schematic of helicon electrostatic thruster which developed in Nagoya University is shown in Fig. 32. This thruster has plasma production region with radio frequency of 13.56 MHz and acceleration region using the voltage drop between anode and field free region generated by solenoid and magnet. Ion energy was measured by retarding potential analyzer, and the result of the energy is equivalent to applied voltage[59]. Thrust performance was measured and the result is shown in Fig. 33.

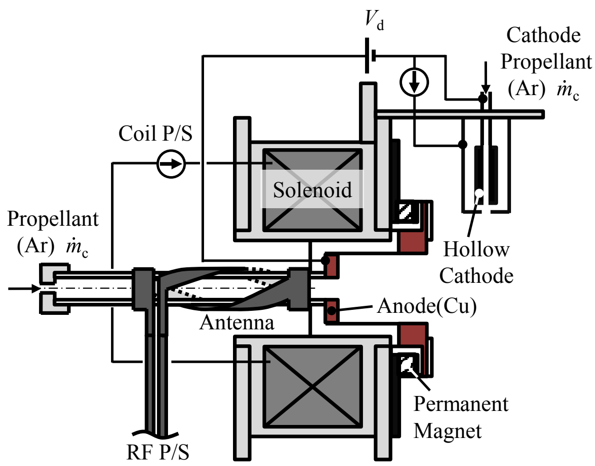


Figure 32. Helicon plasma electrostatic thruster.

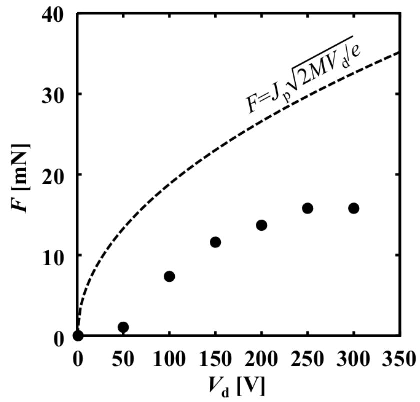


Figure 33. Thrust vs. applied voltage.

J. Research Activities in Gifu University

Operational Characteristics of Hall Thruster Cluster Systems

At Gifu University, to investigate the fundamental characteristics of cluster systems of Hall thruster, side-by-side (SBS) systems have been developed. The fundamental studies on operational characteristics of multi-head systems have been performed.[60-62] The SBS system has two magnetic-layer-type heads and a hollow cathode. In this study, the discharge current profiles of the two heads and the thrusts were measured for two different combinations of directions of magnetic fields applied by the two heads. The phase relation between the 20 kHz-range oscillations of the two discharge currents and the dependence of the thrusts on the discharge voltage were discussed. Figure 34 shows an image of the SBS system in operation. Linear-type magnetic-layer heads named GMK-1 were employed for the SBS system. Figure 35 shows a cross-sectional view of the GMK-I. In the SBS system, a HCN-252 hollow cathode is located in the center between the heads. The distance between the centerlines of the two heads in the measurements of the thrust is 156 mm. The measurements were performed using the space plasma chamber at Institute of ISAS-JAXA. The thrust was measured using a pendulum thrust stand. The propellant was xenon and its mass flow rate for the head was 12.5 sccm. The SBS system operated for two different combinations of magnetic field directions of the two heads.

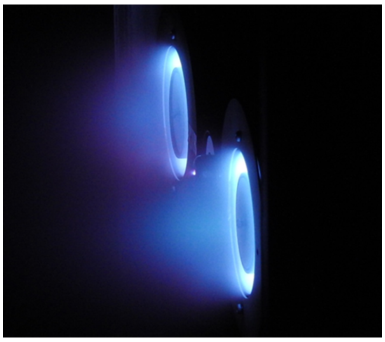


Figure 34. Image of the SBS system in operation.

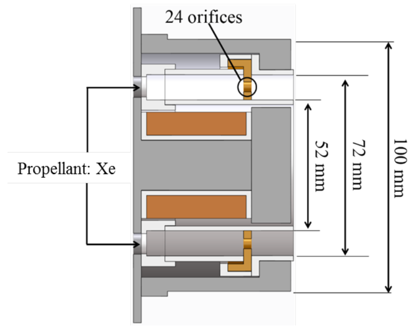


Figure 35. Cross-sectional view of GMK-I.

Figure 36 shows the discharge current profiles of the two heads for opposite directions of the magnetic fields at the discharge voltage of 180 V. In the profiles, 20 kHz-range oscillations in the coordinate phase are observed. The coordinate phase also appeared for the same direction of the magnetic fields. However, at low discharge voltages of 130 V and 150V, no clear phase relation were observed. These results suggest that the discharge characteristics are influenced by interactions between the two heads. The thrust ratio of $F_{opposite}$ for opposite directions of the magnetic field of the two heads to F_{same} for the same direction at various discharge voltages are shown in Fig. 37. The thrust for opposite directions was higher than that for the same direction at every discharge voltage. However, as the discharge voltage increased, the thrust ratio became lower. The dependency of the ratio on the discharge voltage can be explained in terms of the influences of the magnetic field interaction on the plume divergences. These results reveal that effects of the interferences on the discharge characteristics and the thrust performance appear in the cluster operations and depend on the combinations of the magnetic field directions and the discharge voltage.

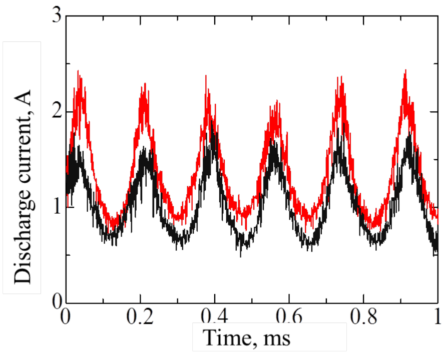


Figure 36. Discharge current profiles for opposite directions of the magnetic fields at 180 V.

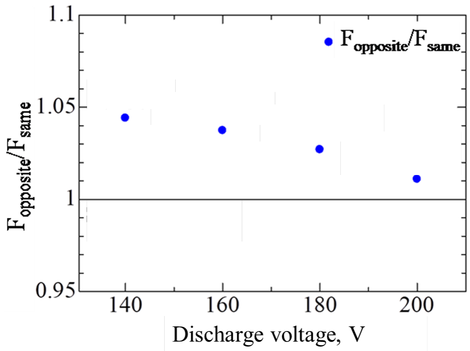


Figure 37. Ratio of thrust for two combinations of magnetic field directions.

K. Research Activities in Osaka Institute of Technology

MPD thruster

5-10 kW steady-state MPD thrusters have been investigated at Osaka Institute of Technology (OIT). In this study, a radiation-cooled MPD thruster system with simple structure has been developed for manned Mars exploration[63]. For an application of axial magnetic field, we use permanent magnets. Also, cathode erosion is one of important problems for practical use. One of the solutions may to use a hollow cathode. Figure 38 shows the three dimensional model of the water-cooled MPD thruster head with a multi-hollow cathode and the plasma plume with hydrogen. Accordingly, we could obtain the results of a thrust of 21.4 mN, a specific impulse of 2,907 s and a thrust efficiency of 4.92 % at 5.18 kW with hydrogen and the performance of 151 mN, 768 s and 5.73 % at 6.71 kW with ammonia. OIT was designing a fully

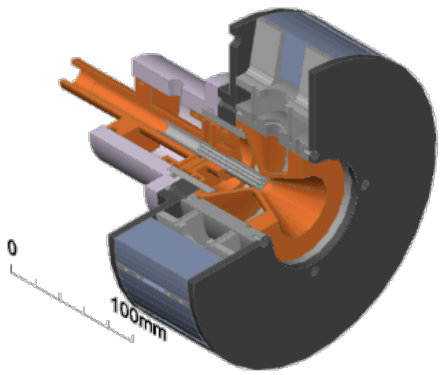


Figure 38. Steady-state water-cooled MPD thruster (3-D Model).

radiation-cooled MPD thruster with a radiation panel[64]. The prototype thruster was under operation.

Arcjet thruster

1 kW-class steady-state arcjet thrusters have been investigated[65]. We focused on HAN which is low toxicity propellant because it is easy to handle. In addition, a combustion performance with HAN is more than that with hydrazine. Therefore, it is believed that it will become a preferable propellant of next-generation satellite propulsion systems. However, initial ignition and stable operation is difficult with HAN. It is important to improve this point for practical use. Figure 39 shows the plasma plume with HAN decomposed gas. At a mass flow rate of 40 mg/s and a discharge current of 8 A, a thrust of 73.39 mN, a specific impulse of 187.29 s, and a thrust efficiency of 5.42 % were achieved at 0.86 kW with HAN compared 103.46 mN, 263.99 s and 5.24 % at 0.95 kW with hydrazine. We also focus on water as a propellant, but it is difficult to use it because of freezing in space. To prevent it from freezing, we manufactured gas generators to vaporize it. Accordingly, we could observe the short time operation using only water[66,67]. The long operation and reduction of the electrodes are future issues.

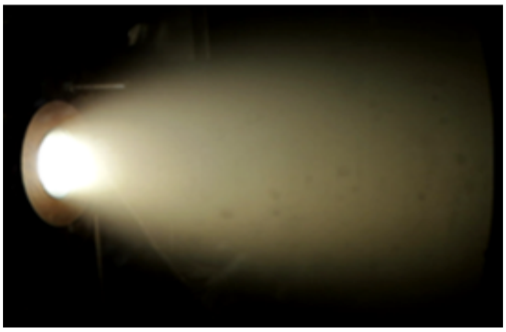


Figure 39. Plasma plume with HAN decomposed gas.

5-10 kW steady-state arcjet thrusters have been studied for orbital transfer or in-space propulsion[68]. Hydrogen and ammonia are used for high-performance and long-time operation. The red heating of the radiation-cooled anode just after 10 minutes operation was observed. The surface temperature of the anode was 1,098 K. The radiation heat loss at the anode was roughly calculated to be 13.18% on the total input power. OIT is designing a fully radiation-cooled arcjet thruster system.

Pulsed plasma thruster

The project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at OIT in 2007[69,70]. In 1st PROITERES, a nano-satellite with electrothermal-acceleration-type Pulsed Plasma Thrusters (PPTs) was successfully launched by the Indian PSLV C-21 rocket on September 9th, 2012. The main mission is to change an orbital altitude orbits as a powered flight by PPT systems for 1 km, and to observe Kansai district in Japan with a high-resolution camera. Furthermore, the project of the 2nd PROITERES was started in 2010. The 2nd PROITERES satellite aims at the powered flight with longer distance, i.e. changing 200-400 km in altitude on near-earth orbits, than that of the 1st PROITERES. The input energy of the PPT system was enlarged from 2.43 to 31.59 J for improvement of thrust performance[71,72]. OIT is developing a high-power and high-total-impulse PPT system with a multi-discharge room as shown in Fig.40.

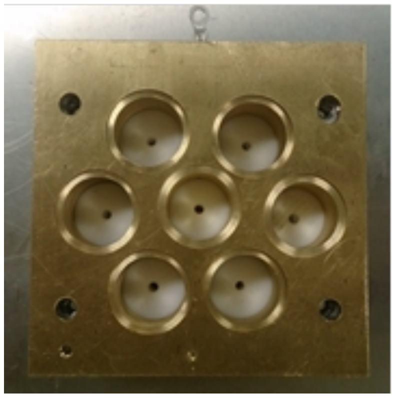
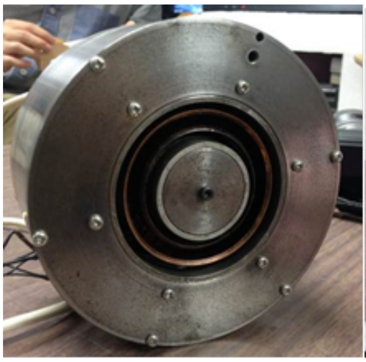
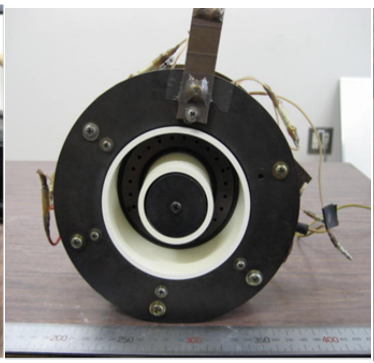


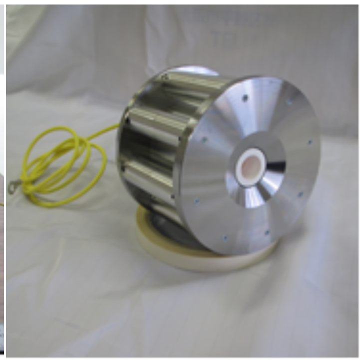
Figure 40. Multi-discharge-room type electrothermal PPT.

Hall thruster

Three types of Hall thruster have been investigated at OIT[73-75]. Figure 41 shows the Anode-Layer-Type Hall thruster (TAL-type) and the Magnetic-Layer-Type Hall thruster (SPT-Type) and the Cylindrical-Type Hall thruster (CHT-type). The high-power TAL and SPT types have been studied for manned Mars exploration, and the CHT-type will be equipped in the 3rd PROITERES nano-satellite for powered-flight to Moon. In order to achieve all missions, we are designing special structures of Hall thruster system with long lifetime. SPT-type achieved a thrust of 47.3-102.0 mN, a specific impulse of 1,608-3,468 s and a thrust efficiency of 48.9-63.4% with an input voltage of 300-1,000 V. CHT-type achieved a thrust of 1.1-5.5 mN, a specific impulse of 366-1,853 s and a thrust efficiency of 8.6-36.4% with an input power of 23-163 W. 5-10 kW TAL-type thrusters are under design.







(a) TAL-type (b) SPT-type (c) CHT-type

Figure 41 . Hall thrusters at Osaka Institute of Technology.

L. Research Activities at Kyushu University

As a part of the collaborative research and development project in Japan for practical use of high power anode layer type Hall thruster, 5 kW class anode layer Hall thruster (RAIJIN94[76]) have been developing and evaluated the thrust performance of it. The thrust was measured in the ion engine endurance test facility at ISAS/JAXA using a pendulum thrust stand developed at the University of Tokyo and Miyazaki University. The thrust performance of 3 kW operation of RAIJIN94 (anode mass flow rate of 9.8 mg/s and cathode mass flow rate of 0.5 mg/s), that is, the thrust, specific impulse, and the thrust efficiency is 160 mN, 1600 sec and 0.42, respectively. (see Fig. 42)

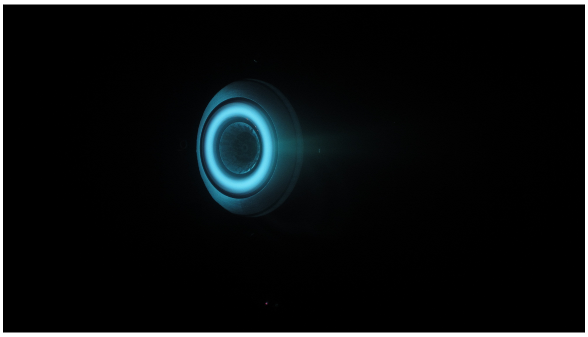
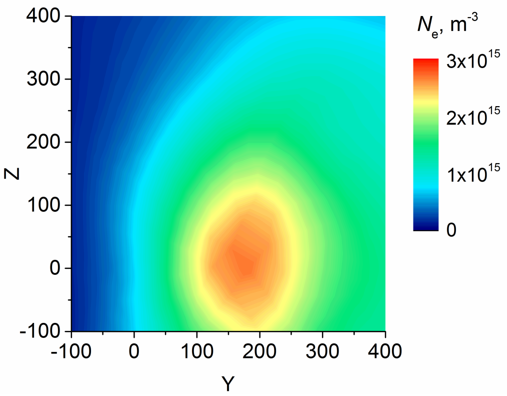


Figure 42. Photo of RAIJIN94. Mass flow rate of 9.8 mg/s, discharge voltage of 300 V.

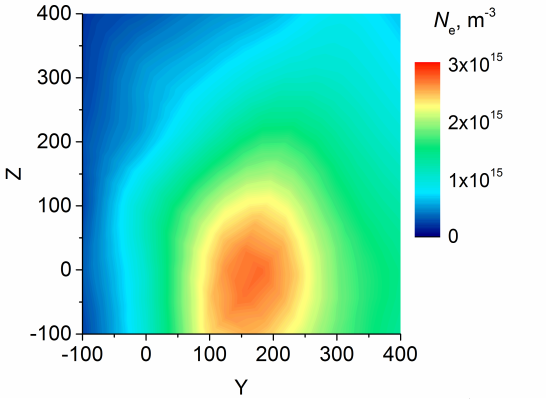
We also investigate the dependency of the plasma density distribution on pressure. Figure 43 shows the plasma density distribution of the side plane(250 mm far plain from the center plane of the thruster) at 1.35×10^{-3} Pa(two cryo pumps) and 2.40×10^{-3} Pa(one cryo pump). Plasma density increases with pressure due to charge exchange collision. These results are useful to validate numerical simulation code which estimates the interference between thruster plume and satellite body.

We built a sputter erosion sensor for estimation of electric propulsion lifetime by Cavity Ring-Down Spectroscopy (CRDS).[77,78] We measured sputtered atoms from an acceleration grid of ion thruster made of aluminum. As a probe laser, an external-cavity diode laser (ECDL) was used to measure the aluminum transition line from ground state to upper state, at 394.512 nm (Vacuum). The mass erosion rate of the grid is estimated as 55±14 ng/s in measuring space and find that the sputtered particles velocity distribution is complexity.

A field emission cathode (FEC) has attractive feature, no need of propellant, less electricity consumption, among other features. Ohkawa shows good performance of FEC with carbon nanotube[79], however, it might be degraded by atomic oxygen at the low earth orbit. We have been developing cubic boron nitride thin film field emission cathode as an electron emitter of the tether system because the film has remarkable properties such negative electron affinity, wide band bending and among other features[80]. The cathode consists of cBN film, a mask and gate grid for applied strong electric field and shield. The F-N plot shows that a field emission from the surface of the film was confirmed. The emitted current is 107 μA, that is 0.55 mA/cm^2.



(a)



(b)

Figure 43. Plasma density at two vacuum conditions. Mass flow rate of 1.36 mg/s, discharge voltage of 250 V.

M. Research Activities in University of Miyazaki and Kyushu Institute of Technology

University of Miyazaki and Kyushu Institute of Technology study electric propulsion devices and thrust evaluation method: a liquid propellant pulsed plasma thruster, arcjet thruster and thrust measurement devices for high-frequency thrust variation. Regarding a liquid propellant pulsed plasma thruster, co-axial electrode type thruster with an anode-nozzle area ratio of 30 (Fig. 44) was tested to evaluate the dependence of impulse bit (impulsive thrust developed by pulsed plasma thrusters), specific impulse and thrust efficiency on nozzle configuration[81]. Half angle of the anode nozzle θ ranged from 10 to 30°, and capacitor stored energy was varied from 0 to 15 J. Time history of pulsed arc discharge current was independent of θ, and showed underdamped oscillation at a 11-kA peak with 100 kHz. Thrust to power ratio was slightly increased with θ. The thrust measurement yielded a maximum impulse bit of 130 μNs at a capacitor-stored energy of 15 J for $\theta = 30°$.

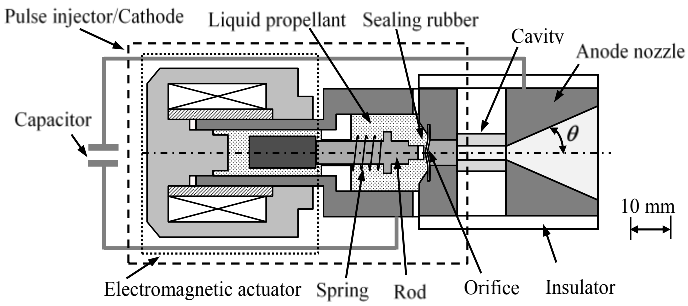


Figure 44. A Liquid Propellant Pulsed Plasma Thruster, Co-axial Electrode Type Thruster with an Anode-Nozzle Area Ratio of 30.

Dimethyl ether (DME) is used as a propellant for arcjet thruster to develop an eco-friendly arcjet thruster with simple structure. DME is a non-toxic liquefied gas of 0.6 MPa in vapor pressure and allows self-pressurization in propellant supply. DME is neither toxic nor reactive to materials so that it is currently used as a propellant for aerosol sprays in households. Hence, DME propellant allows to reduce costs for ground test and to simplify the structure of propellant feed systems. Nevertheless, the previous study shows that soot was produced inside the prototyped thruster and choked the nozzle. The choke due to soot production limits the period for thruster firing to 180 s. Moreover, arc discharge was destabilized by soot adhesion on electrode or nozzle throat. Hence, the group proposed to use water, some of which chemical reaction converts into radicals preventing soot production. At DME and water mass flow rates of 50 mg/s and 10 mg/s, the experiment showed that the soot production became negligible, and that arc discharge was stabilized.

A new thrust measurement method is proposed to evaluate

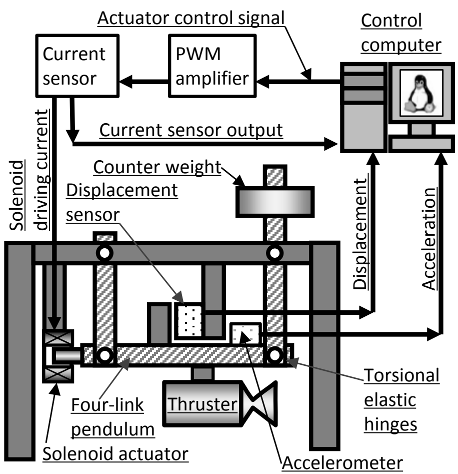


Figure 45. Prototyped thrust stand using null balance method and acceleration compensation.

thrust variation with time at relatively high frequency. Conventional thrust measurement methods, both displacement and null-balance method, have limitations in measurable frequency owing to the resonance of the pendulum[82]. Above one-third or one-tenth of the resonant frequency, the thrust stand shows over- or underestimation of thrust with phase delay owing to the resonance. The conventional null balance method showed resonance at 30 Hz, and thrust was measurable below 7 Hz if accepting 10 % error. Hence, the group proposed that the null balance method is compensated with acceleration measurement of the thrust stand pendulum, as shown in Fig. 45[83]. In the method, thrust is calculated from pendulum acceleration and actuator driving current that is used in the null balance method. Calibration for a prototyped thrust stand showed that 0.1-1 N class thrust was evaluated in the frequency range from 0 to 80 Hz whereas the conventional null balance method measured thrust below 10 Hz because of the resonance at 30 Hz.

Another thrust measurement device is designed and will be used for Hall thrusts. The thrust stand is an on-board type for Hall thruster to monitor thrust and health of the thruster in space. The currently designed thrust stand will be used for thrust measurement of RAIJIN hall thruster.

III. Concluding Remarks

Many research activities on electric propulsion and its accompanying science / technology have been executing for the near / far future space propulsion system by universities, institutes, manufacturers and JAXA. Summaries on our studies including ion thruster, hall thruster (magnetic layer type / anode layer type), MPD Arc Jet, Pulsed Plasma Thruster, Helicon Plasma Thruster, another thrusters and its electron sources, with / without applied magnetic / electric field for both large spacecraft and small satellite are addressed. Their fundamental concepts and state-of-the-arts were introduced and presented. Some studies are in the process of experimental and practical evaluation of performance.

Acknowledgments

The authors would like to express their sincere thanks to all Japanese researchers and engineers, especially, to the forerunners in electric propulsion, for their contribution to the electric / plasma propulsion system for next generation. Unfortunately, some promising researches are not described in this paper because of the restriction.

Some works are supported by JSPS KAKENHI (Grants-in-Aid for Scientific Research) and the sponsorship by JAXA.

References

[1] R. Tsukizaki, T. Ise, H. Koizumi, H. Togo, K. Nishiyama, and H. Kuninaka, "Thrust Enhancement of a Microwave Ion Thruster", Journal of Propulsion and Power, Vol.30, No.5, pp.1383-1389, 2014, 10.2514/1.B35118.

[2] T. Ise, R. Tsukizaki, H. Togo, H. Koizumi and H. Kuninaka, "Electric Field Measurement in Microwave Discharge Ion Thruster with Electro-Optic Probe", Review of Scientific Instruments, Vol.83, 124702, 2012, 10.1063/1.4770116.

[3] S. Kang, W. Choo, J. Choi, Y. Jeong, Y. Kim, S. Kang, H. Kuninaka and H. Cha, "Cathode Power Development of Hall Thruster for Small Satellite using Microwave cathode", Journal of the Korean Society for Aeronautical and Space Sciences, Vol.42, No.11, pp.974-980, 2014, 10.5139/JKSAS.2014.42.11.974.

[4] M. Nakano, Y. Kajimura, I. Funaki, JIEDI Tool: A Numerical Life Qualification Tool for Ion Engine Optics, Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan, Vol.10, 2012, pp.Pb_85-Pb_90.

[5] H. Watanabe, M. Nakano, Y. Kajimura, I. Funaki, Feasibility Study on Numerical Life Qualification of Ion Thruster's Ion Optics Using the JIEDI Tool, Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan, Vol. 12, No.ists29, pp.Pb_65-Pb_72, 2014.

[6] S. Cho, H. Watanabe, K. Kubota, S. Iihara, K. Fuchigami, K. Uematsu, I. Funaki, Parametric Kinetic Simulation of an IHI High Specific Impulse SPT-Type Hall Thruster, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 2014-3426, Cleveland, July 28-30, 2014.

[7] S. Cho, H. Watanabe, K. Kubota, S. Iihara, K. Fuchigami, K. Uematsu, I. Funaki, Particle Simulation of High Specific Impulse Operation of Low-Erosion Magnetic Layer Type Hall thrusters, 34th International Electric Propulsion Conference, IEPC-2015-251, Kobe, July 6-10, 2015.

[8] B. Karadag, S. Cho, I. Funaki, Numerical Validation of a Fully Kinetic Code through Parametric Uncertainty Analysis of a Hall thruster, 34th International Electric Propulsion Conference, IEPC-2015-255, Kobe, July 6-10, 2015.

[9] K. Kubota, Y. Oshio, H. Watanabe, S. Cho, Y. Ohkawa, I. Funaki, Hybrid-PIC Simulation on Plasma Flow of Hollow Cathode, 34th International Electric Propulsion Conference, IEPC-2015-15, Kobe, July 6-10, 2015.

[10] K. Kubota, I. Funaki, and Y. Okuno, Comparison of Simulated Plasma Flow field in a Two-dimensional Magnetoplasmadynamic Thruster with Experimental Data, IEEE Transaction on Plasma Science, Vol.37, No.12, 2009, pp.2390-2398.

[11] A. Kawasaki, K. Kubota, I. Funaki, Y. Okuno, MHD Simulation and Thermal Design of an MPD Thruster, Trans. JSASS, Aerospace Technology Japan, Vol.12, No.ists29, 2014, pp.Pb_19-Pb_25.

[12] A. Kawasaki, K. Kubota, I. Funaki, Y. Okuno, Plasma Flow Simulation of an MPD Thruster with an Electrode Model, 34th International Electric Propulsion Conference, IEPC-2015-201, Kobe, July 6-10, 2015.

[13] R.M., Winglee, J. Slough, T. Ziemba, and A. Goodson, Mini-Magnetospheric Plasma Propulsion: Trapping the Energy of the Solar Wind for Spacecraft Propulsion, Journal of Geophysical Research, Vol. 105, 2000, pp. 21067–21077.

[14] I. Funaki and H. Yamakawa, Solar Wind Sails, in Exploring the Solar Wind, Edited by Marian Lazar, In-Tech., Mar. 2012, pp.439-462.

[15] H. Arita, H. Nishida, I. Funaki, Magnetohydrodynamic Analysis of Thrust Characteristics on Magneto-Plasma Sail with Plasma Magnetic Field Inflation by Low-Beta Plasma, Trans. JSASS, Aerospace Technology Japan, Vol.12, No.ists29, 2014, p.Pb_39-Pb_44.

[16] Y. Ashida, I. Funaki, H. Yamakawa, H. Usui, Y. Kajimura, H. Kojima, Two-dimensional Particle-in-cell Simulation of Magnetic Sails, Journal of Propulsion and Power, Vol.30, 2014, pp.233-245.

[17] Y. Ashida, I. Funaki, H. Yamakawa, Y. Kajimura, Analysis of Small-scale Magneto Plasma Sail and Propulsive Characteristics, Trans. JSASS, Aerospace Technology Japan, Vol.12, No.ists29, 2014, p.Tb_11-Tb_18.

[18] Y. Oshio, K. Ueno, I. Funaki, H. Yamakawa, Thrust Measurement of Magnetoplasma Sail in Laboratory Experiment, Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan, Vol. 12 (2014) No. ists29 p. Pb_45-Pb_51,

[19] Y. Kajimura1, Y. Oshio, I. Funaki, M. Matsumoto, H. Yamakawa, Thrust Performance of Magneto Plasma Sail with a Magnetic Nozzle, 34th International Electric Propulsion Conference, IEPC-2015-329, Kobe, July 6-10, 2015.

[20] Y. Oshio, K. Ueno, T. Sano, I. Funaki, Experimental and Numerical Investigation of Magnetosphere Inflation of Magnetoplasma Sail, 34th International Electric Propulsion Conference, IEPC-2015-330, Kobe, July 6-10, 2015.

[21] K. Ueno, Y. Oshio, I. Funaki, H. Yamakawa, Preliminary Results of Multi-Coilmagnetic Sail Experiment, 34th International Electric Propulsion Conference, IEPC-2015-331, Kobe, July 6-10, 2015.

[22] Y. Nagasaki, I. Funaki, T. Nakamura, H. Yamakawa, Increase in Thrust of Magneto Plasma Sail using Solid or Deployable Superconducting Coil, 34th International Electric Propulsion Conference, IEPC-2015-328, Kobe, July 6-10, 2015.

[23] Izawa, Y., Suzuki, K., Takahashi, K., and Ando, A., "Effect of a Magnetic Nozzle in a MPD Thruster," *Japan Physical Society Conference Proceedings* vol.1, pp.015046-1 – 4, 2014.

[24] Takahashi, K., Charles, C., Boswell, R.W., "Approaching the Theoretical Limit of Diamagnetic-Induced Momentum in a Rapidly Diverging Magnetic Nozzle," *Physical Review Letters*, vol.110, pp.195003-1 – 5 (2013).

[25] Takahashi, K., Chiba, A., Komuro, A., and Ando, A., "Axial Momentum Lost to a Lateral Wall of a Helicon Plasma Source," *Physical Review Letters*, vol.114, pp.195001-1 - 5 (2015).

[26] Takahashi, K., Komuro, A., and Ando, A., *private communication* (2015).

[27] Takahashi, K., Komuro, A., and Ando, A., "Low-pressure, high-density, and supersonic plasma flow generated by a helicon magnetoplasmadynamic thruster," *Appl. Phys. Lett.*, vol.105, pp. 193503-1 – 4, 2014.

[28] Takahashi, K., Charles, C., Boswell, R.W., and Ando, A., "Performance improvement of a permanent magnet helicon plasma thruster," *Journal of Physics D: Applied Physics*, vol. 46, pp. 352001-1 – 5, 2013.

[29] T. Schönherr, R. Kawashima, H. Koizumi, K. Komurasaki, D. Fujita, and Y. Ito, "Design and performance evaluation of thruster with anode layer UT-58 for high-power application," 33rd International Electric Propulsion Conference, IEPC-2013-242, Oct. 2013.

[30] Y. Hirano, "Reduction of the Guard Erosion in a 2 Kw Anode Layer Hall Thruster," 30th International Symposium on Space Technology and Science, ISTS-2015-s-02-b, Jul. 2015.

[31] D. Fujita, R. Kawashima, Y. Ito, S. Akagi, J. Suzuki, T. Schönherr, H. Koizumi, and K. Komurasaki, "Operating parameters and oscillation characteristics of an anode-layer Hall thruster with argon propellant," Vacuum, vol. 110, pp. 159–164, Dec. 2014.

[32] T. Schönherr, F. Nees, Y. Arakawa, K. Komurasaki, and G. Herdrich, "Characteristics of plasma properties in an ablative pulsed plasma thruster," Physics of Plasmas, vol. 20, pp. 033503, Mar. 2013.

[33] M. Lau, S. Manna, G. Herdrich, T. Schönherr, and K. Komurasaki, "Investigation of the plasma current density of a pulsed plasma thruster," Journal of Propulsion and Power, vol. 30, pp. 1459-1470, Nov.-Dec. 2014.

[34] T. Schönherr, M. Stein, K. Komurasaki, and G. Herdrich, "Investigation of discharge arc phenomena in ablative PPT," 34th International Electric Propulsion Conference, IEPC-2015-079, July 2015.

[35] W. Y. L. Ling, H. Koizumi, and T. Schönherr, "Use of liquid propellants in pulsed plasma thrusters for small satellites," 34th International Electric Propulsion Conference, IEPC-2015-139, July 2015.

[36] M. Fukunari, A. Arnault, T. Yamaguchi, and K. Komurasaki, "Replacement of Chemical Rocket Launchers by Beamed Energy Propulsion," Applied Optics, vol. 53, pp. I16-I22, Nov. 2014.

[37] H. Koizumi, K. Komurasaki, J. Aoyama, and K. Yamaguchi, "Engineering Model of the Miniature Ion Propulsion System for the Nano-satellite," Trans. JSASS Space Tech. Japan, vol. 12, pp. Tb_19-Tb_24, 2014.

[38] H. Koizumi, H. Kawahara, K. Yaginuma, J. Asakawa, R. Funase, and K. Komurasaki, "In-Flight Operation of the Miniature Propulsion System Installed on Small Space Probe: PROCYON," 34th International Electric Propulsion Conference, IEPC-2015-276, July 2015.

[39] Shinohara, S., Tanikawa, T. Hada, T., Funaki, I., Nishida, H., Matsuoka, T., Otsuka, F., Shamrai, K. P., Rudenko, T. S., Nakamura, T., Mishio, A., Ishii, H., Teshigahara, N., Fujitsuka, H. Waseda, S., "High-Density Helicon Plasma Sources: Basics and Application to Electrodeless Electric Propulsion," Trans. Fusion Sci. Technol., vol. 63, no. 1T, May, 2013, pp. 164-167.

[40] S. Shinohara, H. Nishida, T. Tanikawa, T. Hada, I. Funaki, K. P. Shamrai, "Development of Electrodelss Plasma Thrusters with High-Density Helicon Plasma Sources: Basics," IEEE Trans. Plasma Sci., vol. 42, no. 5, 6 May, 2014, pp. 1245-1254.

[41]Vladimir Kim, Garri Popov, Boris Arkhipov, Vyacheslav Murashko, Oleg Gorshkov, Anatoly Koroteyev, Valery Garkusha, Alexander Semenkin, Sergei Tverdokhlebov, "Electric Propulsion Activity in Russia," 27th International Electric Propulsion Conference, IEPC Paper 2001-005, Pasadena, CA, 2001.

[42] Shristophe R. Koppel, Frederic Marchandise, Denis Estublier, Laurent Joliver, "The SMART-1 Electric Propulsion Subsystem in Flight Experience," 40th Joint Propulsion Conference, AIAA Paper 2004-3435, Fort Lauderdale, FL, July, 2004.

[43]Alex Mathers, Kristi de Grys, Jonathan Paisley, "Performance Variation in BPT-4000 Hall Thrusters," 31st International Electric Propulsion Conference, IEPC Paper 2009-144, Ann Arbor, MI, September, 2009.

[44] E. M. Oks, "Physics and technique of plasma electron sources," Plasma Source Science and Technology, Vol. 1, 1992, pp. 249-255.

[45] Ikkoh Funaki and Hitoshi Kuninaka, "Overdense Plasma Production in a Low-power Microwave Discharge Electron Source," Japanese Journal of Applied Physics, Vol. 40, Part. 1, No. 4A, 2001, pp. 2495-2500.

[46] B. R. Weatherford, J.E. Foster H. Kamhawi, "Electron current extraction from a permanent magnet waveguide plasma cathode," Review of Scientific Instruments, Vol. 82, 2011, 093507.

[47] L. Liard, Y. Zhu, G. J. M. Hagelaar, J. -P. Boeuf, "Fluid simulation of a microwave plasma cathode," 33rd International Electric Propulsion Conference, IEPC-2013-396, Washington, D.C., Oct., 2013.

[48] St. Weis, K. –H. Schartner, H. Loeb, D. Feili, "Development of a capacitively coupled insert-free RF-neutralizer," 29th International Electric Propulsion Conference, IEPC Paper 2005-086, Princeton, NJ, 2005.

[49] F. Scholze, M. Tartz, H. Neumann, "Inductive coupled radio frequency plasma bridge neutralizer," Review of Scientific Instruments, Vol. 79, 2008, 02B724.

[50] Yevgeny Raitses, Jennifer K. Hendryx and Nathaniel J. Fisch, "A Parametric Study of Electron Extraction from a Low Frequency Inductively Coupled RF-Plasma Source," 31st International Electric Propulsion Conference, IEPC Paper, 2009-024, Ann Arbor, MI, September, 2009.

[51] Hiroki Watanabe, Takuji Okuma, Junichiro Aoyagi and Haruki Takegahara, "Research and Development on Inductively Coupled Plasma Cathode for Ion Engines," 31st International Electric Propulsion Conference, IEPC Paper 2009-027, Ann Arbor, MI, September, 2009.

[52] Ben Longmier and Noah Hershkowitz, "Improved operation of the nonambipolar electron source," Review of Scientific Instruments, Vol. 79, 2008, 093506.

[53] Hiroki Watanabe, Takanori Deguchi, Chisato Ota, Jun Sato, Shuka Takeda, Yuki Miura, Yuki Sato,
Masanori Ichimura, and Haruki Takegahara, "Performance Evaluation of Radio Frequency Plasma Cathode for Hall Effect Thruster," 34th International Electric Propulsion Conference, IEPC Paper 2015-194, Kobe, July 6-10, 2015.

[54] Hiroki Watanabe, Yuki Miura, Masanori Ichimura, Takanori Deguchi, Shuka Takeda, Chisato Ota, and Haruki Takegahara, "Performance Evaluation of TAL-type Hall Thruster with RF Plasma Cathode," 34th International Electric Propulsion Conference, IEPC Paper 2015-217, Kobe, July 6-10, 2015.

[55] Nakano, M., and Koizumi, H., "Grid Wear Analysis of a Miniature Ion Engine," IEPC-2015-187 /ISTS-2015-b-187.

[56] Nakayama, Y. and Nakamura, M., "Electric Propulsion Propellant Flow within Vacuum Chamber," *34th International Electric Propulsion Conference*, 2015-b/IEPC-360, Kobe, Japan, 2015.

[57] Nakayama, Y. and Tanaka F., "Experimental Visualization of Ion Thruster Neutralization Phenomena," *IEEE Transactions on Plasma Science*, Vol. 43, No. 1, 2015, pp. 269-276.

[58] Ichihara, D., Harada, D., Kataoka, H., Yokota, S., Sasoh, A., "Operation Characteristics of Steady-State, Applied Field, Rectangular Magnetoplasmadynamic (MPD) Thruster," *J. Jpn. Soc. Aeronaut. Space Sci.*, **63** (2015), pp. 37-44.

[59] Harada, S., Baba, T., Uchigashima, A., Yokota, S., Iwakawa, A., Sasoh, A., Yamazaki, T., Shimizu, H.: Electrostatic Acceleration of Helicon Plasma Using a Cusped Magnetic Field, *Appl. Phys. Lett.*, **105** (2014), pp. 194101.

[60] Miyasaka, T., Asato, K., Muraki, R., Furuta, D., and Kubota, K., "Investigation of Side by Side of Side by Side Hall Thruster System," 33rd International Electric Propulsion Conference, IEPC-2013-110, Washington, 2013.

[61] Shimizu, D., Miyasaka, T., Asato, K., Furuta, D., Uyama, Y., Goto, R., and Yoshida, M.., "Influences of Plume Interference on Discharge Characteristics of Two Magnetic-Layer Heads," *Plasma Application & Hybrid Functionally Materials*, Vol. 24, Hawaii, 2015.

[62] Furuta, D., Miyasaka, T., Asato, K., Shimizu, D., Uyama, Y., Goto, R., and Yoshida, M., "Thrust Performance on Side by Side Magnetic-Layer System," *Plasma Application & Hybrid Functionally Materials*, Vol. 24, Hawaii, 2015.

[63] Suzuki, T., Koyama, N., Sugiyama, Y., Sakoda, H. and Tahara, H., "Performance Characteristics of Steady-State MPD Thrusters with Permanent Magnets and Multi Hollow Cathodes for Manned Mars Exploration," *30th International Symposium on Space Technology and Science34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, IEPC-2015-197 /ISTS-2015-b-197, Hyogo, Japan, 2015.

[64] Sugiyama, Y., Koyama, N., Suzuki, T., Sakoda, H. and Tahara, H., "Thermal Characteristics of Radiation-Cooled Steady-State MPD Thrusters with Permanent Magnets and Multi Hollow Cathodes for In-Space Propulsion," *30th International Symposium on Space Technology and Science34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, IEPC-2015-198 /ISTS-2015-b-198, Hyogo, Japan, 2015.

[65] Fukutome, Y., Shiraki, S., Matsumoto K, Inoue, F., Tahara1, H., Nogawa, Y., and Momozawa, A., "Performance Characteristics of Low-Power Arcjet Thrusters Using Low-Toxicity Propellants of HAN," *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,* IEPC-2015-229 and ISTS-2015-b-229, Hyogo, Japan, 2015.

[66] Shiraki, S., Fukutome, Y., Inoue, F., Matsumoto, K., Tahara, H., Nogawa, Y., and Momozawa, A., "Performance Characteristics of Low-Power Arcjet Thruster Systems with Gas Generators for Water," *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,* IEPC-2015-230 /ISTS-2015-b-230, Hyogo, Japan, 2015.

[67] Nogawa, Y. and Tahara, H., “Water Electrical Propulsion System Combined with Manned Space Mission,” *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,* IEPC-2015-33 /ISTS-2015-b-33, Hyogo, Japan, 2015.
[68] Inoue, F., Fukutome, Y., Shiraki, S., Matsumoto K., and Tahara1, H., “Performance and Thermal Characteristics of High-Power Hydrogen Arcjet Thrusters with Radiation-Cooled Anodes for In-Space Propulsion,” *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,* IEPC-2015-231 and ISTS-2015-b-231, Hyogo, Japan, 2015.
[69] Kamimura, T., Nishimura, Y., Ikeda, T., and Tahara, H., “R&D and Final Operation of Osaka Institute of Technology 1st PROITERES Nano-Satellite with Electrothermal Pulsed Plasma Thrusters and Development of 2nd and 3rd Satellites,” *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, IEPC-2015-209 /ISTS-2015-b-209, Hyogo, Japan, 2015.
[70] Kojima, Y., Kamimura, T., Nishimura, Y., Ikeda, T., Fujita, R., Tahara, H., and OIT PROITERES Team, “R&D and Final Operation of Osaka Institute of Technology 1st PROITERES Nano-Satellite with Electric Rocket Engines and Development of 2nd and 3rd Satellites,” *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, NSAT-2015-f-13, Hyogo, Japan, 2015.
[71] Fujita, R., Muraoka, R., Kanaoka, K., Huanjun, C., Tanaka, M., Tahara, H. and Wakizono, T., “Flowfield Simulation and Performance Prediction of Electrothermal Pulsed Plasma Thrusters Onboard Osaka Institute of Technology PROITERES Nano-Satellite Series,” *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, IEPC-2015-207 /ISTS-2015-b-207, Hyogo, Japan, 2015.
[72] Kanaoka, K., Fujita, R., Muraoka, R., Tahara, H. and Wakizono, T., “Research and Development of High-Power Electrothermal Pulsed Plasma Thruster Systems for Osaka Institute of Technology 2nd PROITERES Nano-Satellite,” *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, IEPC-2015-22 /ISTS-2015-b-22, Hyogo, Japan, 2015.
[73] Kagota, T., Takahata, Y., Kakuma, T., Nishida, M., Ikeda, T. and Tahara, H., “Performance Characteristics of High-Power, High-Specific-Impulse Anode-Layer-Type Hall Thrusters for In-Space Propulsion,” *30th International Symposium on Space Technology and Science34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, IEPC-2015-153 /ISTS-2015-b-153, Hyogo, Japan, 2015.
[74] Takahata, Y., Kakuma, T., Kagota, T., Nishida, M., Ikeda, T. and Tahara, H., “Research and Development of High-Power, High-Specific-Impulse Magnetic-Layer-Type Hall Thrusters for Manned Mars Exploration,” *30th International Symposium on Space Technology and Science34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, IEPC-2015-151 /ISTS-2015-b-151, Hyogo, Japan, 2015.
[75] Kakuma, T., Ikeda, T., Nishida, M., Kagota, T., Takahata, Y. and Tahara, H., “Research and Development of Low-Power Cylindrical-Type Hall Thrusters for Nano/Micro Satellites,” *30th International Symposium on Space Technology and Science34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, IEPC-2015-302 /ISTS-2015-b-302, Hyogo, Japan, 2015.
[76] N. Yamamoto at el., Developments of Robust Anode-layer Intelligent Thruster for Japan IN-space propulsion system, IEPC paper 2013-244, 2013.
[77] B. C. Lee, W. Huang, L. Tao, N. Yamamoto, A. D. Gallimore and A. P. Yalin, A cavity ring-down spectroscopy sensor for real-time Hall thruster erosion measurements, Rev. Sci. Instrum. 85, 053111 (2014); http://dx.doi.org/10.1063/1.4879135
[78] A. Yamaguchi at el., Measurement of Aluminum Erosion Rate by Cavity Ring-Down Spectroscopy, ISTS paper 2015-b-17-s, 2015.
[79] Y. Ohkawa, S. Kawamoto, M. Higashide, et al: ELECTRODYNAMIC TETHER PROPULSION FOR ORBITAL DEBRIS DEORBIT, The Journal of Space Technology and Science, vol.26, No.1, P33-46, 2012.
[80] K. Teii, R. Yamao, S. Matsumoto: Effect of cubic phase evolution on field emission properties of boron nitride island films, J. Appl. Phys. 106, 113706 (2009)
[81] Miyagi, M., Masui, S., Kakami, K., and Tachibana, T.: Influence of Electrode Configuration of a Liquid Propellant PPT on its Performance, *International Electric propulsion conference*, IEPC-2015-138 (2015)
[82] Kakami, A., Hiyamizu, R., Masaki, S., Tachibana, T: A Preliminary Study on an Active-controlled Thrust Stand for Thrust Variation Measurement, *Selected paper of 25th International Symposium on Space Technology and Science*, ISTS2006-b-19 (2006), pp. 212-217.
[83] Kakami, A., and Tachibana, T: Thrust Evaluation in Wide Frequency Range using Active Control and Disturbance Observer, *Journal of Propulsion and Power*, **29** (2013), pp. 1274-1281.