JOURNAL OF PROPULSION AND POWER
Vol. 14, No. 6, November–December 1998

Development and Demonstration of a Cathodeless Electron Cyclotron Resonance Ion Thruster

Hitoshi Kuninaka* and Shin Satori†
Institute of Space and Astronautical Science, Kanagawa 229, Japan

The electron–cyclotron–resonance microwave-discharge ion thruster system utilizes no cathodes to emit thermionic electrons for plasma generation in both the ion source and the neutralizer. The ion source can generate xenon ions at an ion-production cost of 300 eV and a propellant utilization efficiency of 88%, with a double-charged-ion population of 8%. The neutralizer can output 100 mA of electron current with 10 W of microwave power and 0.5 sccm of xenon flow. The thruster system combining the ion source and the neutralizer operated for 300 h without detectable erosion of the screen grid and ion source. Except for the primary frequency of 4.2 GHz used to generate plasmas, the system proved experimentally compatible with spacecraft electromagnetic interference requirements in the microwave frequency range.

Introduction

MUCH ground testing and many flight demonstrations have been devoted to the development of ion thrusters. Through many development programs, several critical parts have been identified for long-term operation. Reference 1 summarizes seven failure modes on the most modern dc discharge ion engines. Some of these modes originated from the electrostatic acceleration, and others from the plasma production. The screen grid erosion and the cathode heater failure, belonging to the latter group, are indicated as possible failure modes to limit the service life. The screen grid, biased at the cathode potential, attracts ions from the ion source and is worn thin by sputtering.[2] Repetitive thermal shocks of temperature differences over 1000°C between standby and operation will fatigue a heater material. Reference 3 describes the performance, reliability, and life of hollow cathodes that are sensitive to atmospheric exposure. Environmental exposure restrictions of cathodes complicate the integration and testing of spacecraft on preflight ground operations. Residual products in the propellant gas deteriorate the function of the hollow cathodes so that the purity of xenon is severely controlled and/or an oxygen-absorber may be applied in the gas feed line.[4] Design improvements, special procedures, and careful handling solve these critical items on the dc discharge ion thruster system.

Although failure modes associated with electrostatic acceleration are common to all ion engines, the microwave and radio frequency (rf) discharges are fundamentally relieved from the previously mentioned difficulties on the plasma production because of plasma generation without solid electrodes, thermionic electron emission, or a large potential gap. An ion thruster with an rf discharge ion source has been proven in space flight.[5] A microwave discharge ion source using a tunable cylindrical cavity has been researched and developed.[6] It does not generate plasma efficiently enough to apply it in space because the quartz housing separating the discharge zone from the cavity prevents plasma confinement. Another problem encountered in experimental demonstrations was contamination on the quartz housing, located parallel to the electrostatic grids, which attenuate the microwave power. This paper will present another type of plasma source, the electron cyclotron resonance (ECR) microwave discharge plasma source, which avoids these problems through a change in geometry and by the utilization of magnetic fields produced by permanent magnets to confine and keep the plasma away from the vacuum window or the dielectric of the microwave transmission line.[7] To the authors' knowledge, there have been no attempts to apply the microwave and rf discharges to the neutralizer of the ion thruster. The simplified system of the cathodeless ion thruster is proposed in Fig. 1. The ion source and the neutralizer are fed by a single microwave generator and a single gas flow controller through passive dividers. Two dc power supplies are dedicated to biasing the screen and acceleration grids. This system has only four components to control.

The microwave generators required by this system are new components. The traveling-wave-tubes (TWT) and the semiconductor solid-state amplifiers are space-borne microwave generators, which are well qualified and proven in space flight. However, their electrical efficiency is not as high as that of the dc–dc converter.[8,9] The low efficiency of the microwave generation increases the effective ion production cost of the microwave ion thruster. In the state of the art, the 50-W class TWT of 4 GHz is rated as having an efficiency of 60%, and the field-effect-transistor amplifiers as 40%. This paper does not address the resulting system inefficiency, as authors expect to advance the technology of the microwave generators that will be stimulated by wireless telephone systems. An additional concern resulting from these systems is the electromagnetic interference (EMI), in which the microwaves for the ion thruster might interact with the communication link and other spacecraft systems.

This paper describes the development of an ion source and a neutralizer driven by an ECR microwave discharge, reviews the demonstration of the system operation of the cathodeless ECR microwave discharge ion thruster, and presents preliminary data for EMI in the microwave frequency region.

ECR Discharge Ion Source Development

Proof-of-Concept Discharge Chamber

Prior to building the ion thruster, the mechanism of the ECR microwave discharge was studied using a 12 × 12 × 12 cm cubic plasma source made of soft iron.[10] It has an endless square magnet track and a pair of windows 2 cm × 1 cm for internal observation in the vicinity of the magnet. The samarium–cobalt magnets, 1 cm in width, are arranged at 1-cm intervals in the magnetic track. The plasma luminescence is visible along the line of sight parallel to the magnet track, though

Received Jan. 13, 1997; revision received April 16, 1998; accepted for publication May 28, 1998.

*Research Associate, Electric Propulsion, 3-1-1 Yoshinodai, Sagamihara. Senior Member AIAA.

†Research Associate, Electric Propulsion, 3-1-1 Yoshinodai, Sagamihara. Member AIAA.

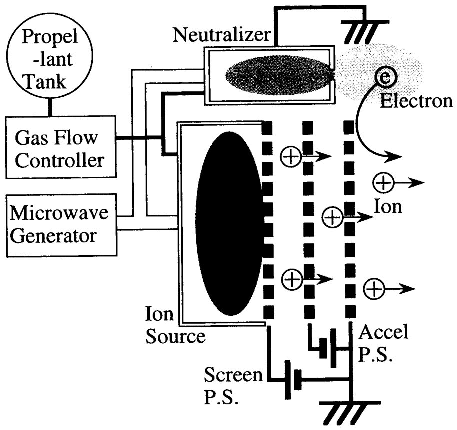

Fig. 1 Concept of the microwave discharge ion thruster system.

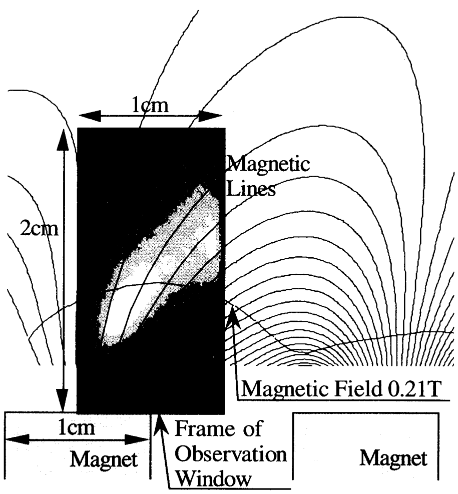

Fig. 2 Luminosity pattern of ArII (476 nm) through observation window at ECR discharge.

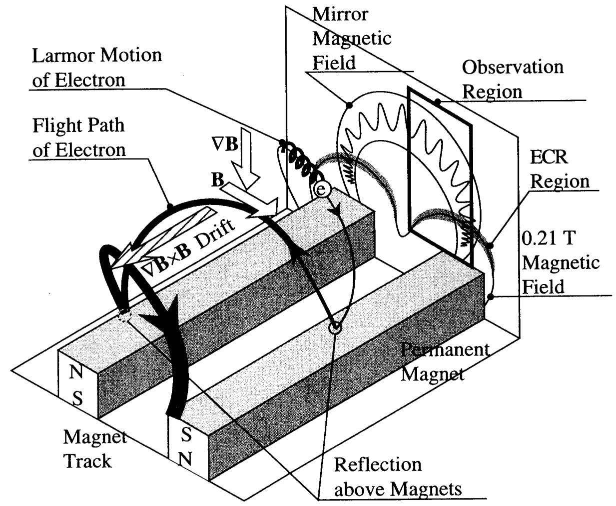

Fig. 3 Mechanism of the ECR discharge.

an irregularity exists at both ends of the line of sight. A TWT amplifier feeds 5.9-GHz microwave power to the plasma source through a rectangular waveguide. The magnets generate an 0.4-T magnetic field on their surface, which exceeds 0.21 T of an ECR magnetic field associated with the 5.9-GHz oscillation. A multiperforated plate attached at the exit of the ion source maintains a neutral gas density but does not extract ions in the electrostatic manner. A mass flow controller supplies argon gas that monitors the internal pressure by an ionization gauge directly installed in the ion source. The experiment was conducted in a vacuum chamber 0.6 m in diameter and 1 m long, evacuated by an oil diffusion pump of 800 l/s. The plasma sustained by the ECR microwave oscillation showed a bow-shaped luminosity, which was observed through a 476-nm optical interferometer filter tuned into ArII. Figure 2 indicates one-half of the entire bow luminosity from the frame of the observation window with the magnetic lines and the contour of a magnetic strength of 0.21 T. The ECR plasma was generated with 50 W of microwave power and 0.07-Pa neutral argon gas density. The magnetic field strength was measured using two-axial small Hall sensors with a 1-mm spatial resolution. The magnetic lines were drawn tracing the vectors of the measured magnetic field by a numerical technique. The plasma by the ECR discharge distributed in a magnetic tube between a pair of magnets. The mechanism of the ECR microwave discharge is illustrated in Fig. 3.[11] The magnetic track composed of a pair of the magnet rows generated a linear bow-shaped magnetic field, where both ends connected the two poles at high magnetic strength. The high-energy primary electrons were confined to the bow-shaped mirror-like magnetic tube. Whenever they passed by the region of an 0.21-T ECR magnetic field, they were gradually heated by the ECR mechanism. The gradient magnetic field caused the $\nabla B \times B$ drift of the electrons along the magnetic track. The high-energy primary electrons ionized neutral particles. A primary electron of 50 eV kinetic energy, for example, which is enough for ionization, had an 80-μm Larmor radius at the 0.21-T ECR magnetic field, and so it never deviated from the mirror magnetic field above the 1-cm-wide magnets.

Thruster Discharge Chamber

To ensure the efficient production of ions, it was important that the strength of the magnetic field on the magnet surface exceeded that of the ECR magnetic field enough to confine the high-energy electrons to the mirror magnetic tube. A long flight path of the primary electrons along the magnetic tube is better to effectively collide with neutral particles. The magnetic track should be endless to avoid derailing the drifting electrons. A thin discharge chamber is preferable to locate the electrostatic grid system near the region of the plasma generation.

The results of the preliminary studies were used to design the ion thruster plasma source. The ion source was designed as a dish-shaped axially symmetric discharge chamber 12 cm in diameter, and is made of a soft iron (Fig. 4). It had two rings of the samarium–cobalt permanent magnets on its tapered internal surface. A solid-state power amplifier fed a 4.2-GHz microwave to the ion source through a circular wave guide. The ECR magnetic field of 0.15 T is associated with the 4.2-GHz microwave. The electrostatic three-grid system was made of a carbon–carbon composite, 10 cm in diameter, extracted and accelerated ions from the ion source. The original screen and deceleration grids were 0.5 mm in thickness, 3 mm in hole diameter, 67% in open area fraction and 857 holes, the acceleration grid 0.8 mm, 1.8 mm, and 24%. They were arranged at 0.5-mm intervals. The screen grid was biased at 1200 V, the acceleration grid at -300 V, and the deceleration grid grounded. The screen grid was directly attached to the ion source without any potential gap. The current through the power supply biasing the screen grid was measured as the extracted beam current. The current to the acceleration grid was less than 0.6 mA in all of the experiments. The accelerated ion beam was neutralized by a filament emitter. A calibrated mass flow controller supplied xenon gas. The vacuum chamber that was 1.5 m in diameter and 2 m long was evacuated to less than 3×10^{-3} Pa at the thruster operation by two oil diffusion pumps of 12,000 l/s total capacity. Figure 5 shows the xenon ion production performance. The ion production cost is defined as the input microwave power divided by the extracted ion current. The reflection microwave power, typically less than 10% of the input power, was not subtracted. The microwave power detectors calibrated using the power meter

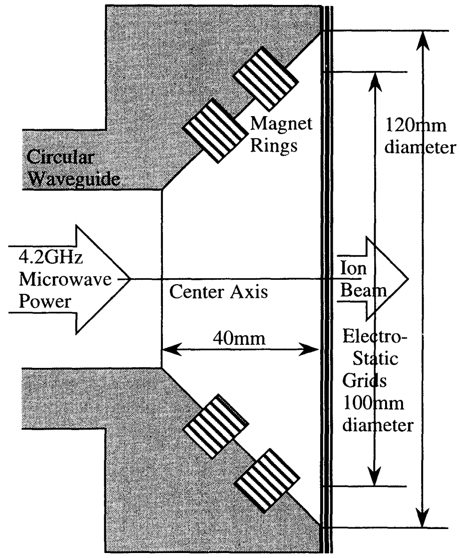

Fig. 4 Configuration of the thruster discharge chamber.

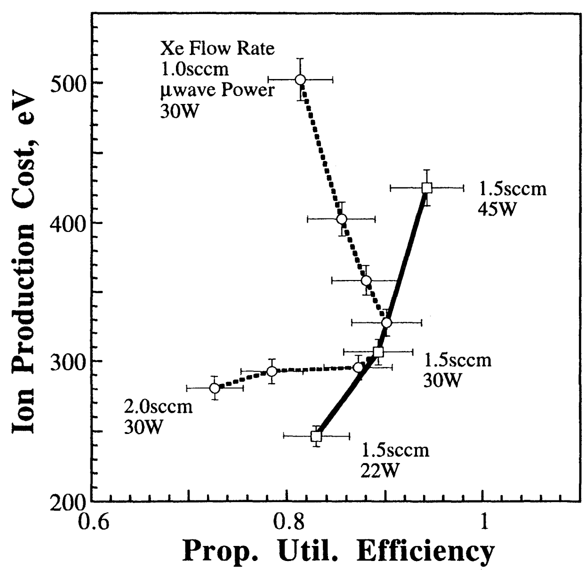

Fig. 5 Performance to produce ions in the ECR microwave discharge ion source.

HP437B/8485A include an error of 2%. The total error in the ion production cost was evaluated at ±3% of its value. The propellant utilization efficiency was calculated as the extracted ion current divided by the sum of the xenon feeding rate and the gas entrainment Γ from the vacuum chamber to the ion source, which was evaluated using the following equation:

$$\Gamma = \tfrac{1}{4} nvSC$$

where n is the particle density in the vacuum chamber, v is the average thermal velocity, S is the open area of the acceleration grid holes, and C is the Clausing's factor. Though the estimated Γ includes an ambiguity of 40%, the total error of the propellant utilization efficiency was ±4% because the value of Γ is less than 10% of the xenon gas fed by the mass flow controller.

The ion production cost of 300 eV and the propellant utilization efficiency of 88% were achieved at a microwave input power of 30 W and a xenon flow rate of 1.5 sccm. The doubly charged ions in the ion beam were measured by the $E \times B$ probe, which has a 5 × 1 mm entrance slit, a 100-mm-long collimator, a 30-mm-long analyzing section with a pair of permanent magnets and parallel electrodes, a Faraday cup, and a 1-pA-resolution current detector. A Xe^{++} density ratio to Xe^{+} was estimated at 8%. This reduced the thrust force to 95% of the ideal value in which all of the ions were assumed to be singly ionized. The ECR microwave discharge ion source had comparable performance to the well-developed dc discharge ion engines in a 10-cm class.[12]

Neutralizer Development

The neutralizer should consume as little power and propellant as possible. The goal of the ECR microwave discharge neutralizer is to extract an electron current of around 100 mA with several watts of microwave power and a sub-sccm gas flow rate. Also, it needs to ignite plasma by injection of a microwave and gas with neither a preignition sequence nor extra hardware. Figure 6 shows a schematic of the ECR microwave discharge neutralizer.[13] The samarium–cobalt magnets and the magnetic poles generated a magnetic field in the 18-mm-diam discharge chamber. The 1.5-mm-diam L-shaped antenna launched a 4.2-GHz microwave power transmitted via a coaxial line. The xenon gas was introduced to the discharge chamber and exhausted through the orifice that was 7 mm in diameter and 10 mm in length. It is thought that the primary electrons were confined in the mirror-like magnetic field and heated at the ECR region in the same manner as within the ion source. The neutralizer was tested using a bell jar evacuated by an oil diffusion pump of 450 l/s. A perforated plate located 15 mm downstream from the neutralizer was biased positively to collect electrons around 100 mA. The dependence of the electron current on the bias voltage is shown in Fig. 7 for a 0.5-sccm xenon flow rate and 10 W of microwave power. The value of the electron current includes an error of ±3 mA caused by hysteresis of the voltage–current characteristics. A 500-h endurance test for the microwave discharge neutralizer

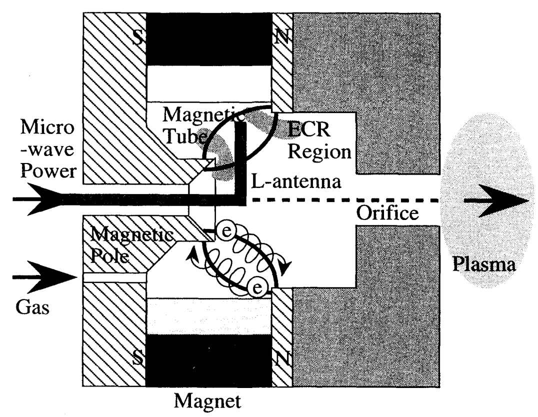

Fig. 6 Configuration of the ECR microwave discharge neutralizer.

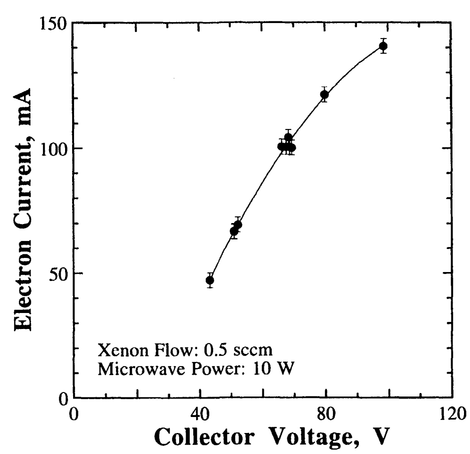

Fig. 7 Electron current of the neutralizer dependent on bias voltage of collector.

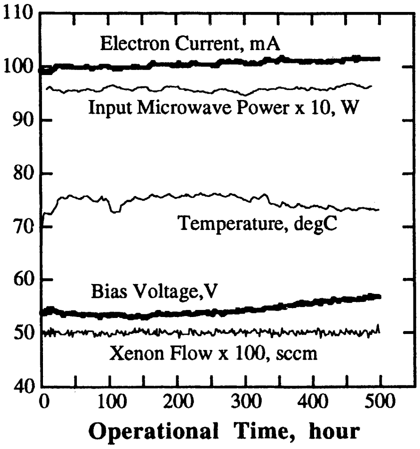

Fig. 8 Five-hundred-h endurance test of the ECR microwave discharge neutralizer.

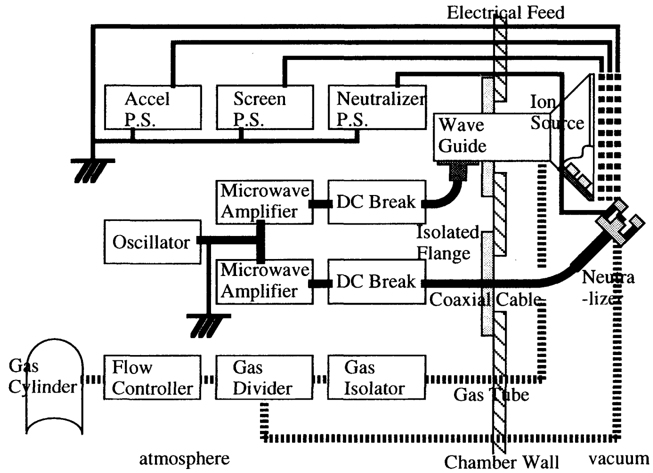

Fig. 9 Test configuration for the ECR microwave discharge ion thruster system.

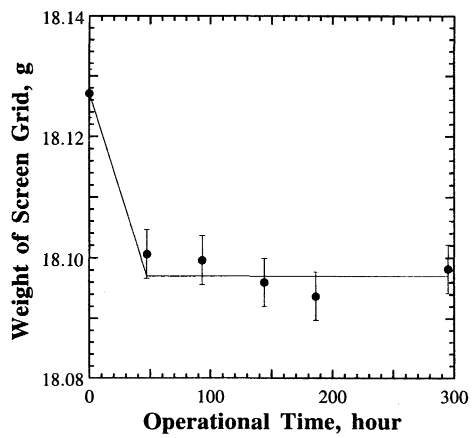

Fig. 10 Weight loss of screen grid in the 300-h long-term operation.

was performed to extract 100-mA electron current. The results are shown in Fig. 8. The bias voltage and temperature were an almost constant 55 V and 75°C during the test. No performance degradation was observed during the 500-h endurance test. Figure 8 shows that the neutralizer can be operated at a relatively low temperature, which never causes material fatigue. The molybdenum orifice and L antenna suffered weight loss at average rates of 30 and 3 μg/h, respectively, which are low enough to endure over 10,000 h. Assuming the same erosion rates for a 10,000-h operation, the orifice enlarged to 7.01 mm from 7 mm in diameter, and the antenna diameter decreased from 1.5 to 1.33 mm.

Development Test

Thruster Assembly

The ion source and neutralizer were combined into an ion thruster system in the vacuum chamber described in the section, Thruster Discharge Chamber. Figure 9 shows the system diagram. The experiment was controlled using a personal computer with an 80286 CPU running at 10 MHz through the General Purpose Interface Bus. A mass flow controller supplied xenon gas to both discharge chambers through a calibrated passive divider. The 4.2-GHz microwave power was fed to each discharge chamber by an independent solid-state amplifier. The system controller turned both amplifiers on and off simultaneously. The amplifiers and gas supply system were electrically isolated from the discharge chambers by two microwave dc brakes and a gas isolator. The screen and acceleration grids were biased by two dc power supplies at 1000 and −300 V, respectively. The neutralizer was also biased at −60 V to suppress electrons from the vacuum chamber wall because the screen and acceleration power supplies were electrically grounded.

The system controller acquired various data and operated the ion thruster system. When there was any trouble in the operation of the thruster, pressure for the vacuum pump system, temperature of the subsystems, etc., the controller immediately terminated the operation of the thruster. The controller automatically restarted the thruster system after resolving the problem. When the propellant gas and the microwave power were supplied to the ion source and neutralizer, the plasmas in both chambers were ignited simultaneously. The ion beam was then extracted by the grid system and electrons were injected by the neutralizer. The thruster operation was started in 20 s in this demonstration.

Long-Term Operation

The system successfully demonstrated two 150-h operation runs in October 1994 and May 1995 for a total of 295 h.[14] The operation was interrupted voluntarily to measure the weight change of the grids made of the carbon–carbon composite material (described in the Thruster Discharge Chamber section). The acceleration grid reduced its weight during the long-term operation because of the sputtering by charge-exchange ions. The ion beam exhausted from the ion thruster caused a severe sputtering of the vacuum chamber wall. The contamination originated from this sputtering increased the weight of the deceleration grid. It is thought that the screen grid had no contamination from the facility because of full coverage with the acceleration and deceleration grids. Figure 10 shows the weight change of the screen grid, depending on the accumulated operational time. The ambiguity of the weight estimation was evaluated at ±3 mg, which was caused from the procedure to assemble and disassemble the grids. In the first 30 h the new set of grids caused a great deal of spark discharges between the grids, which decreased the weight of the screen grid. After the first term the screen grid did not show explicit weight loss. It was concluded that the screen grid was only slightly eroded by the ECR microwave discharge, making it difficult to identify it in the 300-h operation. Any flakes and sputtering erosion by the ECR discharge were not observed in the ion source.

EMI Testing

The wideband discone antenna[15] and the spectral analyzer HP8563E measured the EMI from the ECR microwave discharge ion thruster system in the vacuum chamber. The discone antenna was calibrated using the logarithmic spiral antenna EMCO-93491-2, which covered the frequency range from 1 to 10 GHz, assigned by MIL-STD 461 B. The antenna was directly inserted in the vacuum chamber and was located

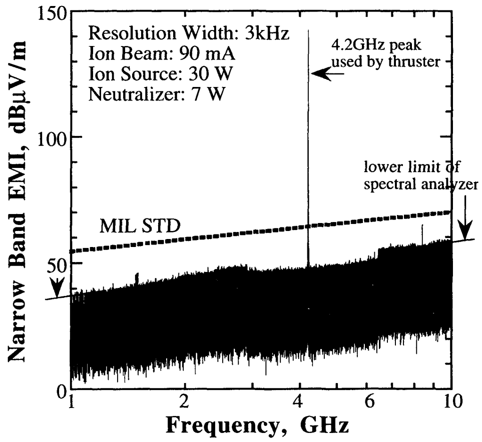

Fig. 11 EMI in microwave range emitted from the ECR microwave discharge ion thruster system.

1 m downstream from the thruster and 1 m apart from the ion beam. Although the vacuum chamber well insulated the test section from noise signal in an environment, it may reflect and enhance EMI from the thruster by the cavity effect. It is adequate to roughly evaluate EMI from the thruster, although the test environment was not based on MIL-STD 461 B. Figure 11 shows the EMI level in the microwave frequency range from 1 to 10 GHz, including the standard level cited in MIL-STD 460 B. The ion thruster emitted a 90-mA ion beam with 30-W microwave power for the ion source and 7 W for the neutralizer. The 1.5-GHz signal may be associated with a noise from wireless telephones in the environment, and the peaks of 4.2 and 8.4 GHz are emitted from the thruster system. The frequency of 4.2 GHz of the ECR microwave discharge exceeded the MIL standard by 80 dB. These EMI signals depend only on the microwave generators, except for the plasma generation and the ion extraction. The ECR microwave discharge ion thruster does not emit wideband noise.

Summary

To realize the concept of the ECR microwave discharge ion thruster system without cathodes, a new ion source and neutralizer were developed. Tests using a proof-of-concept cubic discharge chamber were used to establish the ECR ion thruster design criteria. Results of these tests were used to build an ion thruster ECR-based discharge chamber. The discharge chamber can generate xenon ions with a 300-eV ion production cost, 88% propellant utilization efficiency, and 8% doubly charged ions. An ECR neutralizer was developed that can emit an electron current of 100 mA. A 500-h endurance test of the neutralizer showed no change in the performance and little weight loss of the orifice and the antenna. The ECR-based discharge chamber and neutralizer were combined into an ion thruster system. The system demonstrated a quick thrusting start without any preheating. A 300-h operation was performed, where the erosions of the screen grid and the ion source were too small to detect. EMI measurements showed that all microwave bands, except the primary frequency, were lower than the MIL standard. These tests demonstrated the feasibility of an ECR-based ion thruster system.

Acknowledgments

The authors thank Nobuo Hiroe, Kazuto Kitaoka, and Motoyuki Ohtaki of Nihon University for their contributions to the laboratory experiment. Kazutaka Nishiyama and Takuya Shiraishi of the University of Tokyo were very helpful in the development of the experimental system.

References

[1]Brophy, J. R., Polk, J. E., and Rawlin, V. K., "Ion Engine Service Life Validation by Analysis and Testing," AIAA Paper 96-2715, July 1996.

[2]Shimada, S., Satoh, K., Gotoh, Y., Nishida, E., Noro, T., Takegahara, H., Nakamaru K., and Nagano, H., "Ion Thruster Endurance Test Using Development Model Thruster for ETS-VI," 23rd International Electric Propulsion Conf., 93-169, Sept. 1993.

[3]Patterson, M. J., Verhey, T. R., Soulas, G., and Zakany, J., "Space Station Cathode Design, Performance, and Operating Specifications," International Electric Propulsion Conf., 97-170, Aug. 1997.

[4]Gray, H. L., "Design and Development of an Electric Propulsion Regulator for Use on Ion Propulsion Systems," International Electric Propulsion Conf., 97-033, Aug. 1997.

[5]Bassner, H., Berg, H. P., Kukies, R., and Muller, H., "Flight Test Results of the RITA Experiment on EURECA," 23rd International Electric Propulsion Conf., 93-102, Sept. 1993.

[6]Dahimene, M., Mahoney, L., and Asmussen, J., "An Electron Cyclotron Resonant Multicusp Magnetic Field Microwave Plasma Source for Electric Propulsion," AIAA Paper 87-1015, May 1987.

[7]Goede, H., "30-cm Electron Cyclotron Plasma Generator," *Journal of Spacecraft and Rockets*, Vol. 24, No. 5, 1987, pp. 437–443.

[8]Hansen, J. W., "U.S. TWTs from 1 to 100GHz," *Microwave Journal, State of the Art Reference*, Supplement to Vol. 32, No. 9, 1989, pp. 179–193.

[9]Shih, Y. C., and Kuno, H. J., "Solid-State Sources from 1 to 100GHz," *Microwave Journal, State of the Art Reference*, Supplement to Vol. 32, No. 9, 1989, pp. 145–161.

[10]Satori, S., Nishiyama, K., Kuninaka, H., and Kuriki, K., "Electron Cyclotron Resonance Ion Source for Ion Thruster," *Japanese Journal of Applied Physics*, Vol. 35, Pt. 1, 1A, 1996.

[11]Geisler, M., Kieser, J., Rauchle, E., and Wilhelm, R., "Elongated Microwave Electron Cyclotron Resonance Heating Plasma Source," *Journal of Vacuum Science and Technology*, Vol. A8, No. 2, 1990.

[12]Patterson, M. J., Grisnik, S. P., and Soulas, G. C., "Scaling of Ion Thrusters to Low Power," 25th International Electric Propulsion Conf., 97-098, Aug. 1997.

[13]Kuninaka, H., and Ishikawa, Y., "Microwave Plasma Contactor," 23rd International Electric Propulsion Conf., 93-040, Sept. 1993.

[14]Satori, S., Kuninaka, H., and Kuriki, K., "300 Hours Endurance Test of Microwave Ion Thruster," 24th International Electric Propulsion Conf., 95-89, Sept. 1995.

[15]Jasik, H., *Antenna Engineering Handbook*, McGraw–Hill, New York, 1961, pp. 3–24.