

# 20mN-class Microwave Discharge Ion Thruster\*

Ikkoh Funaki  
Institute of Engineering Mechanics and Systems  
University of Tsukuba  
Tsukuba, Ibaraki, 305-8573, Japan.  
+81-298-53-5130  
funaki@kz.tsukuba.ac.jp

Kazutaka Nishiyama, Hitoshi Kuninaka, Kyoichiro Toki, Yukio Shimizu, and Haruya Toki  
Institute of Space and Astronautical Science  
3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan.

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**A 20-cm-diam., 20-mN class microwave discharge ion thruster for spacecraft propulsion was designed and fabricated. The new thruster will be powered by the microwave of up to 100 W, which is introduced from a microwave power source via coaxial cable followed by a coaxial to waveguide transformer. Inside the discharge chamber, permanent magnets realize electron cyclotron resonance (ECR) discharge and corresponding easy ignition and efficient plasma production. From this ion source, a beam extraction system consisting of flat, 20-cm-diam for effective ion beam diameter Carbon/Carbon composite grids can extract above 200 mA ion beam, and initial performance test results of up to 500 W showed a thrust of 16 mN, which showed a possibility of 20 mN class microwave ion thruster for a total electrical power of 1 kW.**

## Introduction

Following DC- and RF-discharge technologies, microwave discharge is now considered as the third principle which can comprise the ion engine system.[1] The first flight test of a microwave ion engine system is scheduled in 2002, in which four 400 W thrusters are equipped for a Japanese space probe exploring an asteroid.[2],[3] The key feature of the microwave driven system is its simplified architecture and reduced number of components compared to the DC and even the RF based systems. As shown in Fig.1, removing a hollow-cathode from a main discharge chamber, the ion source is totally free from high-temperature components and hence no contamination by electrode materials is expected. Accordingly, the heater for starting up the hollow cathode and corresponding power supplying unit are no longer needed. Furthermore, even the neutralizer doesn't employ a hollow cathode, hence only one microwave power generator is required for both the ion source and the neutralizer. Removing hollow cathode and related components, starting-up the

thruster is drastically simplified, and the plasma is easily ignited after introducing xenon gas and then switching on the microwave power supplying system. In addition to the above mentioned robust thruster head design consisting of only magnets, iron yokes, and aluminum body, the microwave power source is available as a qualified system developed and test for a satellite communication. The only trouble was its low thruster efficiency, however, the model for the MUSES-C was drastically improved, and the performance is nearly comparable to that of the state-of-the-art DC thruster stem in a sub-kilowatt regime.[4]

In order to improve the performance of the microwave ion source, energy transfer from the microwave power to a plasma has to be emphasized, and the discharge loss should be suppressed. Among various microwave ion source designs, we incorporated and revised a microwave plasma generator design proposed by Goede, who introduces the microwave through a waveguide into a line cusp discharge chamber made of samarium cobalt (SmCo) magnets and a soft iron.[5] This design enhances resonant microwave to plasma

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energy transfer mechanism so-called electron cyclotron resonance (ECR), by which magnetically trapped electrons resonantly absorb electric field oscillation perpendicular to the magnetic field, and energize its gyro motions. In this paper, a design and initial test results of a second generation microwave thruster are described. The target thruster features a higher power operation as much as 30 mN for a total input power of 1 kW as indicated in Table.1. Relatively smaller thrust density compared to that of electron bombardment-type thrusters will indicate the different scaling of the microwave ion source. Although the target performance is not yet obtained, some of our efforts, difficulties in scaling up the small 10-cm-diam. thruster design to a high-power regime, are reported, and possible improvements are discussed.

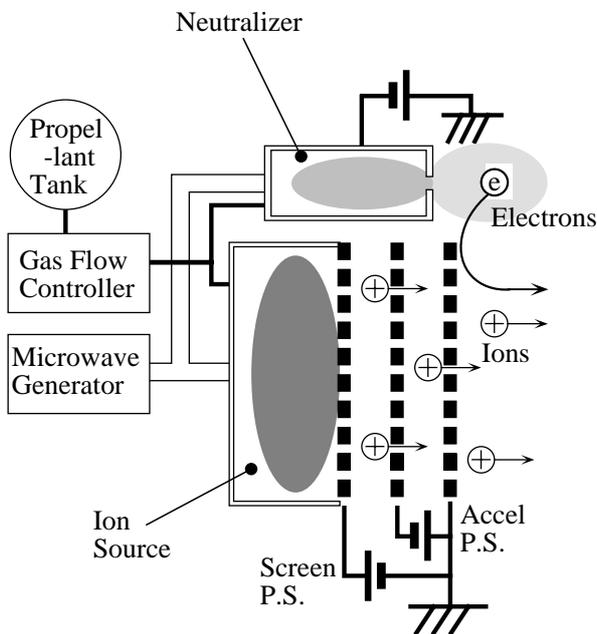


Fig. 1 Schematics of Microwave Discharge Ion Thruster System.

## Design of Thruster Head

### Ion Source

Figure 2 shows a schematics of a microwave discharge ion thruster head (ITH). The ion source consists of a magnetic circuit, which has two ring magnets and iron yokes; after the discharge chamber was fulfilled by xenon gas, the microwave of 4.2 GHz are injected using a circular wave guide in TE 11 mode. Plasma production relies heavily on an energizing process of

electrons which are trapped in the magnetic tube between the two ring cusps. During the movement in the magnet mirror, the electrons are rotating at an angular frequency  $\omega = eB/m_e$ , around the B-field line. A resonant wave-particle interaction occurs when the wave of frequency  $\omega$  has a right-hand circularly polarized electric field component in the plane perpendicular to B. When the electrons see this perpendicular wave component against the magnetic field, the damping of the electromagnetic wave and corresponding collisionless ECR absorption causes a resonant energy gain of the electron. As a result, the electron velocity component in the direction perpendicular to B increases. However, for a bounded plasma device, it is usually impossible to establish a pure right-hand polarized wave, but the electric field also possesses an axial component which does not directly contribute to ECR. Furthermore, for a smaller ion source adopted in this case, it is even difficult to launch the wave along the B-field, hence the wave is perpendicularly introduced in such a way as extraordinary or ordinary waves, both of which are considered to be of importance for the microwave ion engine. Further discussion on such wave-plasma coupling will be conducted later.

Table .1 Target Performance of 20-cm-diam Thruster.

Thruster Size	$\phi$ 10cm	$\phi$ 20cm Target
Beam Voltage, V	1500	1200
Beam Current, mA	140	580
Microwave Power (main), W	32	90
Microwave Power(neut), W	8	18
Xe Flow Rate, sccm	2.9	11.2
Thrust, mN	8.1	30.4
Isp, s	2910	3100
Util. Eff., %	83	80
Ion Prod. Cost, W/A	220	155
Total Power, W	390	1015
T/P, mN/kW	20.3	30.0
PPU Input Power, W	262	770
PPU Eff., %	80.0	90.0
MPA Input Power, W	99.9	196
MPA Eff., %	55	55

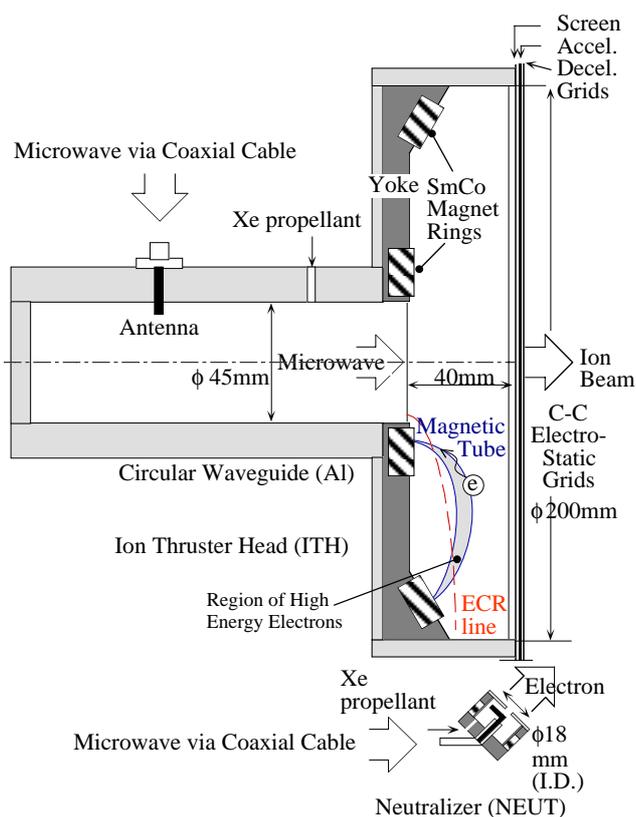


Fig. 2 Microwave Discharge Ion Thruster Head (ITH).

After the power absorption by an adequate wave-particle coupling channel, most of energized particles still remain in the tube. If high-energy electrons above ionization energy collide with the background xenon atoms, and if depleted electron energy is supplemented by a successive injection of the microwave, a microwave discharge starts. The magnetic tube plays a role of supplying primary electrons, hence called a virtual cathode. Once the microwave discharge occurred, the plasma produced in the virtual cathode should be introduced toward an ion optics without losing them to the walls. Here, as one can easily imagine, the plasma production near the wall will result in large wall losses, that also requires large magnetic field compared to DC type ion thrusters.

Before the above mentioned plasma is successfully produced, the microwave transmission circuit should be tuned so as to enhance the microwave absorption into the plasma. This procedure is called impedance matching because the plasma corresponds to a variable load in the end of a  $50 \Omega$  distributed circuit, and the impedance of the load usually deviates from a  $50 \Omega$  microwave line, which should be compensated to pro-

hibit a standing wave along the transmission line. A properly tuned system made it possible that the non-absorbed reflected waves penetrate the plasma again and are partially absorbed. By such a matching system, it is possible to reflect all the reflected wave back to the discharge chamber, however, by inserting a vectored tuning device like a three stub tuner in the transmission line between the discharge chamber and the microwave power supply, as one can easily imagine, a standing wave between both the discharge chamber and the tuning device is induced. To suppress a current loss by this standing wave, a compact tuning system, that can confine the standing wave region in a compact discharge chamber, is strongly preferred for the microwave ion engine. As in Fig.2, the microwave power, which is originally transmitted via a coaxial cable, was converted into a circular waveguide mode, and then, by changing the configuration of this convertor and the discharge chamber itself, it is possible to suppress the reflected wave and to optimize the plasma generation. Note that the chamber geometry should be optimized both for the accelerated and non-accelerated plasma, hence, our goal is to find the optimized configuration that can be used for both the ignition and low-cost ion production without using variable/movable tuning devices.

### Carbon-Carbon Ion Optics

The first fabrication of ion optics for 200 mm diam. ion thruster was conducted. Even for very thin structure of 1-mm thickness, the test fabrication resulted in a flatness of 0.5 mm and a hole placement accuracy of 0.02 mm. Followings are the details of this optics design.

As in Fig.3, 270 mm in diameter and 1 mm in thickness, flat, circular grids were fabricated from a 30-cm-square C/C panel. The effective diameter for ion beam extraction is 200 mm, in which about 2800 straight holes are drilled and located in a 3.5 mm pitch. The hole diameters are different for each grid: 3.0 mm for the screen grid, 1.8 mm the accelerator grid, and 2.4 mm for the decelerator grid.

The grids were fabricated by piling thin fiber sheets. Each sheet contains short pitch based carbon fibers to obtain a quasi-isotropic C/C reinforced in a direction parallel to the surface. This panel was also reinforced by the chemical vapor infiltration (CVI) process, and relatively large flexural modulus was obtained as is summarized in Table.2. Other than short fiber sheets, woven long fibers would be the best as far as mechani-

cal strength is concerned. However, woven fiber is impractical for this case due to a very thin sheet below 1 mm, hence other kinds of design are required if one uses long fibers. For example, in Ref.[6], Mueller et al. fabricated a 0.46-mm-thick screen grid by piling six thin sheets consisting of pitch-based unidirectional long fibers. This panel was also reinforced by the CVI process, and larger flexural modulus compared to the short fiber carbon sheets was obtained. However, the flexural modulus showed strong anisotropy which inherently depends on the direction of the unidirectional fibers; furthermore, machining becomes difficult for these plates, requiring a laser drilling that usually cannot establish a straight hole; but a tapered hole is typically created. As a result of this fabrication difficulty of the long fibers, we decided to adopt the short fiber sheets.

Table .2 Mechanical Property of C/C Composite.

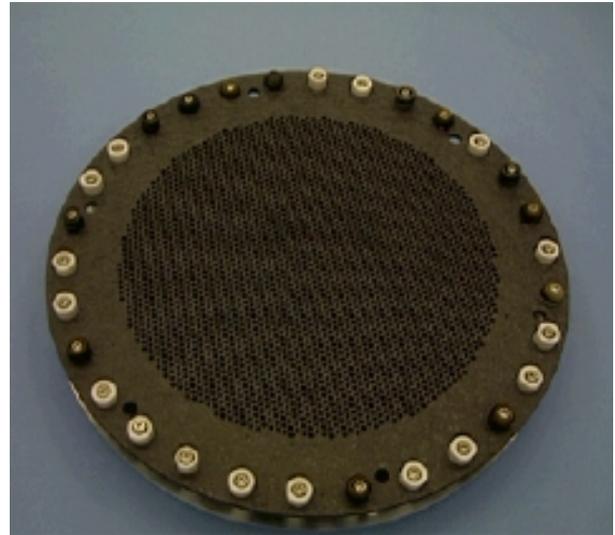
Density	1.85 g/cc
Flexural Strength	180 MPa
Tensile Strength	110 MPa
Elastic Coefficient	68 GPA

Spacing between each grid is kept at 0.5 mm intervals by the rigid mount system shown in Fig.3. The C/C grid plates are mounted via ceramic spacers to an aluminum ring, and the grids are separated from each other by the spacers. Their gaps are precisely adjusted when they are torqued to the ring. With this fastened grid attachment, the grid increases its strength and the grid-to-grid gap can be controlled to 0.04 mm accuracy.

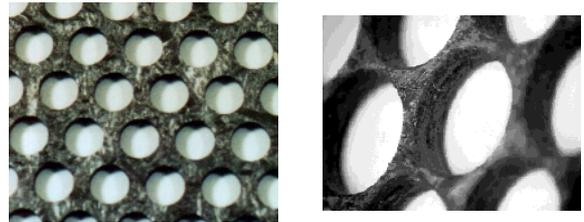
### Neutralizer

As shown in Fig.4, in contrast to the ion source, the neutralizer features a very small discharge chamber of 18 mm inner diameter. The Xe propellant pressure inside the chamber is controlled by a 4-mm-wide orifice; with the conductance of the orifice below 1, the inner pressure is kept at  $5 \times 10^{-3}$  to  $1 \times 10^{-2}$  torr for the Xe mass flow rate of 0.5 - 2.0 sccm. Microwave of 4.2 GHz is fed through a coaxial line followed by an L-shaped antenna, whose tip is inserted into a magnetic field formed by front- and back- yokes and block magnets. Again, the magnetic tube here works as a virtual cathode, along which the high energy electrons actively ionize xenon atoms, and corresponding overdense plasma production is expected as will be stated in the chapter of discussion. The strong magnetic field above

the ECR condition enables easy start-up of the neutralizer; after introducing Xe into the chamber, 5 W microwave is enough to ignite the plasma. The microwave was tuned by a stab located outside near the chamber to keep the reflection power below 0.5 W.



a) Three Grids Mounted on a Ring.



b) Magnified View of Screen Grid.

Fig. 3 The C/C Ion Optics.

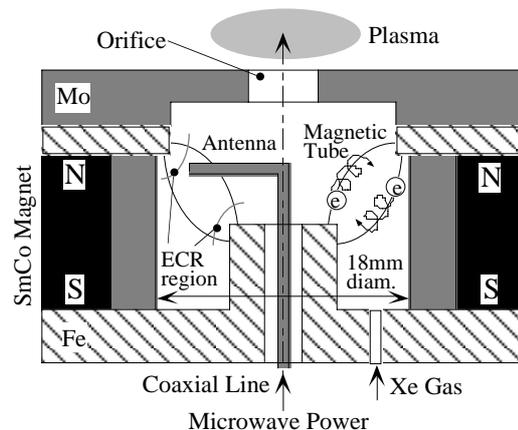


Fig. 4 Microwave Discharge Neutralizer.

## Experimental Apparatus

The thruster was operated in a large vacuum chamber, 2 m in diameter and 5 m in length, which was evacuated by cryogenic pumps, maintaining the pressure below  $5 \times 10^{-6}$  torr during the thruster operation with the mass flow rate of 10 sccm for the ion source and 0.5 sccm for the neutralizer. After the microwave power is introduced, the bias voltages are applied: the screen voltage and the discharge chamber are equipotentially biased to 1500 V, the accelerator grid is 300 V, and the deceleration grid was ground. The neutralizer should be biased to the engine's ground about -30 V, from which electrons are emitted and bridged to the main ion beam. However, this paper only reports the thruster operation with a filament neutralizer. Since those biased components have to be electrically isolated each other, and from the engine's ground, the engine mount, gas port, as well as microwave feed lines have to be isolated using ceramics, DC breaks and gas isolators.

The neutralizer stand-alone test simulates the neutralizer operation. In place of the ion source, electrons are extracted by a metallic plate anode, which is position in front of the orifice, then positively biased toward the neutralizer, and electron current for various bias voltages can be measured. In this configuration, the neutralizer was tested in a small chamber measuring 0.3 m in diameter and 0.5 m in length, which was evacuated below  $1 \times 10^{-5}$  torr by a rotary pump and a diffusion pump. Also, for a inner plasma characterization, Langmuir probe measurement was conducted using a flat 1-mm-diam. probe.

## Initial Test Results

### Ignition of the Ion Source and Beam Extraction

Until now only limited tests of lower microwave powers as much as 60 W were conducted. First, ignition of the ion source was checked without ion beam extraction. The plasma is easily ignited by a microwave power of 30 W for 2 to 10 sccm Xe propellant, and only 10 W is enough to sustain the plasma. The plasma shown in Fig.5 has a dark circle near the center of the ion source where a circular wave guide is located. The strong light emission on the magnetic rings around this waveguide indicates a successful control of the plasma discharge mode keeping the plasma in the ECR mode.

For the ECR mode, low ion production cost and corresponding large amount of ion beam becomes possible, but further increasing the microwave power or the propellant mass flow, the plasma easily dropped into the upper hybrid mode, for which the plasma in front of the waveguide will prohibit the access of the microwave to the ECR region. Figure 6 shows such a mode transition; for 4.0 sccm, the thrust level is below 6 mN for all the cases of input microwave power, but for 4.2 sccm or larger, the mode hop occurs for high power cases above 40 W, resulting in a large thrust operation of the ion source. However, no increase of thrust available for larger mass flow rates above 4.4 sccm because the low-cost ECR mode can only be obtained for only a few combinations of the mass flow rate and the microwave power. So far, the thrust available at this stage is 10 to 16 mN corresponding to 200 to 250 mA for 1.2 kV acceleration voltage for a total input power as much as 450 W. The obtained data are summarized in Fig.6-b) including a few high-power operation data, from which we have to admit that the ion source configuration requires many improvements to obtain a 30 mN class thruster for a total input power of about 1 kW.

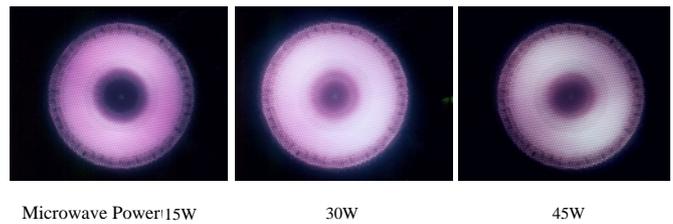
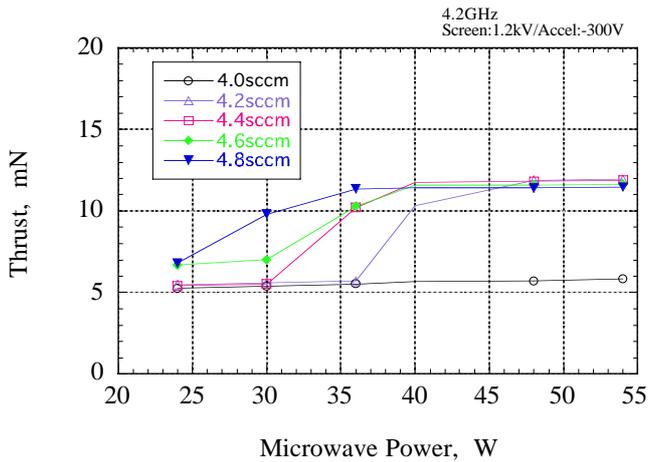


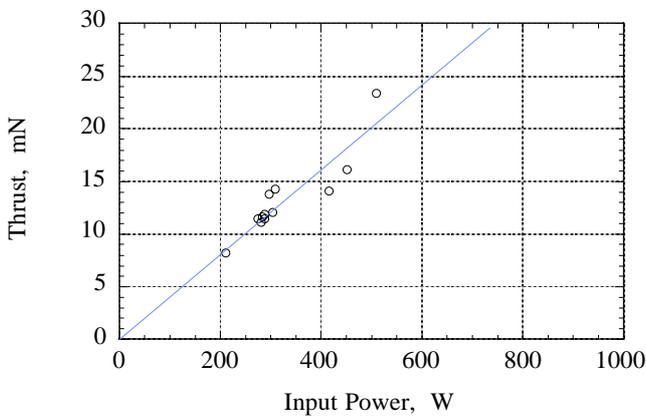
Fig. 5 Plasma Ignition of Microwave Ion Source without Beam Extraction (4sccm).

### Simulated Performance Test

Since considerable improvement is required to achieve the target ion current, 580 mA for an input microwave power of 90 W, various chamber configurations, in particular, the magnetic circuit designs, are proposed and tested. Some of our trials are summarized in Ref.[7]. Figure 7 shows an example of the result, for which the ion current for a simulated pressure was collected by biasing the punching metal plate. Even though the ion current is easily doubled for relatively low microwave power regime, high-power operation is associated with a degraded ion production cost, which will be attributed to the cutoff density inside the microwave discharge chamber. Still more improvement is being pursued to achieve the target performance by optimizing the wave-plasma coupling.



a) Effect of Mass Flow Rate.



b) Thrust vs. Total Input Power (Microwave Power plus DC Power for Ion Beam Extraction ).

Fig. 6 Thrust Characteristics.

### Grid Test

To evaluate the erosion rate of the grid against ion bombardment, the sputter yield, which is the ratio of eroded atoms against the influx of ions, was measured. The measurement was conducted using an approximately a 15-cm-diam. DC discharge plasma source operated inside a 2-m-diam. space chamber, into which a C/C test piece of 10 mm x 10 mm x 1 mm was immersed. Then the test piece was biased to a specific negative value during a specific amount of time, and the sputter yield is calculated as the ratio between the eroded weight against inflow ion current during the test. Usually, the most severely eroded grid (accelerator grid) is biased to around -300 V, and for that typical

biasing voltage, the sputter yield of 0.1 was obtained. This is one third that of molybdenum, which is so far used for many ion thrusters, and hence the result assures three times longer lifetime of the C/C grid for the same thruster operational condition.

### Neutralizer Operation

As in Fig.8, increasing the bias voltages makes it possible to achieve electron current up to, for example, 500 mA for the mass flow rate of 1.0 sccm and the microwave input power of 25 W, however, such a large bias is not preferred from the viewpoint of sputtering, restricting the lifetime to several hundred hours. Such a lifetime will be enough for some applications, but it is not good for the ion engine which requires the operation time at least several thousand hours, and low bias voltage, hence the neutral background density, is required.

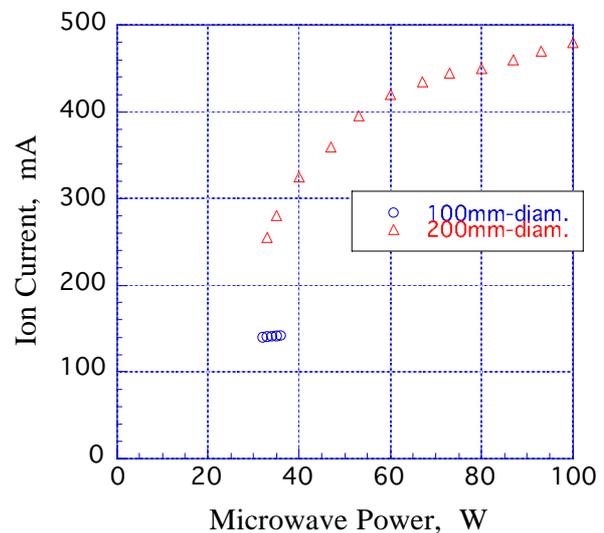


Fig. 7 Ion Beam Current for Simulated Test.

### Discussion

#### Wave-plasma Coupling of The Ion Source

The effect of background pressure on the discharge is discussed. The mode hop of the plasma production appearing in Fig.6 is related to collisional phenomena of electrons in the virtual cathode magnetic tube as will be suggested in the following. However, before going into quantitative discussion, various collision frequencies inside the ion source are calculated for a typical

electron energy, 10 eV. A long-range Coulomb interaction for the cutoff density  $2 \times 10^{11} \text{ cm}^{-3}$  is relatively weak;  $v_{ei} = 2 \times 10^5 \text{ Hz}$ . Other frequencies depend on the discharge chamber pressure; at a low pressure  $10^{-4} \text{ torr}$ ,  $v_{en} = 2 \times 10^6 \text{ Hz}$ ; and  $v_{en} = 2 \times 10^7 \text{ Hz}$  for  $10^{-3} \text{ torr}$ . Since the ionization energy of xenon atom is 12.13 eV, ionization collision is negligible for 10 eV. These collision frequencies are compared with a frequency of ECR energy gain,  $v_{ECR}$ , which is defined as one-fourth of a bouncing time between the two reflection point of the electron in the mirror magnet. Accordingly,  $v_{ECR} = 5 \times 10^6 \text{ Hz}$  corresponds to the frequency of crossing an ECR zone during an electron movement along the B-field.

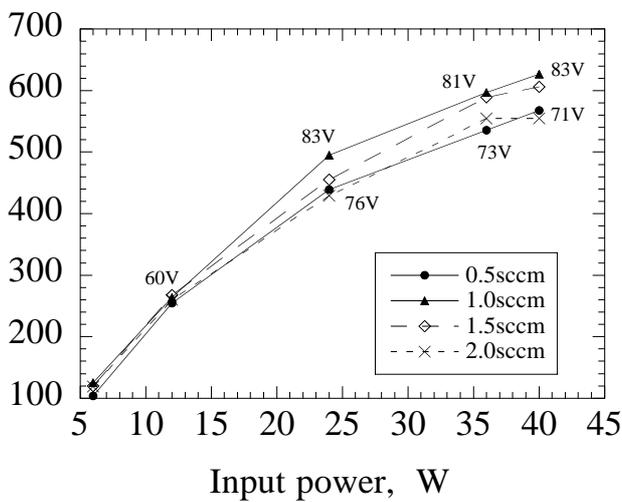


Fig. 8 Electron Current Characteristics of Microwave Discharge Neutralizer (Stand-alone Test).

To sustain the discharge, the mirror magnet region must be full of high energy electrons that can ionize the background neutral particles, hence a typical electron of 10 eV should acquire extra energy by crossing the ECR zone before colliding with a neutral particle. This condition for sustaining the virtual cathode is satisfied for the low pressure case  $10^{-4} \text{ torr}$ , since  $v_{en} < v_{ECR}$ ; for this condition, the energized electron while passing through the ECR zone has a chance to reach another ECR zone before colliding with a neutral gas and loses energy. With such a process, primary electrons above the ionization energy are produced. These tail electrons are not depleted by the Coulomb collision due to small electron-electron collision frequency, but they are rather depleted by a collision with a neutral atom, which will directly produce another electron-ion pair.

In contrast to the above condition, for  $10^{-3} \text{ torr}$ , the above mentioned enhanced plasma production is prohibited because the electron loses its energy in a collision with an atom before receiving extra energy in the ECR zone. Vice versa, for a much lower pressure, since an electron is energized too much, the plasma is driven to a non-Maxwellian state, and corresponding large electron loss to the wall, leading to degradation of plasma production cost. This discussion suggests a possible best combination of pressure and microwave power for a microwave discharge chamber geometry.

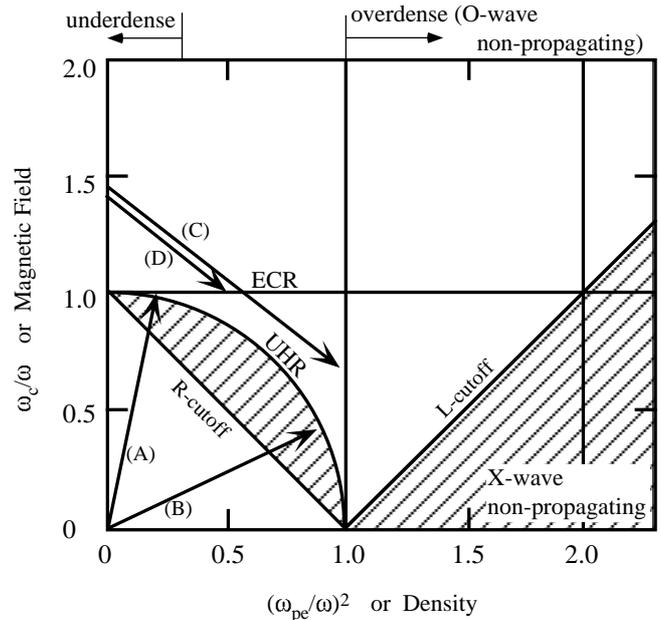


Fig. 9 Expected Propagation and Cutoff Regions of Microwave inside the Ion Source.

In addition to the electron-neutral energy transfer, operational range is also limited by the microwave-electron coupling. The relating most important feature, accessibility, is explained based on Fig.9, in which propagation of cold plasma wave is summarized. Among various plasma waves in the B-field, those propagate along B (circularly polarized R and L waves) seem not be the case for the ion thruster, consequently, transverse waves which will propagate perpendicular to the B-field are considered since the waves access to the resonant zone perpendicularly to the B-field. They are either ordinary mode (electric field oscillation along the B-field), or extraordinary mode (electric field oscillation perpendicularly to the B-field). A resonant energy absorption of an electron requires a wave component perpendicular the B-field to couple with an electron gyro movement, hence the X-wave is the main

energy transfer mechanism. First, we consider an underdense case, in which the plasma density is far below the cutoff density. However, the accessibility already breaks down when the X-wave are launched from the weak field side. The wave penetration into the ECR region is only possible by an evanescent mode, in which the penetrating wave will tunnel through the abandoned zone, R-cutoff, along the path A. This is, however, is not so difficult, because the discharge chamber size is very compact, only 10 cm in diameter, which is below the wavelength of 70 mm, and the wave is transmitted through the R-cutoff before it was totally damped. As the electron density increases, so does the distance between the ECR and the R-cutoff, hence the accessibility to the ECR zone confronts difficulty (the wave propagation along the line B). Even in this condition, the resonant wave absorption is expected on the upper hybrid resonance (UHR) line. Based on the hot plasma theory, the resonant coupling in the UHR zone for a nearly cutoff dense plasma or even an overdense plasma mode was intensively discussed in fusion plasma[8] as well as in process plasmas[9], where very strong wave-plasma coupling is expected, in particular, in a form, for example, wave conversion to an intense electrostatic wave, followed by strong nonlinear absorption processes.[10],[11] However, the accessibility difficulty also arises for this UHR mechanism due to the O-mode propagation; in the ion engine, the O- and the X- waves cannot be separated, but the two waves coexist in the cavity, and only the X-wave is expected to be strongly absorbed. In contrast, the O-wave is reflected because the O-wave is non-propagating above the cutoff density. This is the main reason that the plasma source of this type shows a limited performance for higher input microwave power cases, and the large reflected but not absorbed microwave power is observed experimentally. Off course, there is a possibility that some of the O waves will penetrate into the chamber, then reflected at the wall followed by a mode conversion into the X-wave followed by a resonant wave absorption. But most of the O-wave is only unresonantly damped or reflected back to the matching circuit. As far as wave launching from the weak B-field is not changed, this wave-plasma coupling difficulty restricts the operation of the ion source, and the maximum obtainable plasma density only as much as the cutoff density is possible. Hence it is only below the cutoff density that efficient wave to electron power coupling is realized.

If it is possible to launch the wave from the high-field side along the line C, the above mentioned accessibility

difficulty will be cleared as far as the X-wave is concerned, but still, the O-wave transmission difficulty occurs near the cutoff density, and it is not resolved. Note again that the small discharge chamber for the ion engine prohibits to separate the O-wave and the X-wave. The change of microwave frequency is expected to resolve this problem, but the stronger magnets will be required and transmission efficiency is even worse. As far as pure X-wave cannot be used, for example, along the line D, launch by a waveguide suffers this cutoff related limitation. If one prefers an overdense plasma to obtain a larger ion beam density, a compact antenna type launcher like that used for the neutralizer whose antenna is directly inserted in an overdense plasma seems to be the only way to overcome the accessibility difficulty.

### Neutralizer Plasma

The extraction of large electron current is relying on the mechanism of overdense plasma production inside the discharge chamber. In fact, the electron source is operated in a temperature around 400 K, for which no thermionic electron emission is expected.[12] Hence the charge exchange inside the electron source is mainly made by the ion current, which is proportional to the plasma density inside the electron source. In Fig.10, plasma density far beyond the cutoff density of 4.2 GHz microwave ( $2.1 \times 10^{11} \text{ cm}^{-3}$ ) is observed, and the plasma density is increased proportionally to the microwave input power as well as the mass flow rate. This means that the ratio of the microwave power transfer to the plasma production, which is defined as the plasma density per microwave input power per unit mass flow rate, is nearly constant for wide operational conditions. Hence the chamber works as an ideal microwave applicator. It is therefor expected that by further optimizing the design of electron extraction, much larger electron current will be achieved in a lower biasing voltage

Seeing the above plasma data, a question may arise how this electron source efficiently produces the plasma even in the overdense plasma mode. Accessibility condition of the microwave neutralizer doesn't matter for this direct insertion of the antenna into the ECR magnet, where the electrons are directly oscillated and energized. In such a configuration, the microwave power will be easily transferred to electrons in the mirror magnet, thus the high energy electrons prevail in the whole discharge chamber, enhancing ionization and further increasing the plasma density.[13] .

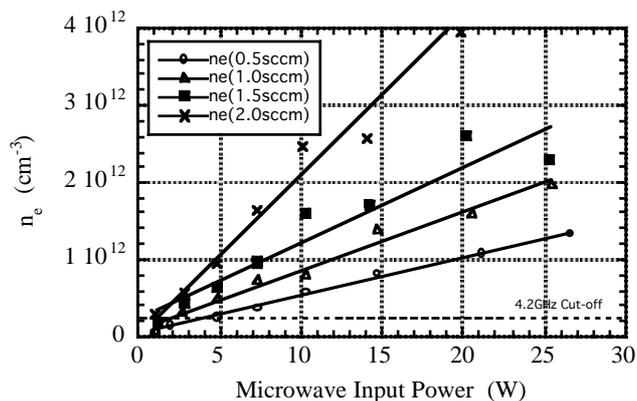


Fig. 10 Plasma Density inside Neutralizer (without Biasing/without Electron Current Extraction).

### Conclusions

A 20-cm-diam. 20-mN class microwave discharge ion thruster for spacecraft propulsion was designed and fabricated. The first ion beam extraction achieved a thrust of 16 mN for an input power level 500 W in a combination with a newly developed, flat, 20cm-diam. C/C grid. As for the microwave ion source, although the ion current was as much as 500 mA by the simulated performance test, it did not meet the target performance due to degraded ion production for a higher microwave input power, hence further improvement is needed to enhance the energy transfer from the microwave to plasma. The microwave neutralizer also has a problem, that needs to be optimized so as to suppress the wall loss, and to enable electron extraction in a lower biasing voltage. Although optimization processes are required for all of the newly designed components, the possibility of the 20-cm-diam. thruster was shown through initial test results described in this paper.

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