PLUME MEASUREMENT OF PLASMA PROPULSION SYSTEM

Taizou Noutsuka, Yoshiyuki Takao, Tomoya Hida, Yoshiki Yano, Gen Kantou,
Kazuhiko Uemura and Hideki Nakashima

Department of Advanced Energy Engineering Science, Kyushu University
6-1 Kasuga-Kouen Kasuga, Fukuoka 816-8580, Japan

Abstract

Some plans for computer simulations and experiments to develop a plasma propulsion system with Electron and Ion Cyclotron Resonance (EICR) plasma are reported. The EICR thruster is an advanced space propulsion concept that has possible uses in satellite station keeping and interplanetary travel. An experimental apparatus to generate EICR plasma was constructed last year. It consists of a cylindrical vacuum chamber, RF power supply, and eight magnetic coils. This experiment aims to generate plasma (without electrodes) by ECR and to accelerate ions (without grids) by ICR under a proper magnetic field configuration. On the other hand, computer simulation codes are being developed to find optimum experimental conditions and to examine characteristic behaviors of electrons and ions in the propulsion system.

Introduction

We are studying an electric propulsion system which utilizes Electron and Ion Cyclotron Resonance (EICR) plasma. The propulsion system will obtain thrust by accelerating ions with electric field or magnetic field gradient in plasma. The thrust of this system is smaller than that of chemical rocket, however it has a very large value of specific impulse. Thus this EICR thruster is an advanced space propulsion concept that has possible uses in satellite station keeping and interplanetary travel. In addition, this system could have a long lifetime and high reliability, since this system does not use any electrodes and grids. Furthermore this system could have advantages of high ion density and high energy efficiency in EICR plasma.

Generation Mechanism of ECR and ICR Plasma

ECR plasma is generated by using electron cyclotron resonance effect which occurs at a resonance point, $\omega = \omega_{ce}$(ω_{ce} stands for electron cyclotron frequency), when introducing microwave at frequency ω. The electrons in a plasma gyrate clockwise along the magnetic field lines at frequency ω_{ce}($\omega_{ce}=eB/m_e$). On the other hand, microwave is introduced at high magnetic field $\omega_{ce} > \omega$, which propagate through plasma as right-circularly -polarized wave called whistler wave[1]. By absorbing the whistler wave, due to Electron Cyclotron Resonance, near the resonance point, $\omega = \omega_{ce}$, the electrons gain energy (Fig. 1). The high energy electrons ionize neutral gas (propellant) to produce plasma.

Generation mechanism of ICR plasma is similar to that of ECR plasma described above except that the ICR plasma is generated with left-circularly -polarized wave and $\omega = \omega_{ci}$ (ω_{ci} stands for ion cyclotron frequency) condition.

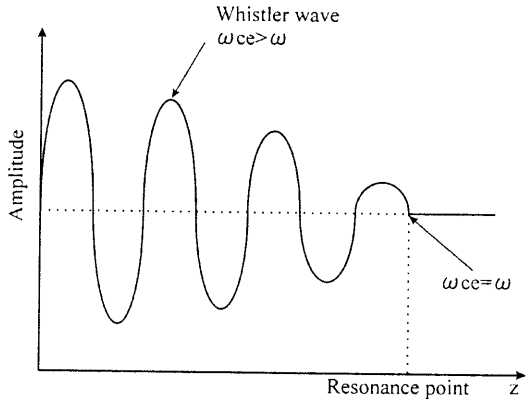

Fig. 1 Absorbing the whistler wave at the resonance point

Simulation Code Development

ECR Plasma

A one-dimensional PIC/Monte Carlo code is developed to study the generation mechanism of ECR plasma in our device. In the code, the motions of charged particles are determined by the equations of motion and collision process as follows,

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) - \frac{\mu}{m}\nabla \mathbf{B}$$

$$\frac{dz}{dt} = v_z$$

where v, z, q and m are the velocity, position, charge and mass of a charged particle, respectively. **E**, **B** and

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μ are the electric field, the magnetic flux density and the magnetic moment, respectively. The electric and magnetic fields are calculated through Maxwell equations[2]. Figure 2 shows axial profiles of transverse wave electric field (electromagnetic fields E_x and E_y) calculated for the following conditions: a right-circularly-polarized electromagnetic plane wave (microwave) enters at the left boundary (z=0) and propagates along the z axis. The external magnetic field has a local minimum at z=0.8m. Ar gas pressure is 0.4mTorr. As shown in Fig. 2 the wave amplitudes are damped pronouncedly before the resonance layer (z=0.63m) and the wave hardly propagates through the ECR layer because of the absorption by the resonant electrons.

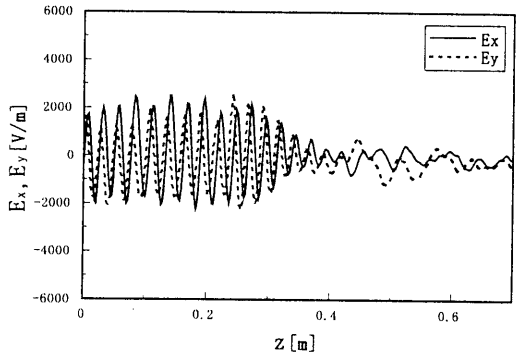


Fig. 2 Axial profiles in transverse wave electric fields

A two-dimensional PIC code is also being developed to study the plasma behaviors (ex. diffusion of plasma under a magnetic field gradient) in our device. In this code, the electrostatic field is determined from the requirement of quasineutrality rather than from Poisson's equations to avoid the statistical fluctuations encountered in use of the Poisson's equations[3],

$$-qE_{\parallel} = \frac{|B|}{n_i}\frac{\partial}{\partial\zeta}\frac{n_i T_{e\parallel}}{|B|} + \bar{\mu}\frac{\partial|B|}{\partial\zeta} + \nu_e m_e u_{e\parallel} + \frac{1}{n_e}\frac{\partial}{\partial t}\left(n_e m_e u_{e\parallel}\right)$$

where n, T, $\bar{\mu}$, ν and u are the number density, temperature, average magnetic moment, momentum transfer frequency and mean fluid velocity. The simulation grid is formed by a chosen set of magnetic field lines and by an equally spaced z-grid as shown in Fig. 3. The representation of ECR heating is simplified in the present simulation: we heat the electrons by giving each electron a random kick in transverse velocity whenever it crosses the resonance surface. Figure 4 shows surface plots of electron temperature (T_e) at time 4.35 μ sec. As shown in Fig.4, the electron temperature increases as the field line becomes shorter, because the electrons on the shorter magnetic field lines go back and forth more times than the ones on the longer magnetic field lines. As a result, high energy electrons are created by heating through the ECR surface.

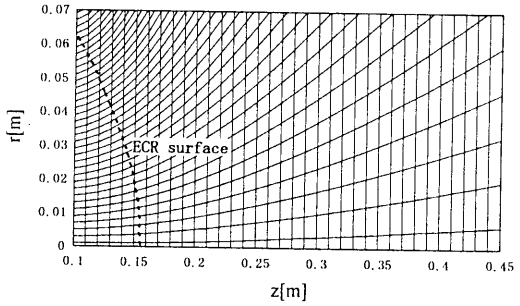


Fig. 3 Simulation grid for two-dimensional PIC code

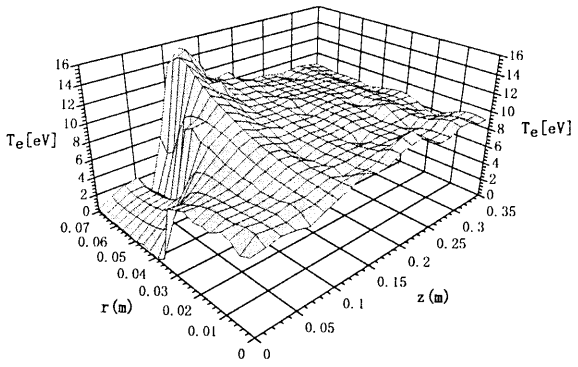


Fig. 4 Surface plot of electron temperature T_e at time 4.35 μ sec

ICR plasma

In order to estimate Ion Cyclotron Resonance (ICR) heating, ICR wave fields are calculated based on the model by Jeager, et al[4]. They assumed cold plasma that is confined in the mirror magnetic fields. The RF electric fields $\mathbf{E_{RF}}$ are obtained by solving Maxwell's equations

$$-\nabla\times\nabla\times\mathbf{E_{RF}} + \frac{\omega^2}{c^2}\mathbf{K}\bullet\mathbf{E_{RF}} = -i\omega\mu_0\mathbf{J_{ext}}$$

where $\mathbf{K}$ is the collisional cold plasma dielectric tensor, and $\mathbf{J_{ext}}$ is an external current density provided by an RF antenna. Since azimuthal symmetry is also assumed, $\mathbf{E_{RF}}$ and $\mathbf{J_{ext}}$ can be expanded into azimuthal modes

$$E_{RF}(r,\phi,z) = \sum_m E_m(r,z)e^{im\phi}$$

In Fig. 5, we show the energy absorption rate in He plasma for m=-1(left-hand-polarized) mode wave produced by an antenna located at z=0.25m. Two peaks are observed at the resonance layer where $\omega = \omega_{ci}$.

The details of the calculational model and results are given in an accompanying paper[5].

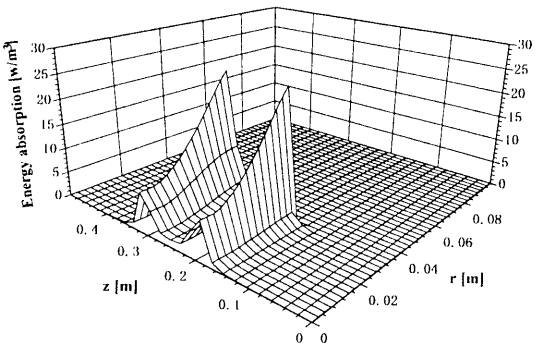


Fig. 5 Energy absorption rate in He plasma for m=-1 mode

Experiments

An experimental apparatus shown in Fig. 6 to generate EICR plasma was constructed last year. It consists of a cylindrical vacuum chamber (inner diameter of 21cm and axial length of 150cm), RF power supply and eight magnetic coils. It is run at pressure in the 10^{-2}Pa range with Ar or He gas as propellant. Microwave power up to 5.0kW with a frequency of 2.45GHz is applied using a magnetron in a continuous wave mode to the resonance area in the vacuum chamber. The propellant is ionized near the resonance region where the electron cyclotron frequency and the microwave frequency are equal (the magnetic field is 875G for the microwave frequency of 2.45GHz), and then plasma diffuses along the magnetic force line.

Measurements with Baffle Plate

As shown in Fig. 6, we set up a baffle plate that separates the vacuum chamber into two parts, has a hole of 30mm in its center and locates at the middle of the chamber. The plasma plume which is exhausted from the central hole of the baffle plate is measured by Langmuir probes. Ar gas was used as propellant. Plume measurements are done in different magnetic field configurations (i.e. mirror and cusp magnetic fields) by adjusting the current flow of the magnetic coils. Typical electric temperature and density profiles are shown in Fig. 7. These measurements were made by the Langmuir probes located along axial direction of the vacuum chamber.

Figure 7 shows that for the mirror configuration T_e=3.2eV and $n_e=2\times10^{12}$cm^{-3} within the baffle plate with a microwave input power of 1.0kW, while outside the baffle plate n_e decrease by an order of magnitude, T_e being the same. For the cusp configuration, T_e=2.7eV and $n_e=5\times10^{11}$cm^{-3} and they are relatively small due to lower confinement of the plasma as compared to those of the mirror configuration.

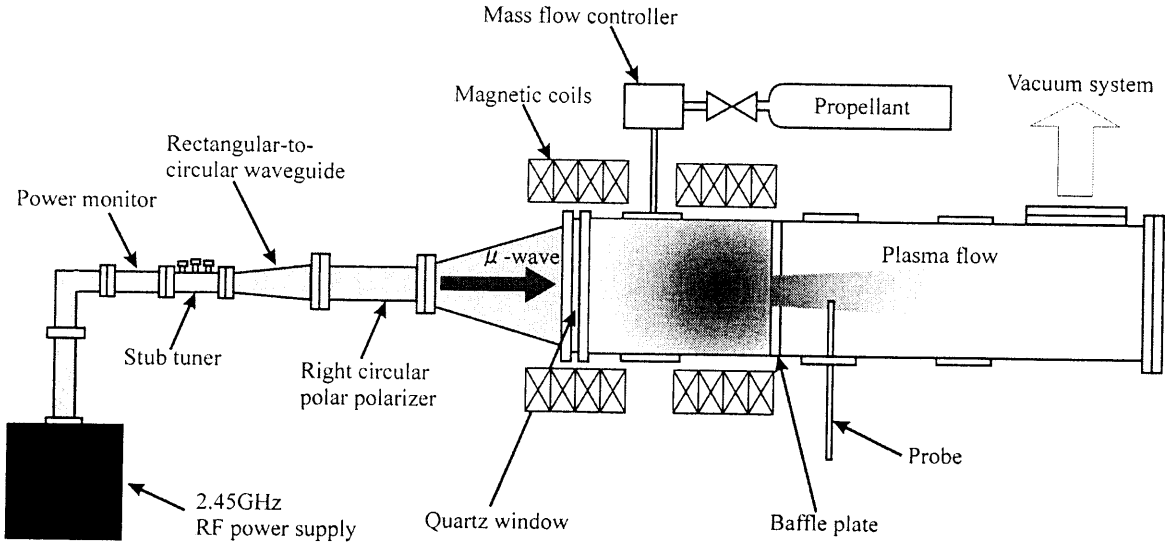
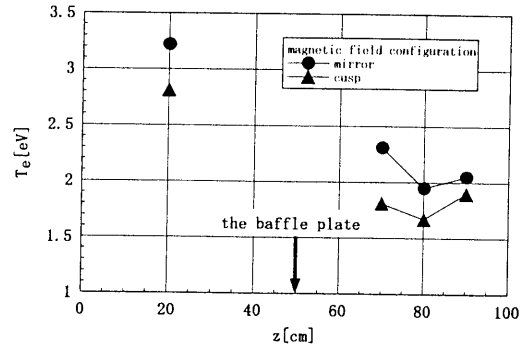
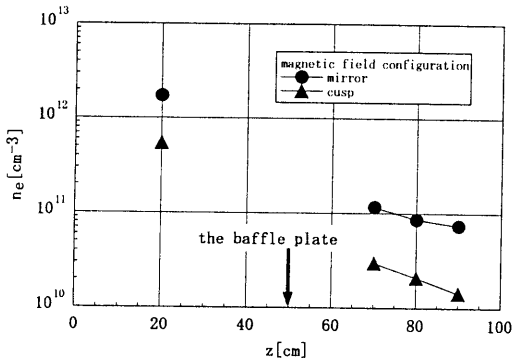


Fig. 6 Experimental apparatus



(a) Electron temperature



(b) Electron density

Fig. 7 Spatial distributions of electron temperature (T_e) and density (n_e) for the mirror and cusp configuration

Measurements with Gas Box

In the experiment stated before, applied microwave and propellant spread out in the vacuum chamber, and then plasma was not generated efficiently. So we set up the gas box as shown in Fig. 8 in the vacuum chamber to prevent microwave and propellant from spreading out, and to generate plasma efficiently.

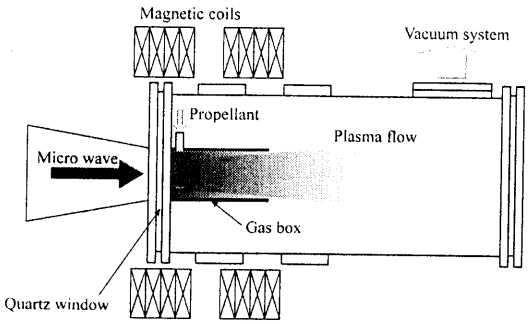
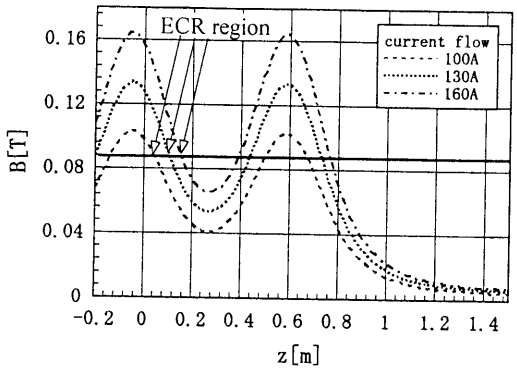
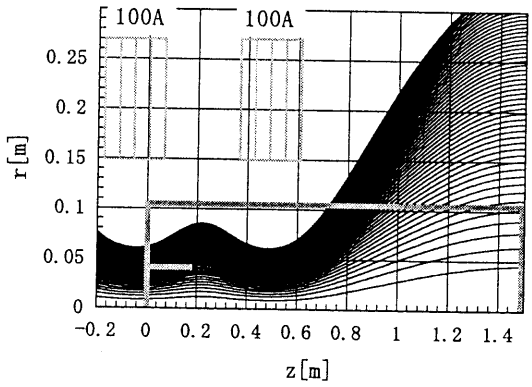


Fig. 8 Schematic diagram of the apparatus with the gas box

Plume measurement is done in mirror magnetic field configurations with a microwave input power of 500W and Ar and He gas are used as propellant. Plasma parameters were measured as changing the current flow of the magnetic coils. The magnetic field configurations and the magnetic force line distributions for the experiment are shown in Fig. 9. Typical data of electron temperature, density and plasma potential profiles with Ar as propellant are shown in Fig. 10 and with He in Fig. 11, respectively. The data in these figures are plotted versus distance from the quartz window (z) through which the microwave is introduced, and are taken along the center of the vacuum chamber.



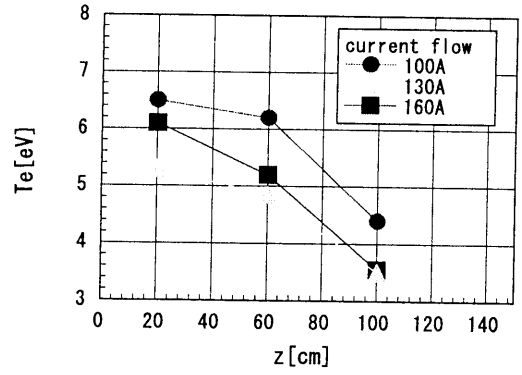
(a) Magnetic field configuration



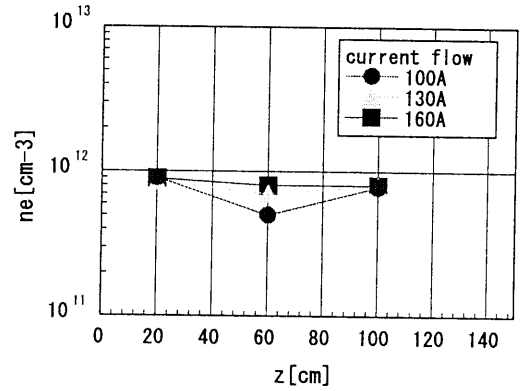
(b) Magnetic force line distribution

Fig. 9 Magnetic field configuration and magnetic force line distribution

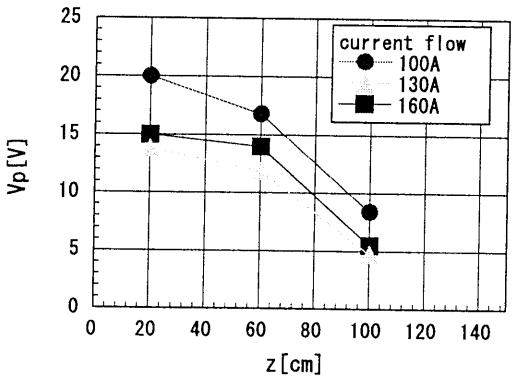
Figure 10 (a) shows that near the ECR region (as shown in Fig. 9 (a)) the electron temperature is peaked and decreases steadily with the increase of z. The electron density has little variation in the axial direction. The plasma potential decreases steadily with the increase of z. The slope of the plasma potential appears to be constant away from the ECR region, indicating a constant axial electric field that accelerates the ions. As shown in Figs. 10 and 11, the same tendency is found in the He experiment.



(a) Electron temperature

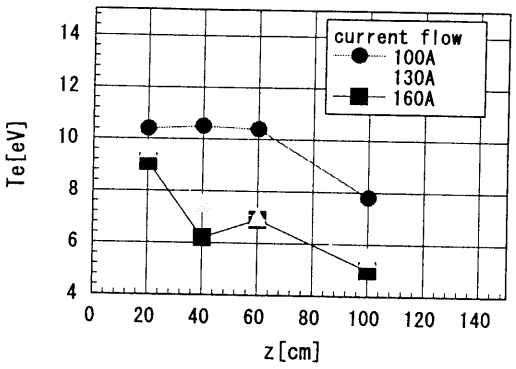


(b) Electron density

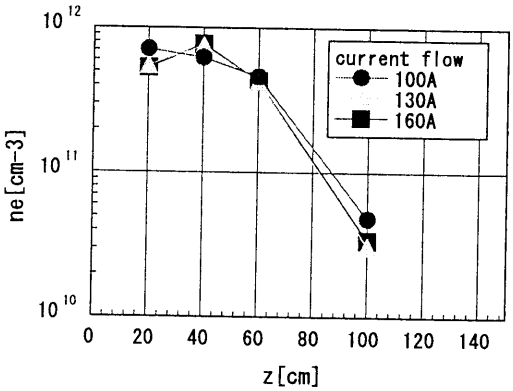


(c) Plasma potential

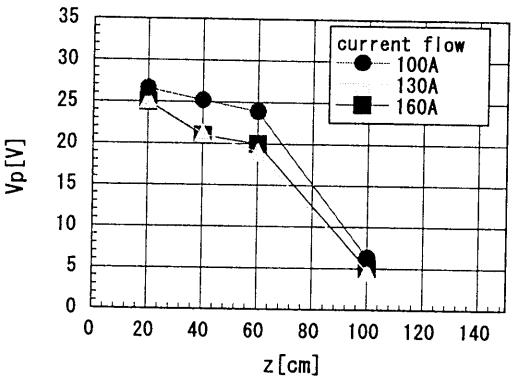
Fig. 10 Spatial distributions of electron temperature (T_e), density (n_e) and plasma potential (V_p) with Ar



(a) Electron temperature



(b) Electron density



(c) Plasma potential

Fig. 11 Spatial distributions of electron temperature (T_e), density (n_e) and plasma potential (V_p) with He

Gas Box with ICR Heating

Ions in the ECR plasma are further energized by ICR heating with an RF antenna installed after the gas box as shown in Fig. 12. In the low density plasma case, the perpendicular motion of the energized ions will be converted into the parallel motion by the action of the diverging magnetic field when the ions move to the open end of the magnetic field.

The energy distribution of the heated ions by ICR will be measured using an energy analyzer. The plasma parameters will also be measured. The optimal conditions will be determined to obtain the highest efficiency of thrust on the basis of these measurements.

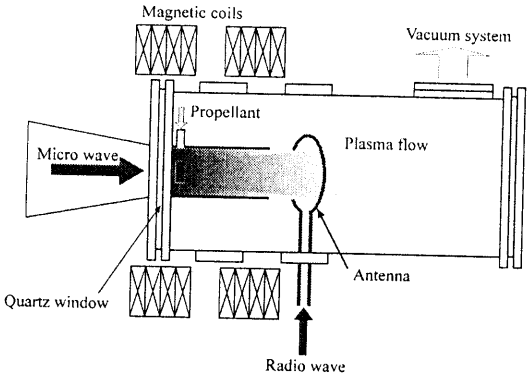


Fig. 12 Schematic diagram of the apparatus with the RF antenna

MUSES-C Type

Figure 13 shows an experimental apparatus of MUSES-C[6] type thruster. It consists of a cylindrical vacuum chamber (inner diameter of 40cm and axial length of 100cm), 2.45GHz Microwave power supply (maximum power is 500W), gas box, two permanent magnets, three grids and vacuum pumps. The apparatus is run with Ar gas as propellant at pressure in the 10^{-4}Torr range. Microwave power is applied from this power supply in a continuous wave mode through the quart window and the wave-guide to the gas box. A resonance field of 875G is generated in the gas box by the permanent magnets. Varying an interval between the permanent magnets controls the magnetic field. ECR plasma is generated and confined in cusp magnetic field produced by the magnets. The ECR surfaces (875G) are shown in Fig. 13. Ions in the plasma are extracted and accelerated by the grids. The plasma parameters will be measured in the same ways as the experiment described above. In addition to the plasma measurements, we will examine several kinds of beam characteristics such as thrust and beam divergence for performance evaluation of the thruster.

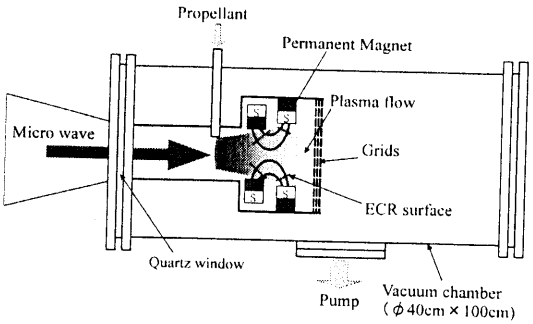


Fig. 13 Schematic diagram of the compact ECR thruster (MUSES-C type)

Hot Electron Plasma

We here suggest a method to accelerate ions by using a hot electron ring generated in ECR plasma. Figure 14 shows an illustration of the apparatus to generate the hot electron ring. Microwave generated by a magnetron is injected across the magnetic field through a classical microwave circuit. Then a hot electron ring is generated in the ECR plasma[7]. Having created a mirror-confined hot electron plasma, the generation of transient potentials is accomplished by turning on a pulsed coil located at a point between the mirror coils. The turn on time is typically within 10 to 20 ns. On this time scale, the plasma ions do not respond, so that their density remains locally constant. The hot electrons, however, feel the repelling force of the pulsed mirror and begin to be expelled from the region. Then ions are accelerated so as to run after this hot electrons[8]. A device is being constructed to create a hot electron plasma and transient potentials.

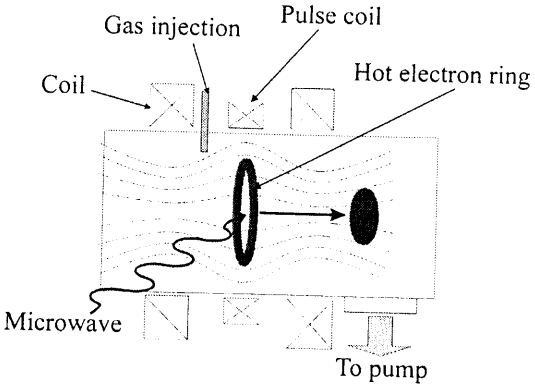


Fig. 14 Illustration of the apparatus to generate the hot-electron ring

Conclusion

Some simulations and experiments to develop a plasma propulsion system by using EICR plasma have been discussed. This experiment aims to generate plasma (without electrodes) by ECR and to accelerate ions (without grids) by ICR under a proper magnetic field configuration. The plasma parameters such as electron temperature are measured for the ECR plasma. Experiments on ion acceleration by ICR heating will soon be conducted. Codes are being developed to simulate ECR and ICR heating mechanisms, i.e. to estimate the absorbed power in the plasma. Another possibility of ion acceleration is also discussed : hot-electron plasma with pulsed coil.

These efforts will help design an advanced propulsion system that could have advantages in flight performance over the conventional systems.

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