Experimental Study of Traveling Wave Plasma Acceleration and Optimization of Magnetic Field Structure for Electrodeless RF Plasma Thruster

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Abstract: An electrodeless plasma thruster is studied to resolve the lifetime issue of the failure of electrodes by the plasma. However, this thruster has issues of low plasma generation and acceleration efficiency. In this paper, it was reported that the effect of the RF antenna length on the thrust performance of the non-uniform magnetic field type RF plasma thruster and preliminary experimental results of the new traveling magnetic field plasma acceleration method. Regarding the non-uniform RF plasma thruster, it was revealed that the RF power should input to the high magnetic field gradient region by short RF antenna to obtain high performance. In regards to the traveling magnetic field acceleration, it was observed that the ion Mach number was increased by applying the traveling magnetic field.

Nomenclature

a	=	thruster inner radius
$\tilde{B}$	=	magnetic field strength of TMF
e	=	elementary charge
E	=	energy of TMF
F	=	thrust
k	=	wave number
k_B	=	Boltzmann's constant
L	=	thruster length
L_a	=	RF antenna length
n	=	electron number density
P_{abs}	=	plasma absorption power
P_T	=	input power with discharge
$P_T^{(0)}$	=	input power without discharge
Δt	=	operation time
T_e	=	electron temperature
v_p	=	phase velocity
v_e	=	electron thermal velocity

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β	=	beta value
η	=	absorption power to electron from TMF
μ_0	=	magnetic permeability in vacuum

I.Introduction

IN recently, Hall thrusters and ion thrusters have been used in many satellites[1-3]. These thrusters have the lifetime issue of failure of electrodes or electron sources by plasma sputtering. Several methods to solve this matter was suggested, but it was not achieved to the fundamental solution[4]. To resolve this lifetime issues, the electrodeless plasma thruster, which the plasma is not directly touched to the electrode, was proposed[5,6]. The typical type thruster is the thruster utilizing radio frequency (RF) discharge as shown in Fig.1. The electrodeless RF plasma thruster consists of the RF antenna, grass tube discharge chamber, magnetic circuit, and propellant gas feed system. The generated plasma by RF discharge is accelerated by the divergence magnetic field which is called the magnetic nozzle. The thrust efficiency of this type thruster is at most under 20%, and this performance is lower than conventional type thrusters[7]. The research of the electrodeless plasma thruster is being conducted to improve the thrust performance.

We are studying the electrodeless RF plasma thruster to improve the plasma generation and acceleration efficiency. Commonly, the almost uniform magnetic field in the discharge chamber is utilized to confine the plasma[7]. Our previous research revealed that the non-uniform magnetic field near the plasma generation region enhanced the thrust performance and exhaust plasma amount[8]. In non-uniform type RF plasma thruster, it was reported that the suitable RF antenna position was existed by the positional relationship between the magnetic field and the RF antenna[9]. We obtained the suitable thruster configuration of RF antenna and magnets, and the thrust performance was improved more than twice as large as the small thruster in same operation parameter in the previous study[10]. In this paper, the relationship between the RF antenna shape and the magnetic field shape is experimentally investigated to further improvement of the thrust performance.

Several electrodeless plasma acceleration methods were suggested as a substitute for the magnetic nozzle acceleration in order to improve acceleration efficiency. Toki and Shinohara have proposed the electromagnetic acceleration by rotating the electric field or rotating the magnetic field[11-12]. VASIMR has achieved 72% of the thrust efficiency by additional Ion cyclotron resonance heating (ICRH)[13-14]. However, this thruster should need over 100 kW power or the massive and complex structure such as the superconductive coil. In the sixties, it was reported the high thrust performance by the traveling magnetic field[15-16]. This acceleration method confines the plasma by the high magnetic field and the high magnetic field region is propagated to the downstream region by plurality coils whose phase is displaced. Therefore, the confined plasma is accelerated with the traveling magnetic field. This acceleration method has issues as the pulse operation and necessity of the high magnetic field over 0.1T to confine ions. We were proposed new traveling magnetic field acceleration method to achieve high performance in relatively lower power. This method is higher phase velocity for fitting the thermal electron velocity. The momentum of the traveling magnetic field is transferred to electrons and electrons are accelerated to the downstream. The ions are accelerated by the generated ambipolar magnetic field by difference between the electron motion and the ion motion. This acceleration method can achieve 50% of the acceleration efficiency in theory. In this paper, we construct the experimental equipment for acceleration demonstration and we report the preliminary experimental results of the acceleration experiment.

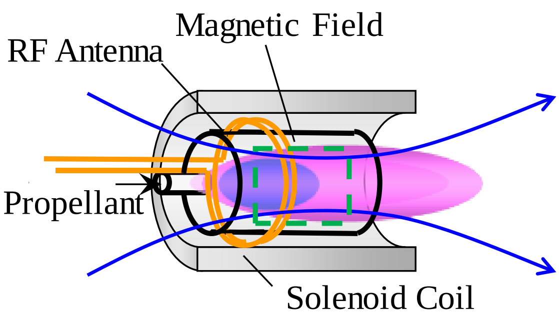


Figure 1. Electrodeless RF plasma thruster.

II.Experimental Setup

A. RF plasma thruster with the non-uniform magnetic field

The schematic diagram of the experimental setup is shown in Fig. 2. This experimental facility consists of the vacuum chamber of 700 mm in diameter and 1200 mm long pumped by a diffusion pump/rotary pumping system. The backpressure is less than 10^{-3} Pa without gas feeding and 1.6×10^{-1} Pa in 1.2 mg/s. The mass flow rate of Ar is controlled by the mass flow controller and Ar gas is fed to the backplate of the discharge chamber from the Ar gas tank. The RF power supplies to the RF antenna through the matching box from the RF power supply of 1000 W and 13.56 MHz. The discharge timing and period is controlled by the function generator. In this experiment, the RF plasma thruster is operated during 500 ms. The thruster head is located on the thrust stand for the thrust measurement. A torsion pendulum-type thrust stand in 470 mm of left arm and 200 mm right arm is employed. The displacement by the thrust generation is measured by the laser displacement sensor, and the calibration is conducted by the coil-magnet actuator. The natural period of the pendulum is approximately 5.0 s which is much longer than the discharge duration of 0.5 ms, and so the impulse thrust of the thruster can be considered to be of infinitely small duration. The thrust is obtained using by the operation time, Δt, as follows,

$$F = \frac{(F\Delta t)}{\Delta t} \tag{1}$$

The error bar of the thrust measurement is estimated by taking into account possible contributions from instrumental errors (dispersion of shot to shot, calibration errors) and curve fitting error. The plasma absorption power, $P_{\rm abs}$, is measured to evaluate the plasma generation efficiency using the following equation[17]

$$P_{abs} = P_T - P_T^{(0)} \tag{2}$$

where $P_{\rm T}$ is the input power with plasma discharge and $P_T^{(0)}$ is input power without plasma discharge in same discharge voltage.

The thruster head consists of the RF antenna, magnetic circuit and the discharge chamber as shown in Fig.1. The generated plasma of 13.56 MHz RF discharge is accelerated by the magnetic nozzle. Figure 3 shows the cross-section of the thruster head and the calculated magnetic field strength by the Finite Element Method (FEM) software. The discharge chamber is a Pyrex tube with 23 mm in inner diameter and 100 in length. Bar magnets are attached the cylindrical yoke and surround around the discharge chamber. This magnetic circuit is simple structure and can generate the non-uniform magnetic field with the magnetic cusp as shown in Fig.3.

In order to investigate the effect of the relationship between the RF antenna shape and the magnetic field shape, the thrust measurement is conducted in four RF antenna shape. The triple loop antenna is employed as the RF antenna because this type antenna was higher performance than another type antenna in this magnetic field structure by the previous study. In this experiment, thrust measurement is conducted in four antenna shapes to investigate the effect of the RF power input region on the thrust performance. The photographs of these four types RF antennas are shown in Fig.4. The upper edge of all antennas is fixed at z=45 mm of Fig.3. The experimental conditions are listed in Table 1.

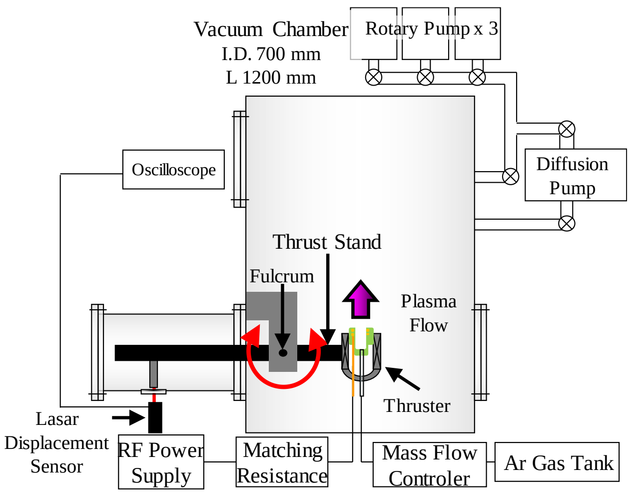


Figure 2. Experimental setup.

B. Traveling magnetic field plasma acceleration

The traveling magnetic field (TMF) plasma acceleration which was suggested by our group is fitted the phase velocity to the electron thermal velocity, and the TMF interacts with the electron. The schematic diagram of this acceleration method is shown in Fig.5 This system consists of the DC coil for plasma confinement and RF discharge, the discharge chamber and the plurality coils for generation the TMF. The momentum of the TMF to the downstream is transferred to the electron by Transit Time Magnetic Pumping (TTMP), which almost corresponds the Landau damping of the magnetic field. In previous studies of nuclear fusion, this effect was utilized as the plasma current generation method using plurality coils in the tokamak[18-19]. The energy absorption efficiency to the electron from the TMF was formulated. The plurality coils are linearly arranged for applying on the thruster. For thruster, the energy absorption efficiency with loss to the discharge chamber wall by Bohm diffusion which corresponds the acceleration efficiency was formulated as follows.

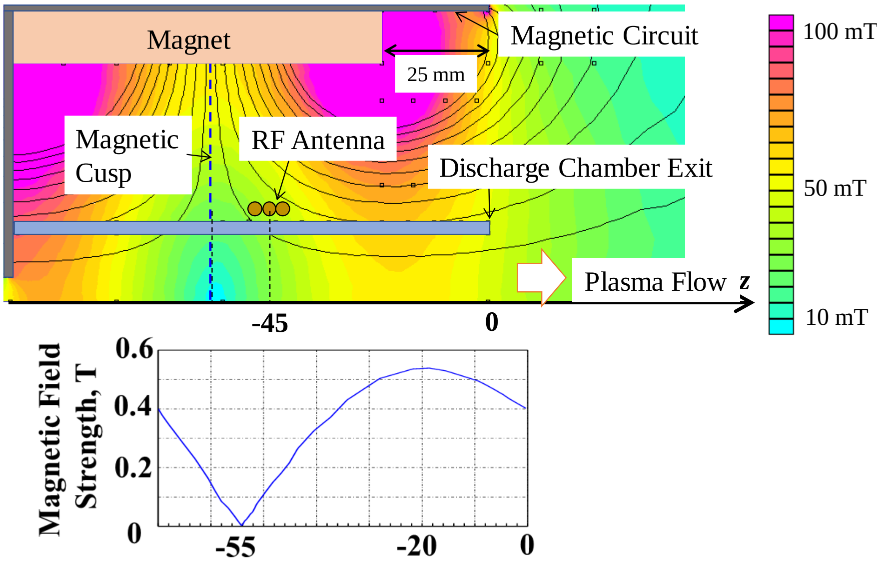
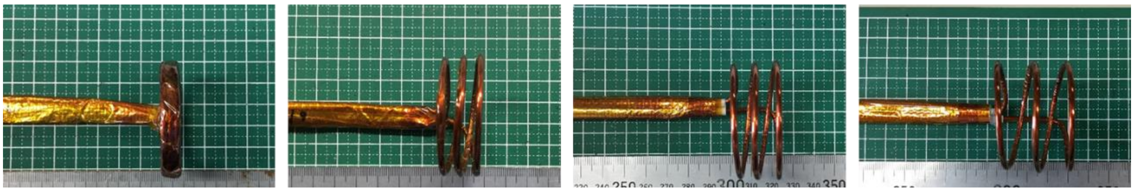


Figure 3. Thruster cross-section and magnetic field contour figure.
(The lower graph is the magnetic field strength distribution along the centerline of the discharge chamber.)



(a) L_a=7 mm. **(b) L_a =15 mm.** **(c) L_a =20 mm.** **(d) L_a =30 mm.**

Figure 4. Photographs of four type RF antennas.

Table 1 Experimental conditions of non-uniform RF plasma thruster.

RF power	1 kW
RF frequency	13.56 MHz
Propellant gas	Ar
Mass flow rate	1.2 mg/s
back pressure	1.6×10^{-1} Pa
RF antenna	Triple loop
Antenna length	7, 15, 20, 30 mm

$$\eta = \sqrt{\pi^3}\frac{\beta\tilde{B}^2}{\mu_0 E}kLa^2\left(\frac{v_p - v_0}{v_e}\right)\exp\left[-\left(\frac{v_p}{v_e}\right)^2\left(1-\frac{v_0}{v_p}\right)^2\right] - \frac{3\pi L}{8eE}\left(\frac{\mu_0 n\left(k_B T_e\right)^3 \beta}{2}\right)^{1/2} \quad (3)$$

where β is ratio between the plasma pressure and the magnetic pressure of the static magnetic field, k is the wavenumber of the TMF, L is thruster length, a is thruster radius, E is the energy of the TMF, $\tilde{B}$ is the strength of TMF, v_p is phase velocity and v_e is the electron thermal velocity. The first term of Eq.(2) is shown the energy absorption efficiency. The absorption power has suitable value of the phase velocity which is almost the electron thermal velocity. In addition, this efficiency is proportional to β value, $\tilde{B}^2$ and k assuming the constant thruster size. The acceleration efficiency of over 50% was estimated by Eq. (3) assuming the middle size thruster of 46 mm of inner diameter. In order to demonstrate this acceleration method in the moderate-size experimental set-up, the small scale demonstration device was constructed. The assumption parameters and calculation parameters are listed in Table 2. This condition of the small scale experiment can be achieved almost 10% of abortion efficiency, and the acceleration effect by the TMF can be measured because the absorption power of 150 W is large enough compared the discharge power of 1000 W. The appearance of the constructed acceleration demonstration devise is shown in Fig.6.Thruster length is 0.2 m and the discharge chamber inner diameter is 26 mm. The magnetic field strength of the static magnetic field and the TMF are 9 mT and 10 mT in 1500 W input power of the TMF respectively. The DC magnetic field is generated by five DC coils and the TMF is generated by seven coils. Each coil for the TMF is shifted the phase by $\pi/2$ through three hybrid couplers. The frequency of RF for the TMF is 4 MHz and the wavenumber is 7.5 in this experiment. The Phase velocity is almost 842 km/s which almost corresponds the electron thermal velocity. The operation conditions are listed in Table 3. The electron number density, electron temperature, and the ion Mach number are measured using the Mach probe. The measurement position is 50 mm upstream position from the most downstream coil to investigate the acceleration effect by the TMF. The probe measurement is conducted six TMF power conditions.

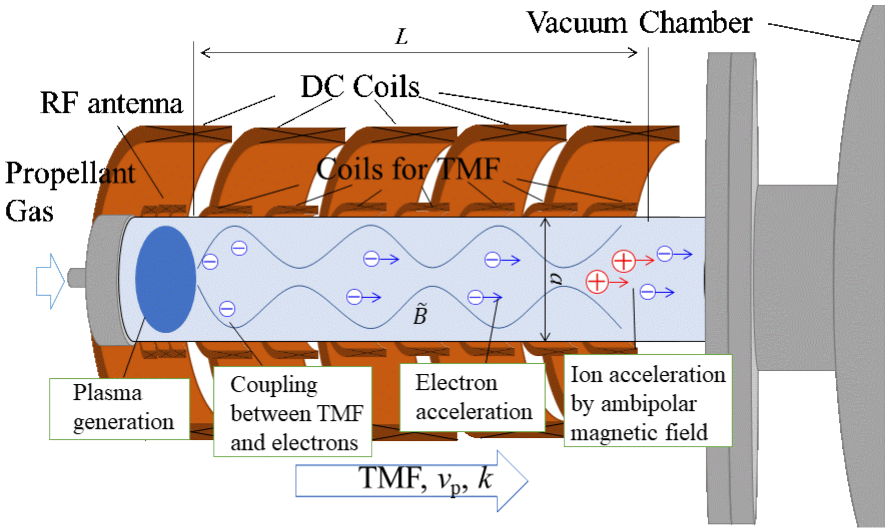


Figure 5. Schematic diagram of traveling magnetic field plasma acceleration.

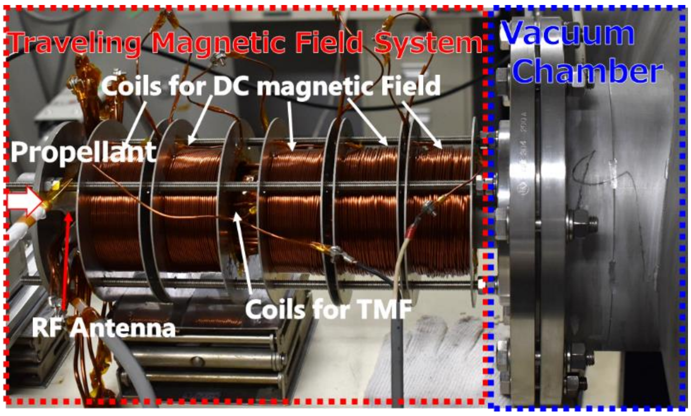


Figure 6. The appearance of a traveling magnetic field plasma acceleration device.

Table 2. Absorption efficiency of TMF plasma acceleration.

	Target scale	Small scale
Assumption parameters		
Thruster lengh	300 mm	200 mm
Thruster diameter	46 mm	23 mm
Input power for RF discharge	several kW	1 kW
Electron number density	1.0×10^{19} m^{-3}	1.0×10^{18} m^{-3}
Electron temperature	4 eV	
Input power for TMF	13 kW	1.5 kW
Magnetic field strength of TMF	15.6 mT	9 mT
Magnetic field strength of DC	15.6 mT	10 mT
Wave number of TMF	10	7.5
Calculation parameters		
Suitable phase velocity	842.5 km/s	
Absorption efficiency	50.2%	9.9%

Table 3. Experimental conditions of traveling magnetic field plasma acceleration.

Mass flow rate	1.2 mg/s
Propellant gas	Ar
RF frequency for discharge	13.56 MHz
RF power for discharge	
RF frequency for TMF	4.0 MHz
RF power for TMF	300, 500, 700, 1000, 1200, 1500 W
Magnetic field strength of DC	10 mT
Magnetic field strength of TMF	4.2, 5.6, 6.7, 8.0, 8.5, 8,9 mT
Operation time	300 ms

III.Experimental Results of RF Plasma Thruster with Non-uniform Magnetic Field

The thrust against the RF input power in four RF antenna length is shown in Fig.7. The thrust of each antenna length is almost proportional to the input power. The shortest antenna length of 7 mm has highest thrust, and the maximum thrust is 5.93 mN at 1000 W. The thrust characteristics in longer RF antenna length are approximately same. Figure 8 shows the thrust and the plasma absorption efficiency against the RF antenna length in 1000 W. The plasma absorption efficiency is defined as ratio between the plasma absorption power estimated by Eq. (2) and the input power. The thrust in short antenna length is higher than the longer RF antenna length as shown in Fig.8. In contrast, the difference in the plasma absorption efficiency is not as great as the thrust. It was reported that the plasma generation amount is increased in broad discharge region. It is considered that the reason for slightly increase at 30 mm of antenna length is the wider discharge region by the long antenna length, but this effect is small. This character which is high thrust in short antenna length is not observed in uniform magnetic field type. The RF antenna upstream edge is located near the magnetic cusp which is large magnetic field gradient region as shown in Fig.3. It was reported that the uniform magnetic field enhances the plasma generation efficiency in the previous study[20]. It is considered that the plasma generation efficiency is enhanced by the location of the RF antenna in this region. In addition, the loss of the generated plasma near the magnetic cusp is lower than other positions. The difference between the thrust and the plasma absorption efficiency can be explained by this effect. From these results, the RF power should be locally supplied to near magnetic cusp in the RF plasma thruster with the non-uniform magnetic field to obtain high thrust performance. The reason is that the plasma generation efficiency and the exhaust efficiency are enhanced by locating the RF antenna at the large magnetic field gradient region.

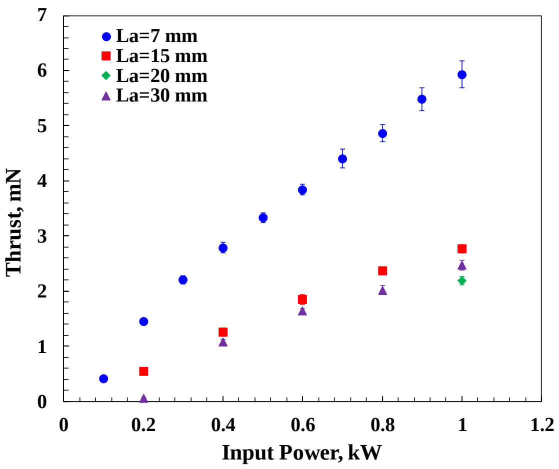


Figure 7. Thrust vs Input power.

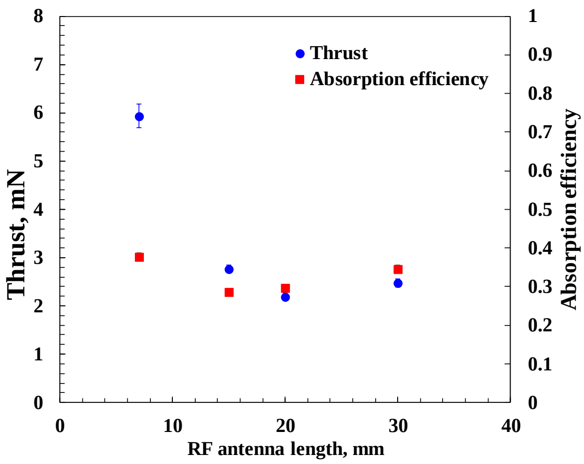
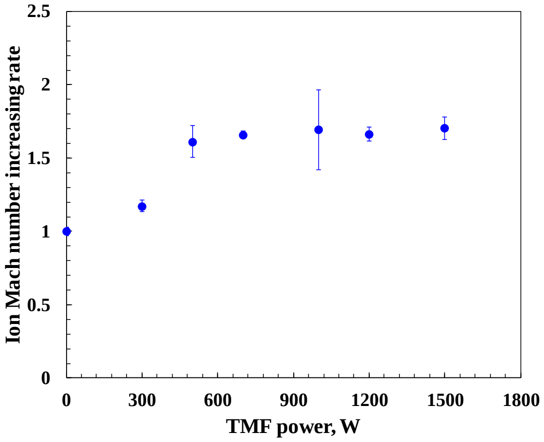


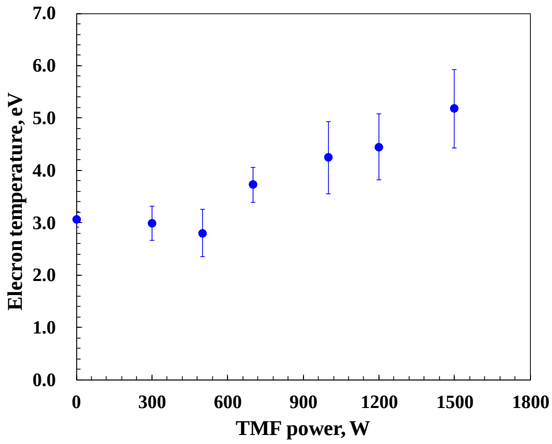
Figure 8. Thrust and absorption efficiency vs RF antenna length.

IV.Demonstration experiment of Traveling Magnetic Field Plasma Acceleration

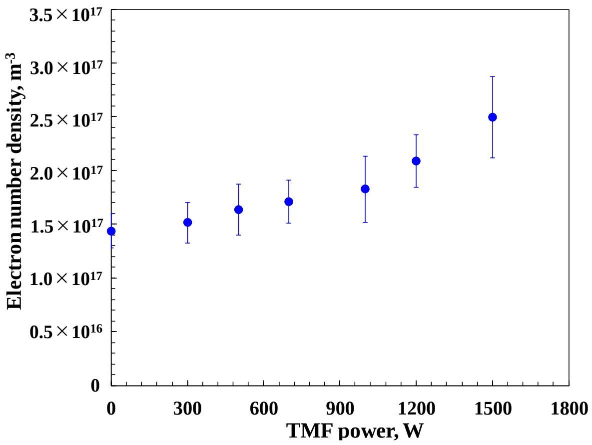
The early experiment to demonstrate the plasma acceleration by the TMF is conducted, and the Ion Mach number, electron temperature, and electron number density are measured using by the Mach probe. The measured Ion Mach number increasing rate, electron temperature, and electron number density are shown in Fig.9. The measurement point is the position of 50 mm upstream than the most downstream coil for the TMF. The ion Mach number with the TMF is normalized by it without the TMF. The horizontal axis is the input power of the TMF, the result of 0 W shows it of only RF discharge. The ion Mach number increasing rate is increased by applying the TMF. The ion Mach number increases at most 70%. From this result, it is shown that the plasma is accelerated by applying the TMF. However, the increase of the Ion Mach number is saturated in over 700 W of the TMF power. Next, the electron temperature and the electron number density against the TMF power are shown in Fig.9 (b) and (c). These parameters increase with increasing TMF power. Both parameters increase gradually under 700 W, but these increase greatly in over 700 W. From this, the TMF power is used as the plasma generation, rather than as the plasma acceleration in this condition. Another factor is that the matching of RF circuit for the TMF is not sufficient during applying the TMF to the plasma in high power condition, because the plasma parameter changes by the TMF. In addition, the plasma pressure is increased by the TMF. The plasma is also accelerated by increasing pressure. We have to investigate the acceleration characteristics and phenomena in order to demonstrate that the measured plasma acceleration is TMF plasma acceleration.



(a) Ion Mach number increasing rate.



(b) Electron temperature.



(c) Electron number density.

Figure 9. Ion Mach number and plasma parameter of traveling magnetic field plasma acceleration.

V.Conclusion

The effect of the RF antenna shape on the thrust performance of the RF plasma thruster with the non-uniform magnetic field and the plasma acceleration by the traveling magnetic field were experimentally investigated. The thrust performance was measured in four triple loop antenna length in the RF plasma thruster with non-uniform magnetic field experiment, and the relationship between the plasma generation region and the magnetic field structure was investigated. Regarding the traveling magnetic field (TMF) acceleration experiment, the small acceleration demonstration device was constructed, and the early experiment was conducted. From these experiments, the following results were clarified.

・The thrust performance was highest in the shortest RF antenna near the magnetic cusp. This means that the local supply of RF power to the large magnetic field gradient region is suitable.

・The difference of plasma absorption energy at each RF antenna length is not large. From these results, the effect of the plasma generation position on thrust performance is important.

・The small TMF device for the plasma acceleration demonstration was constructed.

・The ion Mach number measured using by the Mach probe has increased a maximum of 70% by applying the TMF. However, the plasma pressure was also increased, thus further investigation about the plasma acceleration by the TMF.

Acknowledgments

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