19PB-077

High-Density Helicon Plasma Production and Acceleration Experiments

高密度ヘリコンプラズマ生成と加速実験

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In order to realize a deep space exploration in the future, we have been developing a new electrodeless plasma thruster using an electromagnetic acceleration (an azimuthal mode number m = 0 coil method) applied to high-density helicon plasmas. In the initial analysis by simulations shows that the m = 0 acceleration requires a high-density plasma with a low neutral particle pressure. In this presentation, we report a progress of the m = 0 acceleration experiment in low-pressure discharge using a fast solenoid valve.

1. Introduction

In most of present electric thrusters, its lifetime is limited by an erosion of electrodes due to direct contacts between plasma and electrodes. To solve this problem, we have been developing a completely electrodeless plasma thruster. It utilizes a high density (~10^{13} cm^{-3}) helicon plasma [1-4] accelerated by the Lorentz force, generated by a product of an azimuthal current j_θ induced in the plasma and a radial component of the external magnetic field B_r. In order to excite the j_θ, an azimuthal mode number m = 0 coil method has been proposed [5].

2. m = 0 Coil Acceleration

Figure 1 shows a conceptual diagram of m = 0 acceleration scheme. This is a half cycle acceleration by the use of a low frequency (< 100 kHz) coil current. Required conditions for the acceleration are as follows; 1) accelerated plasma must be exhausted from an m = 0 antenna area before undergoes a deceleration phase, 2) inductance of the plasma is dominant than its resistance, 3) magnetic fields generated by the m = 0 need to be penetrated into a plasma.

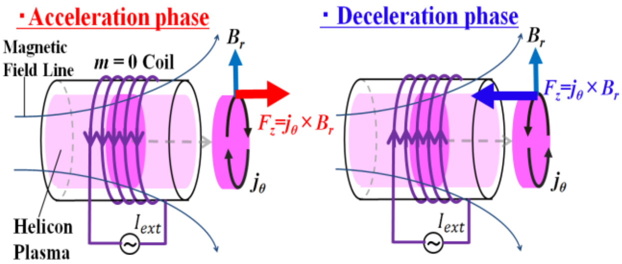

Fig.1　Principle of m = 0 acceleration

Critical operating parameters to achieve an efficient acceleration are an external magnetic field strength B, a coil driving frequency f and magneto motive force F_m of the m = 0 coil.

3. Simulation of m = 0 Acceleration

In order to determine appropriate driving parameters of m = 0 acceleration, a simulation code developed by late Dr. K. P. Shamrai (Institute for Nuclear Research, Ukraine) was used. Important analysis parameters are j_θ and an ion axial excursion length L_{iz}. Initial simulation results [6] showed a good operational window in an ion cyclotron frequency f_{ci} range (shown in Fig. 2), which needs the high electron density n_e (> 10^{12} cm^{-3}) and the low neutral particle pressure p_n (< 0.01 Pa). Therefore, generation of high density and low neutral pressure plasma is required for the m = 0 acceleration.

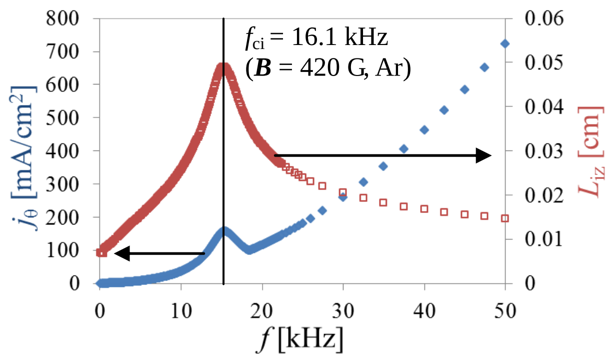

Fig.2　Simulation result of typical experimental parameters (B = 420 G, F_m = 1,000 AT, n_e = 5 $\times 10^{12}$ cm^{-3}, p_n = 0.05 Pa, T_e = 4 eV, T_i = 0.2 eV, radial position: r = 5 cm (plasma periphery))

4. Experimental Device

4.1 *Large Mirror Device*

Figure 3 shows a schematic drawing of Large Mirror Device [7]. A vacuum vessel is composed of a cylindrical chamber (1,700 mm in length and 445 mm in inner diameter) and a quartz discharge tube (1,000 mm in length and 100~170 mm in inner diameter). A high-density plasma is generated by a radio frequency (rf) power of ~ 3 kW with a frequency of 7 MHz. In order to increase B_r, permanent magnets were installed [8]. The m = 0 coil was located in a downstream region of an rf antenna. LMD has two turbo-molecular pumps (1,000 l/s and 2,400 l/s) with a base pressure of ~ 5 $\times 10^{-4}$ Pa.

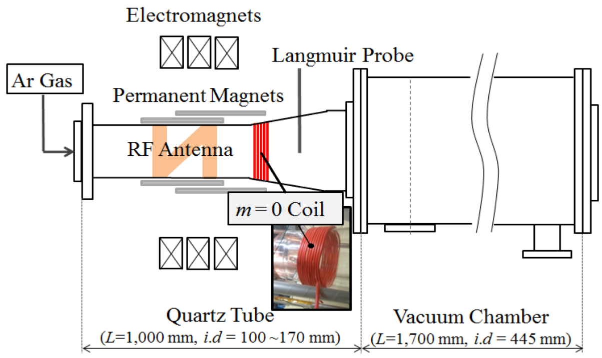

Fig.3 Schematic drawing of LMD

4.2 *Solenoid Valve*

In the low-pressure discharges, a pulsed gas feeding system using a fast solenoid valve (Parker General Valve, 9-279-900) was used. Figure 4 shows a neutral particle pressure in the discharge area as a function of valve opening time.

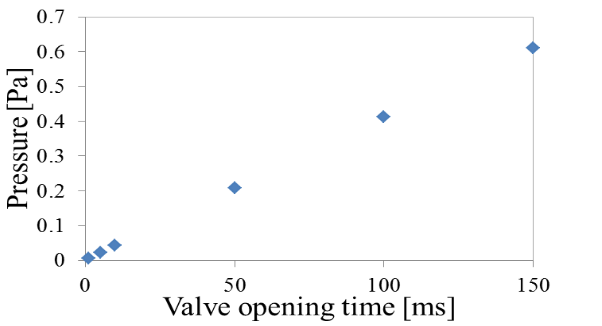

Fig.4 Neutral particle pressure in the discharge area as a function of valve opening time

4.3 *AC Power Supply*

In order to increase the F_m of the m = 0 coil, a high-current AC power supply using a capacitor bank and an IGBT was developed. Figure 5 shows a schematic diagram of this circuit.

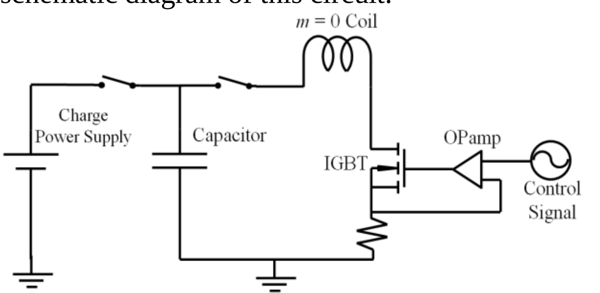

Fig.5 Schematic diagram of circuit

By the use of the circuit, the output current achieves 100 A (f = 10 kHz) ~ 60 A (f = 50 kHz). A duration time of the discharge in this circuit is about 5 ms.

5. Low-pressure Discharge Experiment Result

Figure 6 shows results of the low-pressure discharge experiment measured by a Mach probe. Here, the rf power is 3 kW, and both electromagnets and permanent magnets were used.

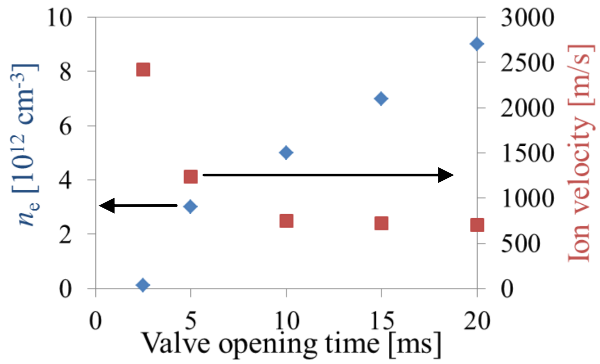

Fig.6 Experimental result of n_e and ion verocity via the valve opening time (B ~ 1,000 G,) radial position: r = 0 cm (center of plasma)

According to Figs. 4 and 6, a high-density plasma (3×10^{12} cm^{-3}) was generated despite of the low gas pressure (0.02 Pa), using the pulsed gas feeding (5 ms valve opening time).

6. Conclusion

The low-pressure discharges with a fast solenoid valve have been successfully executed in generating the improved target plasma, which is necessary for efficient m = 0 acceleration. In the conference, preliminary results using the high-current AC power supply will be presented.

Acknowledgments

This research is dedicated to Dr. K. P. Shamrai, who sadly passed away on Sep. 9, 2013 but made great collaborative researches with us.

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