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Study on electrodeless electric propulsion in high-density helicon plasma with permanent magnets

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To establish electrodeless electric propulsion, we have been developing a new electrodeless plasma acceleration thruster using high-density helicon plasmas and permanent magnets, and characterizing them by, *e.g.*, electrostatic and magnetic probes, a high-resolution spectrometer (measuring argon line intensity and line intensity ratio to derive plasma parameters), and a high-speed camera measurements (deriving radial distribution of electron density), in addition to a laser induced fluorescence (LIF) method to measure plasma flow velocity, where they are under development. Here, we will present preliminary acceleration methods using such as Rotating Magnetic Field coil and m = 0 coil along with results of various measurements mentioned above to estimate the plasma performance.

KEYWORDS: Helicon Plasma Thruster, Electrodeless Acceleration, Diagnostics.

1. Introduction

An electric rocket engine used in space, has a higher specific impulse compared to a chemical one. However, in most of the present system, its lifetime is limited by an erosion of electrodes due to direct contacts between electrodes and a plasma. To overcome this problem, we are proposing an electrodeless electric propulsion system with a high efficiency and a long lifetime as a Helicon Erectrodeless Advanced Thruster (HEAT) project.[1] This scheme employs a high density (~10^{13} cm^{-3}) helicon plasma[2-4] accelerated by the Lorentz force, which is 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. To prove its principle, it is also important to estimate plasma performance. Here, we will show preliminary results of acceleration schemes followed by various measurements.

2. Large Mirror Device

Figure 1 shows a schematic diagram of Large Mirror Device [LMD, 1,700 mm in length, 445 mm in inner diameter (i.d.)].[5] Considering a divergent magnetic field to be applied in the acceleration scheme, a quartz tube (1,000 mm in length, 100~170 mm in i.d.) has a tapered shape to prevent a wall loss of plasmas. LMD has two turbo-molecular pumps (1,000 l/s and 2,400 l/s) with a base pressure ~ 10^{-4} Pa. An argon gas is used as a propellant one, and a typical discharge pressure is $\gtrsim$ 0.1 Pa. A helicon plasma is generated by a radio frequency (rf) power via a half-helical antenna. The rf input power and its excitation frequency are ~ 3 kW and 7 MHz, respectively. An external magnetic field is applied by electromagnets. In order to increase B_r, permanent magnets were also installed. As acceleration antennas, Rotating Magnetic Field (RMF)[7] and *m* (azimuthal mode number) = 0 coils, were put on a tapered quartz tube position where the strong B_r is obtained.

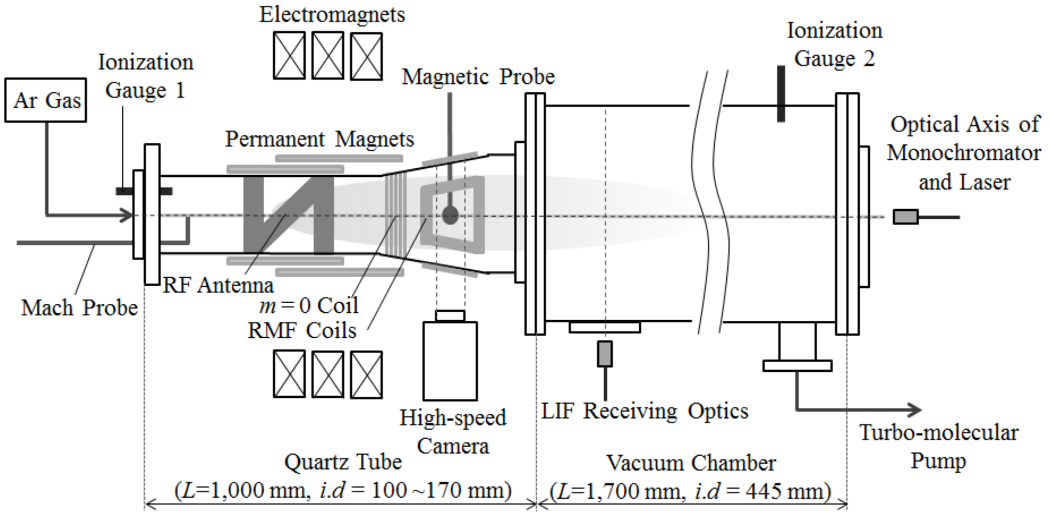

Fig. 1. Schematic drawing of LMD

For plasma measurements, we generally use probes (*e.g.*, Mach probe and magnetic probe) and are developing non-invasive optical measurement systems, which will be described after, not to cause disturbances to a plasma, as shown in Fig. 1.

3. Acceleration Methods

3.1 Permanent Magnets

In order to increase B_r from a few tens of G, which is crucial for accelerating plasma by both RMF and $m = 0$ methods, permanent magnets were installed in addition to the present electromagnets. Permanent magnets were placed in a quartz tube straight section (see Figs. 2 and 3).

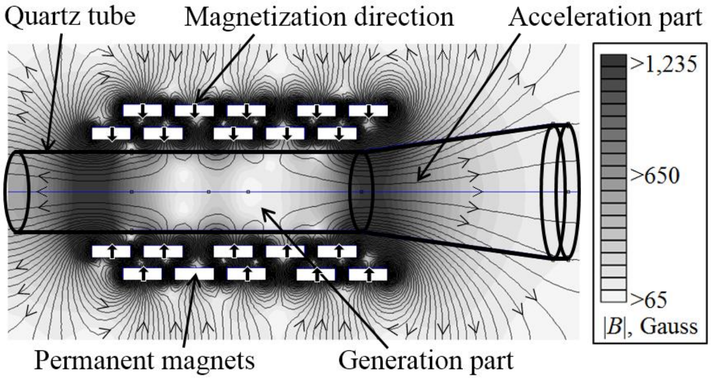

Fig. 2. Magnetic field by permanent magnets.

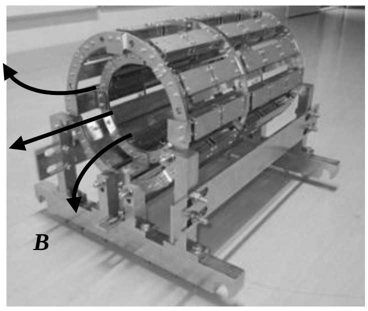

Fig. 3. Photo of the magnet holder.

The maximum magnetic fields generated by the permanent magnets are as follows: the axial magnetic field B_z is 909 G, and B_r is 149 G. Compared with the case using only electromagnets, B_r is increased by ~ 3 times using permanent magnets only. With the permanent magnets, we have achieved by a Mach probe measurement that the electron density is 3.3×10^{12} cm^{-3} in the generation region, and ion velocity is 1.4 km/s in the acceleration region. Compared with the case using only electromagnets, an increase of ion velocity in the acceleration region by ~ 0.5 km/s was confirmed by the use of permanent magnets mainly due to the effect of $-\mu\nabla B$ force, where μ is a magnetic moment.

3.2 Rotating Magnetic Field acceleration

RMF is generated by two opposing sets of currents, which have a phase difference of 90 degrees (Fig. 4). If $\omega_{ci} < \omega < \omega_{ce}$, only electron rotates, then j_θ can be generated. Note that this idea of Lorentz force ($j_\theta \times B_r$) comes from the Field Reversed Configuration (FRC) concept (j_θ generation) in a fusion field[7]. Here, ω_{ci} (ω_{ce}) is an ion (electron) cyclotron angular frequency and ω is an angular frequency of RMF.

A penetration ratio of RMF into a plasma, which is essential to produce j_θ, depends on two dimensionless parameters: normalized plasma radius λ and Hall parameter γ. [8] In order to check this, an experiment was done under a partial penetration condition : rf power = 2.8 kW, RMF = 2.5 G, RMF frequency = 1 MHz, plasma diameter = 5 cm, plasma density ~ 2×10^{12} cm^{-3}, estimated collisional skin depth ~ 1 cm[9], λ ~ 2.5, and γ ~ 0.9. A radial distribution of RMF signal in plasma was measured by a magnetic probe, as shown in Fig. 5. RMF penetrated into plasma fully, even the partial penetration condition is expected from a simulation. Here, the magnetic field strength into plasma was expected to be less than the one in vacuum under a partial penetration condition. This result of the full field penetration shows promising for our propulsion scheme and operating conditions can be extended.

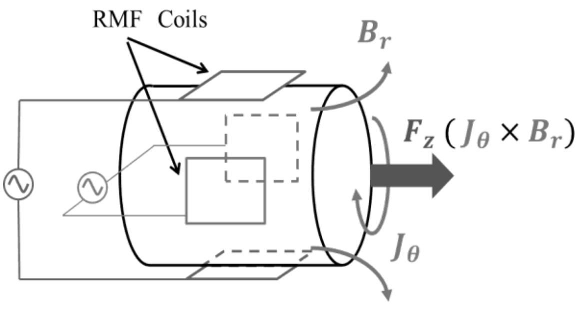

Fig. 4. Principle of RMF acceleration.

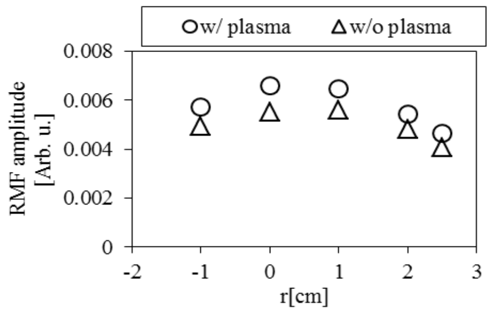

Fig. 5. RMF penetration to plasma.

3.3 m = 0 Coil Acceleration

This $m = 0$ coil acceleration proposed is a half cyclic one by the use of a low frequency current, whose concept is briefly shown in Refs. 6 and 10. Figure 6 shows a conceptual diagram of this scheme. It is an electromagnetic acceleration by the product of B_r and induced current j_θ in plasmas with $m = 0$ coil. Conditions required for the acceleration are follows: 1) accelerated plasma needs an exhaust from an $m = 0$ antenna area before undergoes a deceleration phase, 2) an inductance of the plasma is dominant than a resistance, 3) electric and magnetic fields generated by $m = 0$ coil need to be penetrated into a plasma.

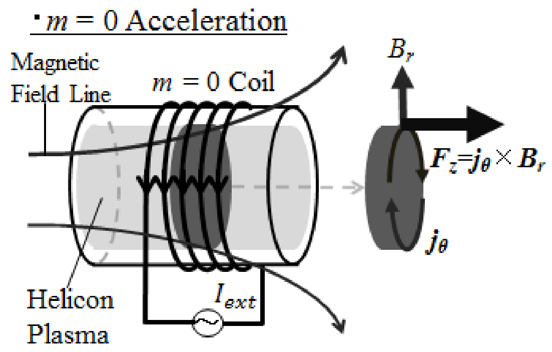

Fig. 6. Principle of $m = 0$ acceleration.

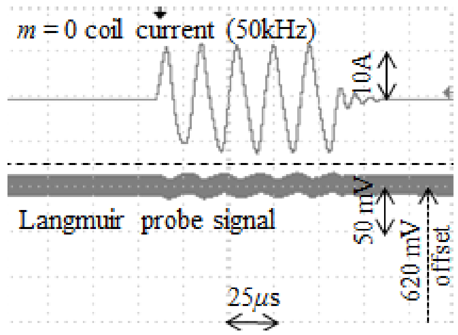

Fig. 7. Langmuir probe signal by using $m = 0$ coil during a discharge.

Critical operating parameters to achieve an efficient acceleration condition is an external magnetic field strength**,** a driving frequency and magneto motive force of an $m = 0$ coil. Initial simulation results [11] showed an operation window in an ion cyclotron frequency range. Preliminary measurements show a change of Langmuir probe signal (10 cm downstream from a coil) with $m = 0$ coil driving frequency, as shown in Fig. 7: a density change in a plasma (rf power = continuous 100 W, electron density ~ 5×10^{11} cm^{-3}) was observed, by applying $m = 0$ coil current (~ 24 A p-p) with 50 kHz modulation.

3. Diagnostics

3.1 Spectroscopy

In order to estimate an ion flow velocity and its temperature, we measured an ion Doppler shift and a broadening of emission spectrum by using a high-resolution spectrometer, Ritu Oyo Kougaku, Czerny-Turner type MC-150 (wavelength range: 190~600 nm, focal length of collimating lens: 1,500 mm, grating: 2,400 lines/mm, resolution: 0.006 nm).

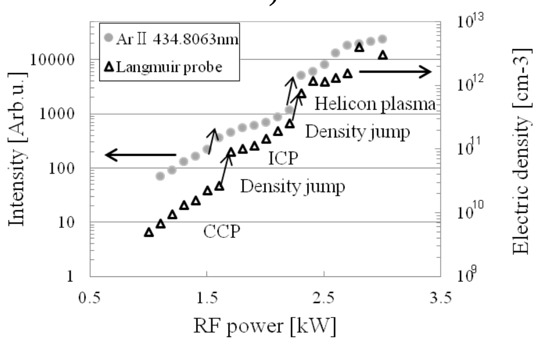

Fig. 8. Dependences of ArII intensity and electron density on RF power.

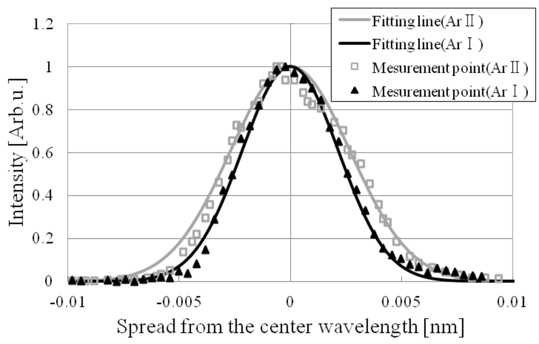

Fig. 9. Mesurements of ArI and ArII lines and their gauss fitting results.

An accuracy of an ion flow velocity of 1 km/s or less was obtained. Figure 8 shows dependences of a singly-charged ion emission ArII intensity and electron density on RF power measured at 60 cm downstream from a RF antenna. Here, density jumps, coming from discharge mode transitions, corresponded to intensity jumps of the ArII line. Figure 9 shows measurements of a neutral emission ArI (434.51670 nm) and ArII (434.8063 nm) lines and their gauss fitting results. We measured ArI line from Ar lamp for calibration and ArII one from helicon plasma (RF power = 2.8 kW, plasma density ~ 3×10^{12} cm^{-3}). From this, we could estimate an ion temperature of ~ 0.5 eV. Now we are developing a spectroscopic method of determining an electron density and its temperature from emission intensity ratio of ArI, based on a collisional radiative model (CR model). [12]

3.2 High-speed camera

A high-speed camera can take 2D emission profiles of plasma cross section, and emission lines can be selected by using interference filters. However, this profile taken by the high-speed camera is a projection (line integration), so we have applied Algebraic Reconstruction Technique (ART[13]) to figure out a spatial distribution of the emission to deduce an electron density n_e, comparing data by a Langmuir probe.

Figure 8 shows a configuration of the experimental devices. The high-speed camera (Photron FASTCAM SA-5) takes two orthogonal views of ArII by the use of an interference filter (center wavelength 488 nm, FWHM 1 nm), and the Langmuir probe can measure n_e in this area.

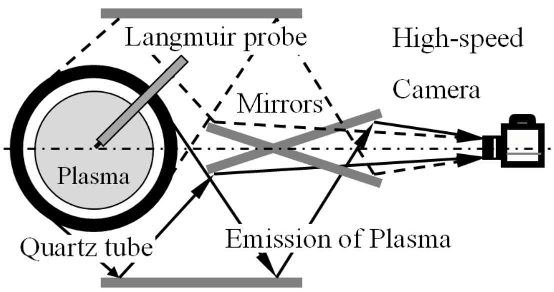

Fig. 10. Optical system of high-speed camera

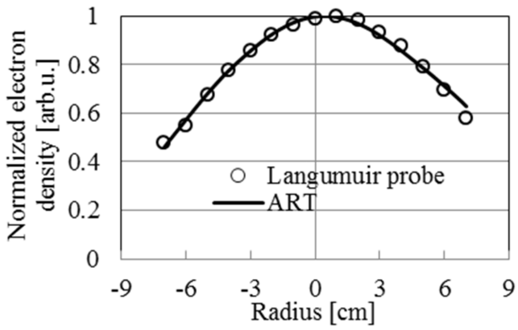

Fig. 11. Radial profiles measured by a Langmuir probe and a high speed camera (reconstructed by ART method).

Assuming that an electron impact excitation is dominant and an electron temperature is uniform, the ArII intensity is proportional to n_e. Figure 9 shows n_e profiles taken by the Langmuir probe and by ART, which shows a good agreement between them.

3.3 Laser Induced Fluorescence

Since Laser Induced Fluorescence (LIF) [14] is a powerful tool for plasma diagnostics, because of a non-invasive method with a high spatial resolution, it can deduce to velocity distributions of any particles (ions, atoms and molecules). For an argon ion, we used a classical LIF scheme, in which Ar II $3d^4F_{7/2}$ metastable state is optically pumped by 668.16 nm (in vacuum) laser light to $4p^4D_{5/2}$ state, which decays to $4s^4P_{3/2}$ state by an emission at 442.60 nm. The laser light was electrically chopped at 50 kHz by Electro-Optic Modulators (EOM). The fluorescent emission was collected by a fiber optical cable, and then it passes through a 4 nm bandwidth interference filter to reach a high-gain photomultiplier tube (PMT). In order to separate LIF signal from background radiation, fluorescence radiation and electric noise, we employed a Fast Fourier Transform (FFT) method. In Fig. 11, we show an example of a measured Ion Velocity Distribution Function (IVDF) (parallel component). The ion temperature and velocity derived are ~ 0.11 eV and ~ 340 m/s, respectively. We are planning to measure 2D profiles of an argon ion and a neutral velocity distribution function in the plasma acceleration phase using LMD with LIF.

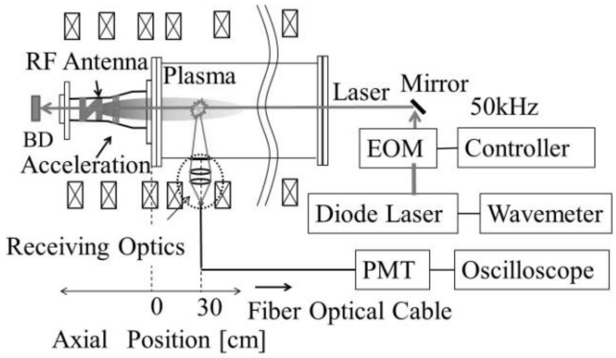

Fig. 12. LIF system on LMD.

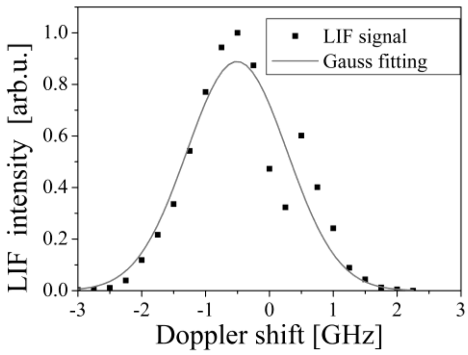

Fig. 13. Obtained IVDF.

4. Conclusion

An electric propulsion system with a long lifetime is needed for a deep space exploration. Here, in order to solve this, we have reviewed our schemes of an electrodeless electric propulsion such as RMF and m = 0 coil accelerations, using a high-density helicon plasma. Initial results of demonstrating these schemes such as a penetration of RMF and a density change by m = 0 coil current seem to be promising. By using permanent magnets, we could increase B_r component along with a higher axial plasma flow even without an acceleration scheme.

Development of non-invasive spectroscopic measurements, *e.g.*, a high-resolution spectrometer to estimate the ion temperature and a high-speed camera deriving radial distribution of electron density along with a diode laser to measure plasma flow by LIF method are described.

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Reference

[1] S. Shinohara *et al*.: Proc. 32nd Int. Electric Propulsion Conf., 2011, IEPC-2011-056.
[2] R. W. Boswell: Phys. Lett. **33A** (1970) 457.
[3] S. Shinohara: Jpn. J. Appl. Phys. **36** (1997) 4695.
[4] R. W. Boswell and F. F. Chen: IEEE Trans. Plasma Sci. **25** (1997) 1229.
[5] S. Shinohara, S. Takechi and Y. Kawai: Jpn. J. Appl. Phys. **35** (1996) 4503.
[6] S. Shinohara, *et al*.: Trans. Fus. Sci. Technol. **63** (2013) 164.
[7] I. R. Jones: Phys. Plasmas **6** (1990) 1950.
[8] R. D. Milroy: Phys. Plasmas **6** (1999) 2771.
[9] S. Shinohara and Y. Kawai : Jpn. J. Appl. Phys. **35** (1996) L725.
[10] S. Shinohara *et al*.: Phys. Plasmas **16** (2009) 057104.
[11] K. P. Shamrai: Private communication (2012).
[12] J. Vlček: J. Phys. D **22** (1989) 623.
[13] R. Gordon and Gabor T. Herman: Int. Rev. Cytol. **38** (1974) 111.
[14] R. F. Boivin and E. E. Scime: Rev. Sci. Instrum. **74**（2003) 4352.