HIGH-DENSITY HELICON PLASMA SOURCES: BASICS AND APPLICATION TO ELECTRODELESS ELECTRIC PROPULSION

S. Shinohara,[1] T. Tanikawa,[2] T. Hada,[3] I. Funaki,[4] H. Nishida,[1] T. Matsuoka,[4] F. Otsuka,[3] K. P. Shamrai,[5] T. S. Rudenko,[5] T. Nakamura,[1] A. Mishio,[1] H. Ishii,[1] N. Teshigahara,[1] H. Fujitsuka,[1] S. Waseda[1]

[1]Tokyo University of Agriculture and Technology, 2-24-16, Naka-cho, Tokyo 184-8588, Japan
[2]Tokai University, 4-1-1, Kita-kaname, Hiratsuka, Kanagawa 259-1292, Japan
[3]Kyushu University, 6-1, Kasuga Koen, Kasuga, Fukuoka 816-8580, Japan
[4]Institute of Space and Astronautical Science, 3-1-1, Yoshinodai, Sagamihara, Kanagawa 252-5210, Japan
[5]Institute of Nuclear Research, 47 Prospect Nauki, Kiev 03680, Ukraine
Email Address: sshinoha@cc.tuat.ac.jp (S. Shinohara)

The development of unique, high-density helicon plasma sources is described. Characterization of the largest and the smallest source sizes is made along with a discussion of particle production efficiency using Ar gas. Next, we describe an application of helicon sources to plasma propulsion using a new advanced concept without any eroding electrodes, as a review of our Helicon Electrodeless Advanced Thruster (HEAT) project.

I. Introduction

Developing high-density plasma sources is important, since they can be utilized in many fields such as the application of plasmas, fusion and basic fields including space plasmas. Among many sources, a helicon source[1,2] is one of the most important ones, since it can supply high-density (~ 10^{13} cm^{-3}) plasma with a high ionization degree (> several tens of %) with flexible external parameters.

In the field of plasma propulsion, whose system can provide higher specific impulse I_{sp} than chemical propulsion system, a critical problem is finite lifetime due to the erosion of various electrodes that are in direct contact with plasmas. In order to solve this problem, several novel methods are proposed, mostly using helicon plasma sources: e.g., Variable Specific Impulse Magnetoplasma Rocket (VASIMR)[3] and Double Layer (DL) Thruster,[4] including ours, e.g., Refs. 5-10.

Here, we will show our developed unique, featured helicon sources, e.g., the largest or the smallest diameters and the smallest aspect ratio A (ratio of the axial length to the diameter) in the world with a discussion of scaling laws of particle production efficiency. Next, their application to plasma propulsion with a concept of electrodeless thruster to overcome the problem of the lifetime will be presented, i.e., the HEAT project to develop advanced-concept electric thrusters.

II. High-Density Helicon Plasma Sources

First, we will describe the largest diameter plasma in the world, briefly, using the Large Helicon Plasma Device (LHPD) developed with an inner diameter (i.d.) of 74 cm and an axial length L_p up to 486 cm.[7,11-13] With the increase in the input RF power P_{inp}, the electron density n_e (Ar plasma) inceases regardless of L_p: the discharge mode generally changes from Capacitively Coupled Plasma (CCP) to Helicon Plasma (HP) (10^{12}-10^{13} cm^{-3} with less than several kW RF power) through Inductively Coupled Plasma (ICP). Even though L_p is reduced to 5.5 cm, where A is 0.075 (the smallest value in the world, which is important, e.g., in the plasma processing and propulsion fields), we can still maintain $n_e \sim 10^{12}$ cm^{-3}.

Next, we will mention the small plasma: we have successfully built the machine named Small Helicon Device (SHD), and produced a small diameter Ar plasma down to 1 cm. Near the double-loop antenna region, $n_e \sim 8 \times 10^{12}$ cm^{-3} can be generated with 2 cm i.d., which is the smallest size in the world in a helicon discharge regime.

Now, we will discuss a particle production efficiency. In the case of a long cylinder plasma source with a small diameter and a weak magnetic field, N_e/P_{inp} is expected to be proportional to a^2 from the classical diffusion (mainly the radial diffusion in this case),[13] where N_e (a) is a total number of electrons in a whole plasma (plasma radius). From Fig. 1, this scaling, showning close to a theoretical upper limit of a plasma production, holds good in a wide range of the plasma radius. Here, closed circles are taken by our several devices, and a dotted line shows an eye-guide of this scaling. The top right circle obtained in Fig. 1 is LHPD (plasma volume is up to 2.1 m^3) case. Two circles at the bottom left show the data of small source[5] (i.d. is 2.5 cm, and L_p can be lowered to 4.7 cm, leading to the smallest volume in the world of 23 cm^3) and a source of SHD with i.d. of 2 cm in a non-uniform magentic field.

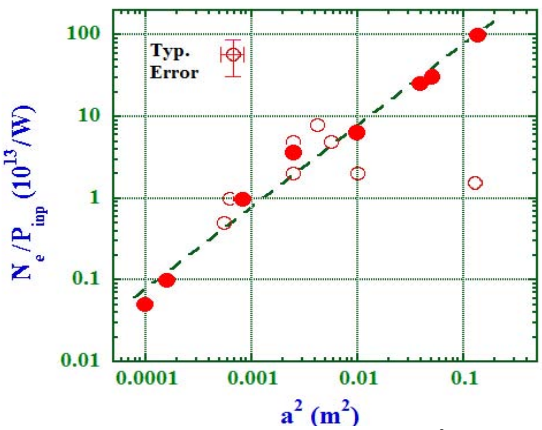

Fig. 1. Relationship between N_e/P_{inp} vs. a^2 for different helicon sources.

In the case of a short cylinder plasma source with the large diameter and the strong magnetic field, contrary to the case shown in Fig. 1, N_e/P_{inp} is expected to be proportional to L_p from the classical diffusion (mainly the axial diffusion in this case).[13] Experimental data of the relation between N_e/P_{inp} and L_p in LHPD and Large Diameter Device (LDD),[11] i.d. of 40 cm, also show a good agreement with the expected scaling, demonstrating an excellent production efficiency (not shown).

III. Plasma Acceleration Schemes

In this section, we will present three proposed acceleration schemes, i.e., Rotating Magnetic Field (RMF),[7,10] Rotating Electric Field (REF)[5-10] and Ion Cyclotron Resonance/Ponderomotive Acceleration (ICR/PA)[10] schemes. Here, in these concepts, the acceleration electrodes are indirect contact with the plasma, leading to a longer life time operation due to a reduction of the strong plasma-wall interaction.

III.A. RMF Scheme

The initial RMF experiments have been carried out using the Large Mirror Device (LMD),[14] as shown in Fig. 2. This RMF acceleration scheme is based on the Field Reversed Configuration (FRC) concept in a fusion field.[15] The RMF coils (10 turns) are mounted on the quartz glass tube (5 cm i.d. and 50 cm axial length), which is inserted into the vacuum chamber. To generate a helicon plasma, a single loop antenna of 4 cm in width is also installed.

Here, the penetration of the RMF is important, and its penetration conditions are determined by the following two parameters:[16] γ (the Hall parameter using RMF field) and λ (plasma radius normalized by a skin depth). In order to have a full penetration, a higher value of γ/λ is required, showing that the larger B_{RMF} and smaller n_e, f_{RMF} (RMF frequency) a, P_{Ar} (Ar pressure) and η (plasma resistivity) are necessary. On the other hand, a plasma thrust by this RMF scheme is expected to be proportional to n_e, f_{RMF}, B_r (radial magnetic field) and a^3. This is contradictory to the above penetration condition, and experimentally we must make a compromise between two conditions of the field penetration and the thrust.

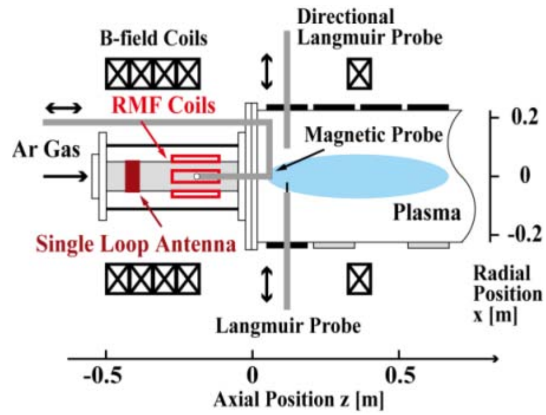

Fig. 2. Experimental setup for RMF scheme in LMD.

Initial measurements show a demonstration of the RMF field penetration: 1) Radial profile of the RMF field measured by a magnetic probe w/o plasma is almost the same as that w/ plasma (see Fig. 3) in the case of satisfying the theoretical penetration condition.[16] Even though this condition is not satisfied, the field penetration is observed in some cases. 2) With the increase in the RMF coil current, the observed RMF field increases. We are now checking the change of plasma flow and other plasma parameters by this scheme.

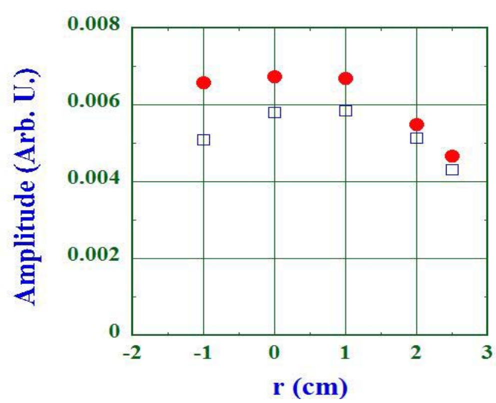

Fig. 3. Radial profiles of the RMF field w/ (closed circles) and w/o (open boxes) plasmas.

For further studies, we need to consider the following processes, using fluid or kinetic plasma treatments: 1) the RMF penetration and the induced azimuthal current channel, 2) a spin-up time scale of the plasma rotation, 3) an electron axial flow, and an electron transit time normalized by $1/f_{RMF}$, 4) a plasma acceleration via the electron current in the divergent field and 5) a plasma detachment.

III.B. REF Scheme

The principle of this REF acceleration[5-10] can be explained by using an electron trajectory analysis. The gyration and drift motions in the presence of the REF and a radial density gradient produce the azimuthal electric current, being the source of the thrust in the divergent field.

The plume measurement has been conducted using a Mach probe. Figure 4 shows an example of the axial profiles of the plasma velocity v ($z = 0$ corresponds to the center of the acceleration antenna). Here, around a glass tube, 2.5 cm i.d. and an axial length of ~ 40 cm, a double saddle type antenna is wound for the helicon plasma production, and the two pairs of flat plate electrodes are used to apply the REF. The excitation frequencies (RF powers) for the plasma production and acceleration are fixed at 27.12 MHz (300 W) and 13.56 MHz (450 W), respectively, with the Ar mass flow rate of 1 mg/s.

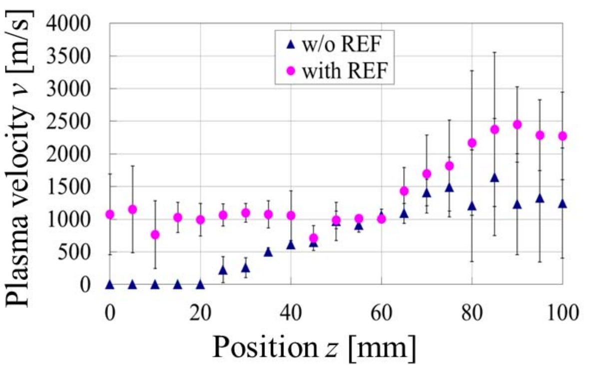

Fig. 4. Axial profiles of plasma velocity w/ and w/o REFs.

From this figure, v is increased in and downstream of the acceleration area. However, the velocity increment is not only due to the electromagnetic effect, but also to the RF heating effect. In future works, a parameter survey will be conducted to clear the electromagnetic effect.

TABLE I. Thermal Thrust Performance (50 mm i.d.)

	Mass Flow Rate (mg/s)	Thrust (mN)	I_{sp} (s)	Efficiency (%)
Max. Thrust Efficiency	0.89	2.5 ± 0.7	290 ± 80	0.19 ± 0.1
Max. I_{sp}	0.24	0.90 ± 0.3	390 ± 130	0.083 ± 0.06

We have developed two thrust stands. As a first step, we have done a parameter survey of the thermal thrust, i.e., w/o REF, by changing an Ar mass flow rate, the axial magnetic field and a thruster diameter (26 mm and 50 mm i.d.) in order to find better operation points. Experimental conditions for maximum efficiency and maximum I_{sp} are summarized in Tables I. Note that I_{sp} = 390 s is obtained, and we conclude that a larger diameter (50 mm i.d.) thruster is better than a 26 mm i.d. thruster as a thermal thruster, since a better efficiency is achieved at the fixed input RF power (1.8-2.3 kW). However, more optimized conditions must be found experimentally.

III.C. ICR/PA Scheme

Here, we will discuss the ICR/PA method. The ions can be efficiently heated perpendicularly by ICR. In the divergent field, as the ions travel into a weaker magnetic field region, their perpendicular energy can be converted into the parallel energy, producing the thrust. In addition, by applying the RF waves in such a way that the resonance point coincides with the peak of the wave energy density, ions can gain parallel acceleration due to the electromagnetic ponderomotive force.[17]

The ICR and the PA are inseparable, yet the latter is preferred since it is less likely to be influenced by the ion-wall interaction (due to the smaller gyro radius). The thrust by this scheme has been formulated with ions crossing the region of the ponderomotive potential, which is written as $(q^2/4m)\,[E_{rf}^{\,2}/(\omega^2 - \Omega_{ci}^{\,2})]$. Here, q, m, E_{rf}, ω, and Ω_{ci} are ion charge, mass of ion, RF electric field, applied angular frequency of this electric field and ion cyclotron angular frequency.

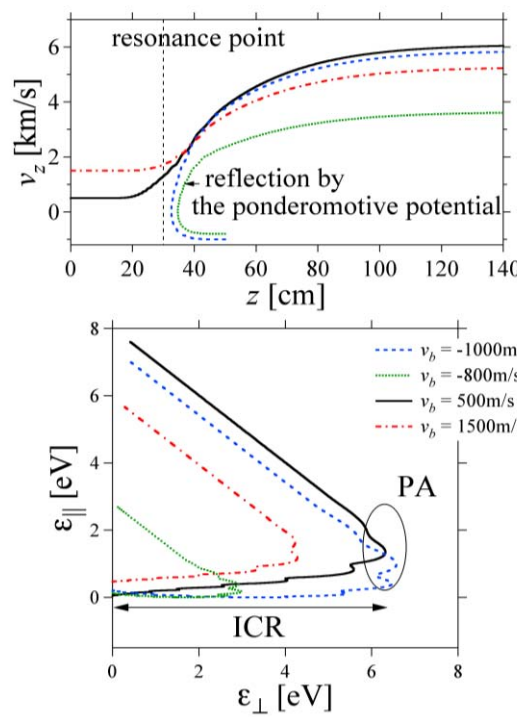

Fig. 5. (top) Ion trajectories in (z, v_z) plane and (bottom) increments of ion energy in ($\varepsilon_\perp$, $\varepsilon_{//}$) plane.

Figure 5 shows a typical example of (top) the ion trajectory and (bottom) the energy increment in ($\varepsilon_\perp$, $\varepsilon_{//}$) plane by changing the initial parallel velocity v_b. Here, $\varepsilon_{//}$ and $\varepsilon_\perp$ shows the parallel and perpendicular ion energies to the axial magnetic field, respectively. The increment of the ion energy $\Delta\varepsilon$ is investigated changing external parameters, and it is found that the PA can add the incremental energy done by ICR alone.

Now, we have initiated the proof of principle experiment in this scheme using the Tokai Helicon Device (THD), considering a collision and a plasma-wall interaction.

IV. CONCLUSIONS

We have shown the development of unique, high-density helicon plasma sources along with the characterization of them: e.g., the largest or the smallest diameters, the lowest A and the longest L_p helicon sources. Discussions on the excellent particle production efficiency based on the classical diffusion model in two extreme cases, i.e., main particle diffusion is along the axial or the radial directions, have been also made.

Next, as a review of our HEAT project, an application of helicon sources to plasma propulsion using a new advanced concept without any eroding electrodes are introduced in order to have a longer life time operation: three main acceleration schemes of RMF, REF and ICR/PA are described experimentally and theoretically. Now, we are also considering an azimuthal mode number of $m = 0$ acceleration scheme[7] as an additional candidate.

In order to verify the proposed schemes, we need further studies on the above methods by changing various parameters supported by theoretical results, along with new measurements: e.g., electrostatic probes (sophisticated Langmuir and Mach probes as well as an ion energy analyzer) and magnetic probes, optical instruments (a diode laser for laser induced fluorescence method, a fast-speed camera and a high-resolution monochromator) in addition to a supplemental thrust stand.

ACKNOWLEDGMENTS

We appreciate a great contribution of late Prof. K. Toki to found this propulsion study, and would like to thank Dr. Y. Yamagata, Dr. T. Motomura and Ms. S. Takei in performing the experiments. This work is partly supported by the Grants-in Aid for Scientific Research under Contract Nos. (S) 21226019, (A) 17206084, (B) 20340163 and (C) 19540524 from the Japan Society for the Promotion of Science.

REFERENCES

1. R.W. BOSWELL, *Phys. Lett*., **33A**, 457 (1970).
2. S. SHINOHARA, *Jpn. J. Appl. Phys*., **36**, 4695 (1997); J. *Plasma Fusion Res*., **78**, 5 (2002); *BUTSURI*, **64**, 519 (2009).
3. F. R. CHANG–DÍAZ, *Sci. Am.,* **283** (2000) 90.
4. C. CHARLES, R. W. BOSWELL, A. BOUCHOULE, C. LAURE and P. RANSON, *J. Vac. Sci. Technol.*, A **19**, 661 (1991).
5. K. TOKI, S. SHINOHARA, T. TANIKAWA, I. FUNAKI and K. P. SHAMRAI, "Preliminary Investigation of Helicon Plasma Source for Electric Propulsion Applications," *28th. Int. Electric Propul. Conf.*, Toulouse, Mar. 17-21, 2003, IEPC 03-0168.
6. K. TOKI, S. SHINOHARA, T. TANIKAWA and K. SHAMRAI, *Thin Solid Films*, **506-507**, 597 (2006).
7. S. SHINOHARA et al., *Phys. Plasmas*, **16**, 057104 (2009).
8. K. TOKI et al, *J. Plasma Fus. Res. SERIES*, **8**, 25 (2009).
9. T. MATSUOKA et al., *Plasma Fusion Res.*, **6**, 2406103 (2011).
10. S. SHINOHARA et al., **"**Research and Development of Electrodeless Plasma Thrusters Using High-Density Helicon Sources: The Heat Project," *32nd Int. Electric Propul. Conf.*, Wiesbaden, Sept. 11-15, 2011, IEPC-2011-056.
11. S. SHINOHARA *et al*., *Rev. Sci. Instrum.*, **75**, 1941 (2004); *Plasma Sources Sci. Technol.*, **19**, 034108 (2010).
12. T. MOTOMURA, S. SHINOHARA, T. TANIKAWA and K. P. SHAMRAI, *Phys. Plasma*s, **19**, 043504 (2012).
13. T. TANIKAWA and S. SHINOHARA., "Large-Volume, Helicon-Plasma Source for Simulation Experiments of Space Plasmas," *Int. Cong. on Plasma Phys.*, Nice, Oct. 25-29, 2004, URL: http://hal.archives-ouvertes.fr/hal-00002013/en/.
14. S. SHINOHARA, S. TAKECHI and Y. KAWAI, *Jpn. J. Appl*. *Phys*., **35**, 4503 (1996).
15. I. R. JONES, *Phys. Plasmas*, **6**, 1950 (1999).
16. R. D. MILROY, *Phys. Plasmas*, **6**, 2771 (1999).
17. I. Y. DODIN, N. J. FISCH and J. M. RAX, *Phys. Plasmas*, **11**, 5046 (2004).