# Production of Large Diameter, High-Density Helicon Plasma with Short Axial Length Using a Flat Spiral Antenna

Motomura, Taisei
Department of Advanced Energy Engineering Science, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

Tanaka, Kenji
Department of Advanced Energy Engineering Science, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

Shinohara, Shunjiro
Department of Advanced Energy Engineering Science, Kyushu University

Tanikawa, Takao
Research Insutitute of Science and Technology, Tokai University

https://doi.org/10.15017/14602

出版情報：九州大学大学院総合理工学報告. 30 (1), pp.29-31, 2008-06. 九州大学大学院総合理工学府
バージョン：
権利関係：

九州大学大学院総合理工学報告
第30巻　第1号　29-31頁　平成20年6月

Engineering Sciences Reports, Kyushu University
Vol. 30, No. 1, pp. 29-31, JUN. 2008

# Production of Large Diameter, High-Density Helicon Plasma with Short Axial Length Using a Flat Spiral Antenna

Taisei MOTOMURA [*1,†], Kenji TANAKA [*1], Shunjiro SHINOHARA [*2]
and Takao TANIKAWA [*3]
[†]E-mail of corresponding author: *tmoto@aees.kyushu-u.ac.jp*

(Received May 8, 2008)

A large diameter (73.8 cm), high-density helicon plasma with a short axial length (81 cm) has been successfully produced using a flat spiral antenna. The electron plasma density can reach $\sim 6\times10^{12}\mathrm{cm}^{-3}$ with the input rf power of $< 4$ kW. The stronger the degree of magnetic field convergence is from the antenna to the bulk plasma region, the lower the minimum input rf power required is to obtain a helicon plasma. This signifies the important role of the magnetic field structure near the antenna and is similar to the previous result obtained with a helicon plasma of a much longer axial length of 486 cm.

**Key words :** *Helicon Plasma, Flat Spiral Antenna, Density Jump, Large Diameter, Short Axial Length*

## 1. Introduction

High-density helicon plasmas [1,2] are potentially very useful in various plasma applications, such as in plasma processing, fusion, basic science fields including the study of space plasmas and magnetoplasma rockets. A helicon wave for plasma production has advantages of having an easy operation and a wide range of operational parameters. Developing a large volume plasma source with a large diameter is also important, and a high-density helicon plasma with the diameter up to 73.8 cm and 486 cm in axial length (very large plasma volume of $2.1\mathrm{m}^3$) has been obtained using a device at ISAS/JAXA (Institute of Space and Astronautical Science/Japan Aerospace eXploration Agency) [3-5].

However, having a shorter axial length with a large diameter (or a lower aspect ratio $A$, where $A$ is the ratio of axial length to diameter) is often desirable in some of the above applications. Therefore, using the same device at ISAS/JASA, we attempted to effectively shorten the plasma column length from 486 cm to 81 cm by installing a termination plate inside the device [Fig.1 (a)], reducing $A$ from 6.6 to 1.1. Here, we report the successful production of a high-density helicon plasma with $A = 1.1$, which is much smaller than that of plasmas produced in conventional helicon sources. Note that although the axial length of the shortest helicon plasma ever produced is a mere 4.7 cm [6], the plasma diameter is 2.5 cm, resulting in $A = 1.9$ that is larger than ours.

## 2. Experiment

In our device at ISAS/JAXA [3-5] [Fig. 1 (a)], the magnetic field is produced by 14 main coils and a newly installed separate coil. The magnetic field line near the antenna can be controlled more flexibly using this separate coil than with the old one used in the previous experiments [3-5], as shown in Fig. 1 (b) (the 14 main coils generate the uniform field of 140 G in the central region). A 4-turn flat spiral antenna (43 cm in diameter) is connected to the rf power supply (maximum power of 5 kW with 7 MHz excitation frequency) through an impedance matching circuitry. The termination plate placed at $z = 81$ cm is a 0.5 mm thick stainless steel punching metal with a transparency of ~35% and electrically floating. Two Langmuir probes were used to monitor the plasma density at $z = 45$ cm (inside the plasma production region) and at $z = 336$ cm (to monitor the plasma leaked through the termination plate). A magnetic probe was used to measure the profiles of the $z$-component of the excited rf magnetic field.

---

[*1] Department of Advanced Energy Engineering Science, Graduate student
[*2] Department of Energy Engineering Science
[*3] Research Institute of Science and Technology, Tokai University

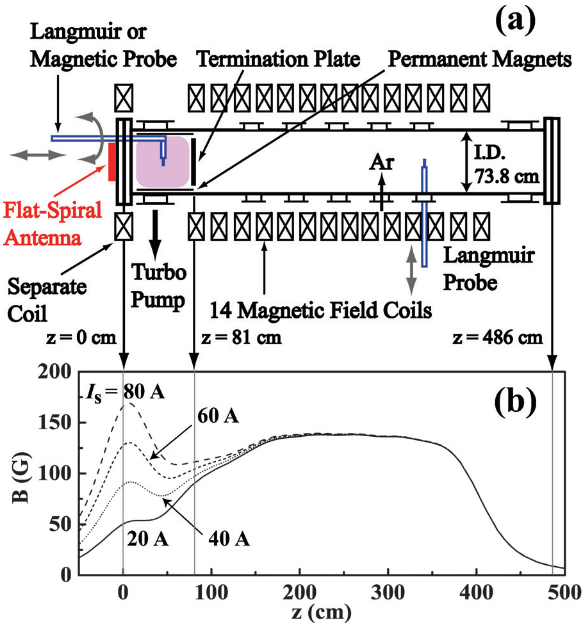

**Fig. 1** (a) Schematic drawing of the plasma device. (b) Axial magnetic field configurations [$r$ (radial position) = 0] for various values of the separate coil current $I_\mathrm{s}$.

The working gas was argon with a fill pressure of 0.75 mTorr.

Figure 2 shows the electron density $n_\mathrm{e}$ versus the input rf power $P_\mathrm{inp}$ for four different magnetic field configurations realized by changing the separate coil current $I_\mathrm{s}$. The black vertical bars show the threshold power $P_\mathrm{th}$, which causes the density jump from ICP (inductively coupled plasma) to helicon plasma discharges. Typical values of $n_\mathrm{e}$ at $z = 45$ cm were $10^{10} - 10^{11}\mathrm{cm}^{-3}$ and $> 10^{12}\mathrm{cm}^{-3}$ below and above $P_\mathrm{th}$, respectively; whereas, $n_\mathrm{e}$ at $z = 336$ cm was $10^9 - 10^{10}\mathrm{cm}^{-3}$ with no clear density jumps. With the increase in the magnetic field strength near the antenna, i.e., with the increase in $I_\mathrm{s}$, $P_\mathrm{th}$ was increased, and further increase in $I_\mathrm{s}$ (= 80 A) showed no density jump below $P_\mathrm{inp} = 3$ kW. These results are consistent with the previous ones with a long axial length of 486 cm [3–5], the capability of the separate coil was limited then. They are also consistent with the general tendency that the higher magnetic field strength in the plasma production region (uniform field case) needs more rf power to have helicon jumps [7]. Note that the plasma production efficiency, $N_\mathrm{e}/P_\mathrm{inp}$ ($N_\mathrm{e}$: total number of electrons) of $\sim 10^{14}$ (1/W), is one order of magnitude smaller than that of the 486 cm axial length case, as expected. This is due to the fact that shortening the axial length results in the

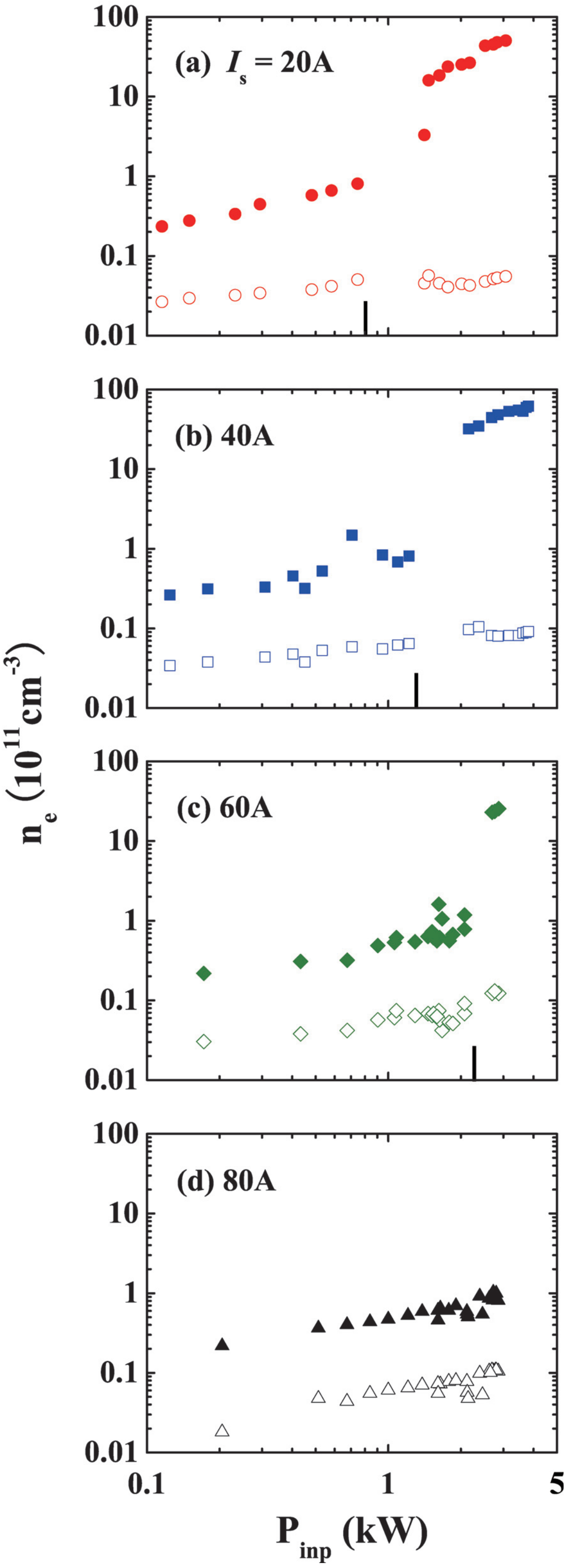

**Fig. 2** Electron density $n_\mathrm{e}$ as a function of the rf input power $P_\mathrm{inp}$ for different values of the separate coil current $I_\mathrm{s}$: (a) 20 A, (b) 40 A, (c) 60 A and (d) 80 A. ● and ○ show the data taken at $z = 45$ cm and $z = 336$ cm, respectively.

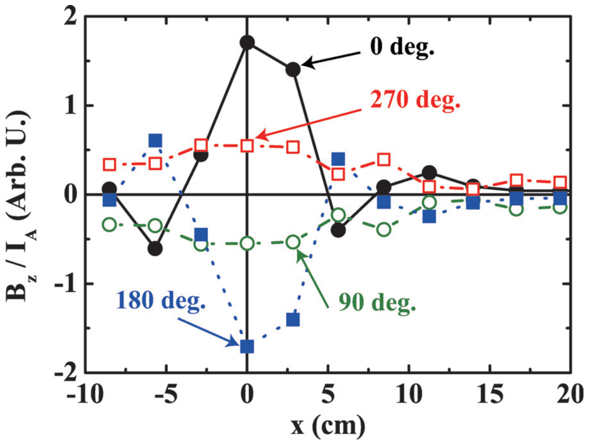

**Fig. 3** Radial profiles of $B_z/I_A$ with $I_s$ = 60 A and $P_{inp}$ = 3 kW at $z$ = 51.5 cm.

enhancement of the axial ion loss relative to the radial one [8].

Figure 3 shows the radial profiles of $B_z/I_A$, the ratio of the excited rf magnetic field to the rf antenna current, at four phases during one rf period for the $I_s$ = 60A case. Contrary to expectations for a uniform plasma, the observed profile was not a simple fundamental mode of the Bessel function $J_0(k_{\perp 1}r)$ with $m$ (azimuthal mode number) = 0. This can be interpreted as a combination of at least two Bessel functions: $J_0(k_{\perp n}r)$ with $n = 1$ and 2 [9,10]. Here, $k_{\perp n}a$ is the $n$th zero of the $J_1$ Bessel function ($a$: effective plasma radius). For the other cases of the magnetic field configuration, the wave profiles were even more complex, so that including $J_0(k_{\perp n}r)$ with $n > 2$ is necessary in order to fully understand the data. This point will be discussed in a separate paper.

## 3. Conclusions

We have successfully produced a large diameter (73.8 cm), short axial length (81 cm) high-density helicon plasma (up to $\sim 6 \times 10^{12}$cm$^{-3}$) with an rf power of $< 4$ kW. The observed wave structure is consistent with the $m = 0$ helicon mode. The magnetic field structure near the antenna critically influences the plasma production. The higher the magnetic field strength near the antenna, the higher the rf input power necessary to achieve a helicon density jump.

### Acknowledgments

Our experiments were performed at ISAS/JAXA under their research collaboration program. We thank Drs. I. Funaki, S. Sato and T. Takeda and Prof. K. Yamagiwa for their assistance in carrying out the experiments. The research was partially supported by the Grants-in-Aid for Scientific Research (A) 17206084 and (C) 19540524 from the Japan Society for the Promotion of Science.

### References

1) R. W. Boswell, Phys. Lett. **33A** (1970) 457.

2) S. Shinohara, Jpn. J. Appl. Phys. **36** (1997) 4695.

3) S. Shinohara and T. Tanikawa, Rev. Sci. Instrum. **75** (2004) 1941.

4) S. Shinohara and T. Tanikawa, Phys. Plasmas **12** (2005) 044502.

5) T. Tanikawa and S. Shinohara, Thin Solid. Films **506-507** (2006) 559.

6) K. Toki, S. Shinohara, T. Tanikawa, I. Funaki and K.P. Shamrai, the 28th Int. Conf. Electric Propulsion (Toulouse, France, Mar. 17-21, 2003) IEPC 03-1168.

7) S. Shinohara and K. Yonekura, Plasma Phys. Control. Fusion **42** (2000) 41.

8) T. Tanikawa and S. Shinohara, e-Proc. Int. Cong. on Plasma Phys. (Nice, France, Oct 25-29, 2004) hal-00002013.

9) M. Light, Issac D. Sudit, Francis F. Chen and Donald Arnush, Phys. Plasmas **2** (1995) 4094.

10) Y. Sakawa, N. Koshikawa and T. Shoji, Plasma Sources Sci. Technol. **6** (1997) 96.