Dependence of Plasma Parameters in Hydrogen Discharges on Magnetic Field Configuration and Neutral Pressure in the DT-ALPHA Device

Tomohiro SEINO, Hiroyuki TAKAHASHI, Peerapat BOONYARITTIPONG, Takeshi SAIKYO,
Kenta OGASAWARA, Atsushi OKAMOTO[1)], Sumio KITAJIMA and Kenji TOBITA

Department of Quantum Science and Energy Engineering, Tohoku University, Sendai 980-8579, Japan
[1)]*Department of Applied Energy, Nagoya University, Nagoya 464-8603, Japan*

The dependence of hydrogen plasma parameters on magnetic field configuration and neutral pressure was investigated in the radio-frequency (RF) plasma source DT-ALPHA. It was found that higher electron density was obtained when the lower hybrid resonance condition was satisfied near the RF antenna. It was also found that use of lower hydrogen neutral pressure yielded higher electron density plasma. By optimizing the resonance condition and neutral pressure, the hydrogen plasma of $T_e \sim 10\,\text{eV}$ and $n_e > 1 \times 10^{17}\,\text{m}^{-3}$ was achieved.

Divertor plates in magnetic confinement fusion devices are exposed to large plasma heat loads. Therefore, plasma heat load removal using volumetric recombination has been studied in terms of divertor protection. Molecular activated recombination (MAR) has been theoretically predicted [1], and its effectiveness has been experimentally demonstrated in linear and toroidal plasma devices [2, 3]. Typically, the hydrogen plasma of $T_e \sim 2$ - $4\,\text{eV}$ and $n_e \sim 1$ - $5 \times 10^{17}\,\text{m}^{-3}$ is necessary to enhance plasma detachment owing to MAR [4–6]. Although MAR itself has been experimentally demonstrated, its physics is not yet fully understood. We propose a divertor plasma simulating research using the radio-frequency (RF) plasma source DT-ALPHA. To produce hydrogen detached plasma using MAR in the DT-ALPHA device, the abovementioned parameters are required. Although T_e and n_e in RF plasma devices strongly depend on magnetic field configuration and neutral pressure, the dependence of hydrogen plasma in the DT-ALPHA device have not been investigated yet. Therefore, in this study, the dependence of T_e and n_e on those parameters was investigated.

Experiments were conducted in the RF plasma source DT-ALPHA [7]. Figure 1 shows the schematic diagram of the DT-ALPHA device. DT-ALPHA consists of a quartz pipe and a SUS chamber. The inner diameters of the quartz pipe and SUS chamber are 36 mm and 63 mm, respectively. As illustrated in Fig. 1, the z-axis is defined toward the downstream region. An RF antenna is wound around the quartz pipe ($z \sim 0.50$ - $0.65\,\text{m}$) and the RF of 13.56 MHz is supplied from an RF power supply to produce plasma.
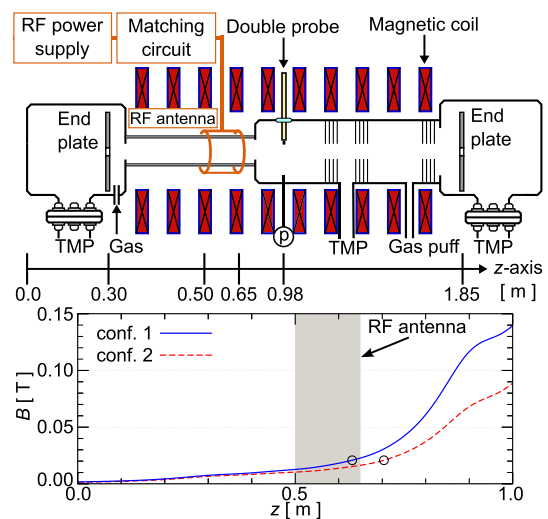

Fig. 1 Schematic diagram of the DT-ALPHA device (top) and magnetic configurations (bottom). The gray box shows the RF antenna region. Solid and dashed lines in the bottom correspond to conf. 1 and conf. 2, respectively. Circles represent the axial positions where B becomes 0.02 T.

A total of 10 magnetic coils are placed around the DT-ALPHA device. Magnetic field configuration can be flexibly controlled by changing the coil current. Hydrogen working gas was supplied into the device near the upstream end-plate. Secondary gas puffing was not performed in this experiment. T_e and n_e were measured using a double probe at $z = 0.98\,\text{m}$. The radial position of probe electrodes was fixed near the plasma center during the measurements. Hy-

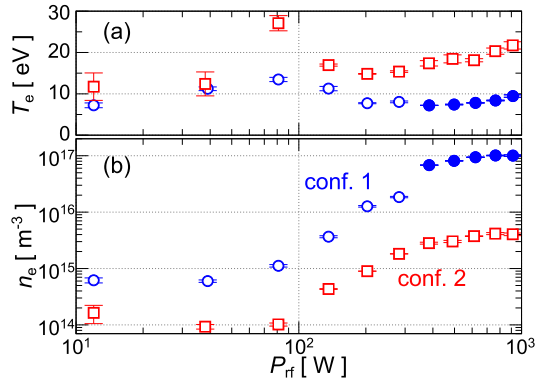*author's e-mail: tomohiro.seino.p7@dc.tohoku.ac.jp*

Fig. 2　RF power dependence of (a) electron temperature and (b) electron density. Circles and squares correspond to conf. 1 and conf. 2, respectively. The sheath length of open symbols is much longer than $d/2$, whereas that of filled circles is comparable to $d/2$.

Fig. 3　Neutral pressure dependence of (a) electron temperature and (b) electron density. Magnetic field configuration is conf. 1, and $P_{rf} \sim 620\,\mathrm{W}$.

drogen neutral pressure described in the following section was also measured at $z = 0.98$ m.

In RF devices, plasma parameters strongly depend on magnetic field configuration. In Ref. [8], it has been reported that high density hydrogen plasma can be obtained when the lower hybrid resonance (LHR) frequency matches the RF frequency. Since the frequency of RF utilized in the DT-ALPHA device is 13.56 MHz, the above-mentioned relation is satisfied only when the magnetic field strength is larger than 0.02 T. In this study, we utilized two magnetic configurations. Hereafter, these configurations are referred to as conf. 1 and conf. 2. In conf. 1, the LHR condition was satisfied at 0.02 m inside the RF antenna edge, while that in conf. 2 was satisfied at 0.05 m outside the antenna. Solid and dashed lines at the bottom of Fig. 1 represent conf. 1 and conf. 2, respectively.

Figure 2 shows the RF power (P_{rf}) dependences of T_e and n_e. Circles and squares correspond to conf. 1 and conf. 2, respectively. During the measurement, neutral pressure was maintained at approximately 0.9 Pa. For simplicity, ions except for H^+ were ignored when I-V curves were analyzed. Since plasma sheath formed around probe tips are overlapped, the double probe technique becomes invalid when it is used to measure low electron density plasma. The sheath length (l_{sh}) at $P_{rf} < 400$ W in conf. 1 was much longer than half of the inter-electrode distance $d/2$ ($d = 0.5$ mm). Here, sheath length was calculated as $l_{sh} = 10\lambda_D$. λ_D represents the Debye length. Similarly, l_{sh} in conf. 2 was considerably longer than $d/2$. Therefore, T_e and n_e of these conditions were possibly affected by sheath overlapping. However, for reference, these values are shown in Fig. 2 with open symbols. On the other hand, at $P_{rf} > 400$ W in conf. 1, l_{sh} decreased to less than 3 times of $d/2$. Although the experimental condition was slightly different from one used in this study, the comparison of single probe and double probe measurements in-
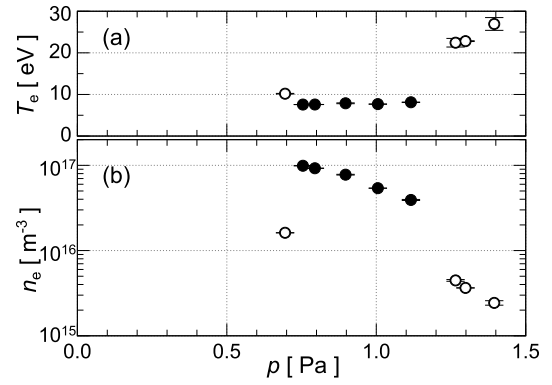
dicated that T_e obtained by two different methods showed good agreement and the difference in n_e was within three times, even though $l_{sh}/(d/2)$ was approximately 3. Therefore, T_e and n_e in this region are considered to be relatively valid and plotted with filled symbols. As shown in Fig. 2, T_e in conf. 1 slightly decreased from 14 eV to 7 eV when P_{rf} increased from 100 W to 400 W. Then, T_e showed a slight increase at $P_{rf} > 400$ W. T_e in conf. 2 was approximately two times larger than that in conf. 1. n_e in conf. 1 monotonically increased with an increase in P_{rf}. At approximately $P_{rf} = 1$ kW, n_e became slightly larger than $1 \times 10^{17}\,\mathrm{m^{-3}}$. Compared to conf. 1, an increase in n_e in conf. 2 was not so large and n_e was smaller than $10^{16}\,\mathrm{m^{-3}}$ even though P_{rf} was increased up to 1 kW. Other magnetic configurations similar to conf. 1 showed similar RF power dependences. In the DT-ALPHA device, high electron density that exceeds $10^{17}\,\mathrm{m^{-3}}$ was already achieved in helium and argon plasma. Similar to this study, in the case of helium plasma, n_e close to $10^{18}\,\mathrm{m^{-3}}$ was obtained when the LHR condition was satisfied near the RF antenna whereas n_e became much smaller when it was not satisfied. However, n_e of argon plasma can exceed $10^{18}\,\mathrm{m^{-3}}$ even though the LHR condition is not satisfied. Previously obtained n_e in hydrogen plasma was approximately $10^{16}\,\mathrm{m^{-3}}$ [9]. LHR frequency depends on n_e, and resonance density decreases as magnetic field strength increases. In Ref. [9], the LHR condition was satisfied at lower n_e because the magnetic field strength near the RF antenna edge was larger than that in this study. Although the RF heating power was smaller than that in this study, the reason for lower n_e is considered to be mainly the un-optimized LHR condition. The investigation of these different tendencies is necessary, but LHR condition seems to have important role for producing high density plasma.

Using conf. 1, neutral pressure dependence was investigated, and Fig. 3 summarizes the results. RF power was maintained at approximately 620 W. Similar to Fig. 2, filled circles are considered to be relatively valid. As

shown in Fig. 3, T_e was larger than 20 eV and n_e was smaller than 10^{16} m^{-3} at $p > 1.2$ Pa. On the other hand, T_e was almost constant and approximately 10 eV at $p < 1.2$ Pa. At 0.7 Pa $< p <$ 1.2 Pa, n_e showed an increasing tendency with a decrease in neutral pressure. n_e peaked at $p = 0.75$ Pa and its value was $n_e \sim 10^{17}$ m^{-3}. However, when neutral pressure was 0.69 Pa, n_e rapidly decreased to approximately 2×10^{16} m^{-3}. In addition, below 0.69 Pa, a stable RF discharge was not obtained. By satisfying LHR condition near the RF antenna and using lower neutral pressure, the hydrogen plasma of $T_e \sim 10$ eV and $n_e \sim 1 \times 10^{17}$ m^{-3} was obtained. Although this T_e is several eV higher and n_e is several times smaller than those in MAR plasmas produced in other devices, lower temperature and higher density plasma is expected by secondary gas puffing. Furthermore, higher electron temperature would be advantageous for enhancing the MAR reaction rate because vibrationally excited hydrogen molecules, which start the MAR processes, are produced by electron collisions.

In summary, the magnetic field and neutral pressure dependences of hydrogen plasma were investigated in the DT-ALPHA device. It was found that higher electron density can be obtained when the lower hybrid resonance condition was satisfied near the RF antenna. In addition, it was also found that the use of lower neutral pressure yielded higher electron density. By satisfying the resonance condition and using lower neutral pressure of approximately 0.75 Pa, the hydrogen plasma of $T_e \sim 10$ eV and $n_e \sim 1 \times 10^{17}$ m^{-3} was obtained. The enhancement of the MAR reaction rate and plasma detachment owing to MAR are expected by conducting secondary gas puffing.

[1] S.I. Krasheninnikov *et al.*, Phys. Lett. A **214**, 285 (1996).
[2] N. Ohno *et al.*, Nucl. Fusion **41**, 1055 (2001).
[3] J.L. Terry *et al.*, Phys. Plasmas **5**, 1759 (1998).
[4] M. Sakamoto *et al.*, Nucl. Mater. Energy **12**, 1004 (2017).
[5] S. Kado *et al.*, J. Nucl. Mater. **337-339**, 166 (2005).
[6] A. Tonegawa *et al.*, J. Nucl. Mater. **313-316**, 1046 (2003).
[7] A. Okamoto *et al.*, Plasma Fusion Res. **3**, 059 (2008).
[8] Y. Sakawa *et al.*, Phys. Plasmas **6**, 4759 (1999).
[9] H. Takahashi *et al.*, Plasma Fusion Res. **13**, 3401053 (2018).