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High density plasma generation by RF ohmic discharge in toroidal divertor simulator NAGDIS-T

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Abstract

A new toroidal divertor plasma simulator, NAGDIS-T (NAGoya DIvertor plasma Simulator with Toroidal magnetic configuration) has been constructed, in which the toroidal plasma is generated by RF Joule and/or DC discharge. In order to obtain high density deuterium plasmas relevant to divertor conditions in fusion devices, the optimum condition of RF ohmic discharge was investigated by varying gas pressure, driving frequency and RF transformer turn ratio. The experimental result was compared with the simple numerical modeling.

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Keywords: NAGDIS-T; RF discharge; Steady state; Modeling; Gas injection

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1. Introduction

Linear divertor plasma simulators (L-DPS), like NAGDIS-II [1], have contributed to understanding of the various physics in boundary plasmas of fusion devices, such as plasma detachment, intermittent non-local plasma transport, plasma–material interactions and so on, since they have a good accessibility for comprehensive diagnostics and a flexible control of plasma parameters. However, L-DPS, which has a simple magnetic configuration, cannot simulate some important phenomena appeared in tokamak boundary plasmas related to the magnetic configuration, such as curvature and grad *B* effects and long connection length of magnetic field lines. For example, recent observations in tokamak edge plasmas indicated non-diffusive blobby plasma transports across the magnetic field [2,3], which is thought to be driven by a charge separation due to the grad *B* effect in the scrape-off layer (SOL) region with open magnetic field. It is difficult to study these phenomena in L-DPS. To overcome these insufficient capabilities, we have developed a new toroidal divertor plasma simulator, NAGDIS-T (NAGoya DIvertor plasma Simulator with Troidal magnetic configuration) to investigate the SOL/Divertor plasma physics in toroidal fusion plasma devices.

In the NAGDIS-T, deuterium plasmas can be generated by RF ohmic discharge and/or DC discharge. In order to simulate the divertor plasmas

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of fusion devices, it is necessary to generate high density and high heat flux plasmas, possibly, in steady state. In the similar toroidal device, HELIMAK, the typical electron density n_e and temperature T_e are $10^{17}\,m^{-3}$ and $T_e \sim 10$ eV [4]. In order to investigate the SOL/Divertor plasma physics, much higher plasma density should be required because $n_e \sim 10^{19}\,m^{-3}$ in the SOL regions of tokamaks.

In this article, we focus on the RF ohmic discharge in NAGDIS-T. We have optimized discharge parameters: such as neutral gas pressure, RF driving frequency, RF transformer turn-ratio, plasma volume, etc., in order to obtain high density deuterium plasmas with an electron density of above $10^{18}\,m^{-3}$. The experimental results show that the optimum condition for RF ohmic discharge strongly depends on both the driving frequency and the neutral gas pressure. The optimization of discharge parameters gives an electron density beyond $10^{18}\,m^{-3}$ and an electron temperature above 10 eV or in deuterium plasmas with large plasma volume.

2. Toroidal divertor plasma simulator

NAGDIS-T consists of 12 toroidal magnetic field coils and four vertical field coils as shown in Fig. 1. Major radius is 0.34 m and the poloidal cross section of the vacuum chamber has a rectangular shape with a height of 0.28 m and a horizontal width of 0.18 m. These coil currents produce a helix magnetic configuration, in which a magnetic line of force starting from the top surface of the vacuum chamber with a rectangular cross section is rotating toroidally and gradually going down to reach the bottom surface. The incident angle of the magnetic line of force to target plates and its connection length L can be controlled by changing a ratio of the vertical magnetic field strength to the toroidal one ($40\,m < L < 300\,m$). This magnetic configuration in the NAGDIS-T can makes it possible to simulate such as particle transports in long and curved magnetic lines of force, and a plasma–surface interaction with strongly inclined magnetic lines of force to the divertor plate, and so on.

Fig. 2 shows the circuit diagram of the RF Joule heating system. The RF Joule power is introduced into plasmas through a transformer made of a ferrite core instead of an iron one in order to reduce hysteresis losses at an employed frequency range, a few hundred kilohertz. The transformer was powered by a inverter RF power supply #1 (9 kW with 30 A and 300 V, $R_0 \sim 10\,\Omega$). High power RF power supply #2 (30 kW with 150 A and 220 V, $R_0 \sim 1.5\,\Omega$) was also equipped recently to obtain higher density plasmas. The RF driving frequency is sufficiently high that the a.c. time scale of $\sim 10^{-5}$ s is much shorter than the particle confinement time of $\sim 10^{-3}$ s. Then, the plasma parameters will not change rapidly even with the application of a.c. ohmic heating. The turn ratio of the primary to secondary windings is adjusted to set 7 to 1 for the RF power supply #1, and 3 to 1 for #2. Primary circuit has a capacitor C to achieve an electrical series resonance condition with the inductance of plasma loop. The resonance frequency can be varied by changing the capacitance.

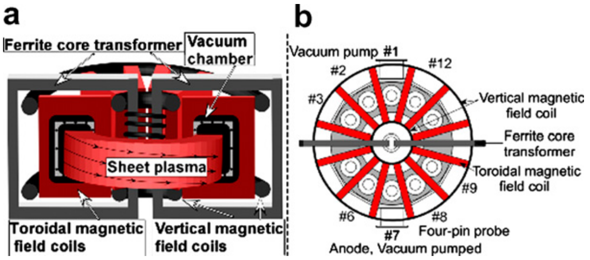

Fig. 1. Schematic diagram of the toroidal divertor plasma simulator, NAGDIS-T. (a) The cross section, (b) the top view. Major radius is 0.32 m and the poroidal cross section of the vacuum chamber has a rectangular shape with a height of 0.28 m and a horizontal width of 0.18 m.

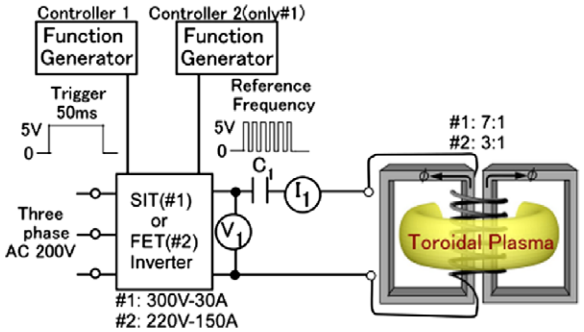

Fig. 2. The circuit diagram of RF Joule heating system. The series capacitor in the primary side is employed for the electrical resonance condition. The turn ratio is chosen so as to have an impedance matching between RF inverter and the load viewed from primary circuit.

3. Experimental results

We have investigated optimized experimental conditions for the RF ohmic discharge to get high electron densities n_e above $10^{18}\ m^{-3}$. In this experiment, the toroidal magnetic field was 0.1 T at the center of the vacuum vessel, and the vertical magnetic field B_v is $(1–6) \times 10^{-4}$ T. Electron density and temperature were measured with a Langmuir probe movable in the radial direction.

3.1. Basic property of RF discharge

Basic property of RF plasma generation has been investigated with the RF power supply #1 with a moderate maximum output power of 9 kW. The deuterium gas pressure p_n and the driving frequency of the RF power source, f_d, were varied from 0.03 Pa to 2 Pa and from 155 kHz to 290 kHz, respectively. Fig. 3 shows the gas pressure p_n's dependence of the electron density n_e normalized by the input RF power as a parameter of the driving frequency. In this experiment, we set a molybdenum limiter inside of the vacuum vessel in the low field side, leaving a space of 4.5 cm between the limiter and the vessel wall, to reduce the plasma volume and to increase the injected RF power density. n_e was measured at $X = -4.5$ cm, where X represents a horizontal position from the center of the vacuum vessel at the equatorial plane. The positive X means locations in the low field side. As is clear from the figure, there is the optimum value of a gas pressure around $p_n = 0.03$ Pa. This tendency can be predicted by the simple numerical modeling [5]. According to the numerical analysis, the optimum gas pressure is found to be determined by balance between ionization processes and energy losses by charge exchange processes. For the f_d's of 155 and 210 kHz, unfortunately, there is no experimental data at a low gas pressure region because of the limitation of the RF current of the power supply.

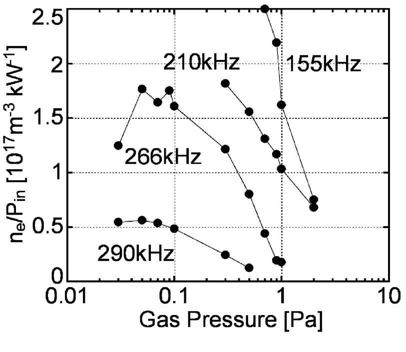

Fig. 3. The electron density n_e normalized by the input RF power as a function of the gas pressure p_n with the limiter, taking the driving frequency as a parameter.

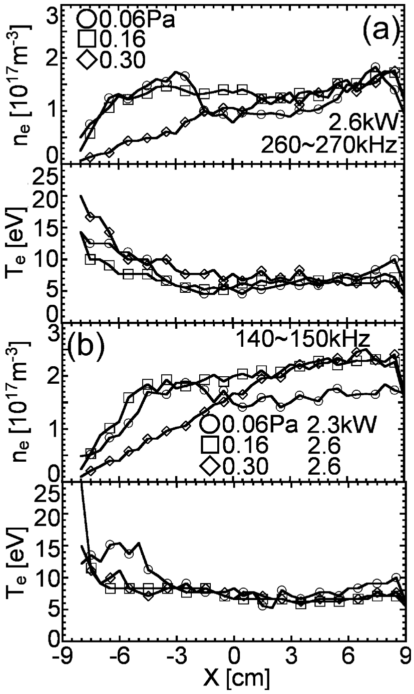

Fig. 4. Horizontal profiles of electron density and temperature taking the gas pressure as a parameter, (a) 270 kHz, (b) 150 kHz with the RF power supply #1. X is horizontal position at the equator of the vacuum vessel.

Fig. 4 shows the horizontal profiles of electron density n_e and electron temperature T_e taking p_n as a parameter. The driving RF frequencies are about 150 kHz and 270 kHz in Fig. 4(a) and (b), respectively. At a higher driving frequency of 270 kHz in Fig. 4(a), the horizontal profile of n_e at 0.06 Pa becomes hollow, which could be due to the RF skin effect. The RF skin effect prevents a penetration of RF power into the central region of plasma, resulting in a relatively high percentage of the RF power being deposited in the plasma edge, especially at high field side where the RF electric field is stronger than that in the low field side. The electron temperature T_e ranged from 5 through 20 eV, has similar profile at the various gas pressures and the frequencies, that is, high temperature in the high field side.

3.2. High density plasma generation by high power RF source

In this section, based on studies about basic properties of RF ohmic discharges mentioned in 3.1 and results of the simple numerical modeling, generation of higher density plasmas were attempted by employing a high power RF source #2 with a maximum available power of 30 kW. The driving frequency f_d around 100 kHz.

Fig. 5 shows horizontal profiles of n_e and T_e at $p_n = 0.1$ and 0.2 Pa, respectively. The profiles of the electron temperature are always hollow because the induced RF electric field is large near the vessel wall, similar to those in the lower RF power source. Especially, T_e near the inner vessel wall is very high probably because of the large RF electric field. When the p_n is decreasing from 0.2 Pa to 0.1 Pa, T_e near the inner vessel wall at $p_n = 0.1$ Pa becomes almost twice as high as that at $p_n = 0.2$ Pa. The reason why the T_e dramatically increases at $p_n = 0.1$ Pa could be associated with penetration of neutral gases. In this experiment, the gas inlet was located at the outer vacuum vessel. At lower p_n, which means a lower gas flow rate through the inlet, there could be a smaller number of neutrals near the inner wall because neutrals are not able to penetrate deeply inside of plasma due to its small ionization mean free path. Then, the RF power is mainly consumed to heat up electrons near the inner wall. Fig. 6 shows horizontal profiles of n_e and T_e when the gas inlet is located near the inner wall. The gas pressure was varied from 0.1 through 0.3 Pa. It is found that the gas pressure dependence of T_e near the inner wall becomes moderate compared with that in Fig. 5. This experimental result also indicates that quite high electron temperature T_e observed at $p_n = 0.1$ Pa in Fig. 5 is attributed to a lack of neutrals near the inner wall associated with the penetration of neutrals into plasmas.

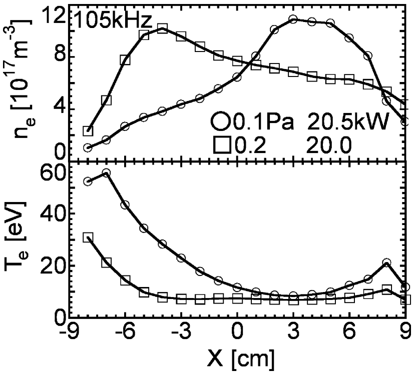

Fig. 5. Horizontal profiles of electron density and temperature in the steady state taking the gas pressure as a parameter with the driving frequency of 105 kHz in the case of RF power supply #2. Gas inlet is located at the low field side.

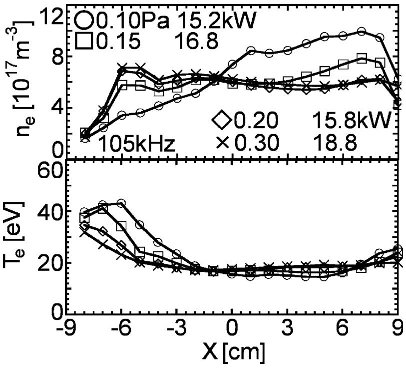

Fig. 6. Horizontal profiles of electron density and temperature taking the gas pressure as a parameter with the driving frequency of 105 kHz in the case of RF power supply #2. Gas inlet is put at high field side.

At p_n above 0.2 Pa, the profile of the electron density n_e has a peak in the high field side as shown both in Figs. 5 and 6. Interestingly, as decreasing p_n from 0.2 Pa, the density peak moves outward. We cannot explain the shift of the density peak by the penetration of neutrals because the shift was observed both in Figs. 5 and 6. We have not understood the mech-

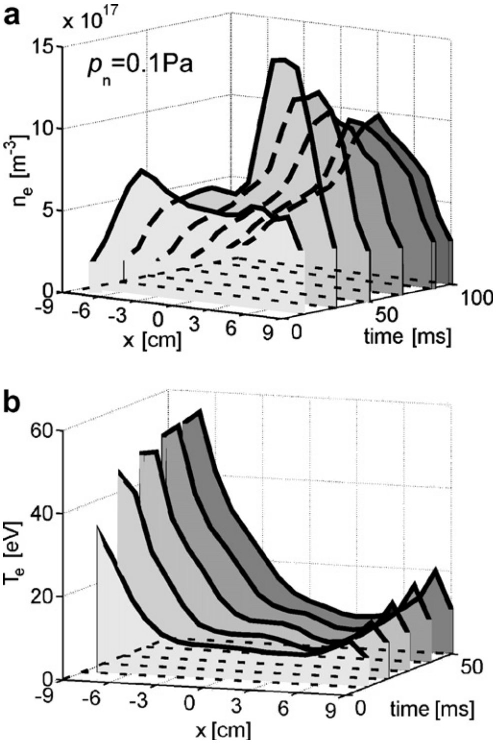

Fig. 7. Time evolution of horizontal profiles at $p_n = 0.1$ Pa. (a) Electron density, (b) electron temperature, in which the gas inlet is located at the low field side.

anism of the density peak shift in Figs. 5 and 6, but we also found the interesting phenomena, which could be related to the density peak shift.

Fig. 7 shows that the time evolution of the density and the temperature profiles averaged over every 10 ms from the plasma ignition at $p_n = 0.1$ Pa, corresponding to Fig. 5. The temperature profile does not change in time, but the density profile does. At the beginning of the RF ohmic discharge, the density peak appears at $X = -4$ cm in the high field side. Shortly after that, the density around $X = 4$ cm at the low field side abruptly increases to be a sharp density peak, while the density peak at $X = -4$ cm decreases. The sharp density peak around $X = 4$ cm is gradually decreasing to be stationary density profile. Similar phenomenon was also observed at $p_n = 0.1$ Pa in Fig. 6. Such a slow density change was not observed at p_n above 0.2 Pa. The timescale of the evolution of the density profile is about a 10 ms as shown in Fig. 7, which is very long time compared with that determined by atomic processes such as ionization. One of the possible explanations for a slow density change in time is that better confinement region appeared at the low field side due to bootstrap current [6].

4. Summary

We have investigated generation of high density deuterium plasmas by using RF ohmic discharge in the toroidal divertor plasma simulator, NAGDIS-T. Discharge parameters were optimized to give a high density deuterium plasma by varying neutral pressure, driving RF frequency and so on. The electron density n_e increases with the decrease of driving frequency at the gas pressure of several 10^{-2} Pa. By using high power RF source of 30 kW, we can successfully generate large-volume deuterium plasmas with an electron density n_e above 10^{18} m^{-3} and an electron temperature T_e around 15 eV in the NAGDIS-T. The horizontal profiles of n_e and T_e were also measured, which shows the electron temperature near the inner wall is extremely high, and its value is strongly influenced by the position of the gas inlet associated with the neutral penetration into plasma. The electron density has a peak in the high field side, or almost flat profile at a neutral pressure above 0.2 Pa. On the other hand, the density peak shifts to the low field side at a lower neutral pressure of 0.1 Pa. Furthermore, a slow change of the density profile at a pressure of 0.1 Pa was also observed. Detailed study of this phenomenon is future work.

References

[1] N. Ohno, Y. Kobayashi, T. Sugimoto, S. Takamura, J. Nucl. Mater. 337–339 (2005) 35.
[2] D.P. Coster, K. Borrass, R. Schneider, J. Nucl. Mater. 266–269 (1999) 804.
[3] D.A. D'Ippolito, J.R. Myra, S.I. Krasheninnikov, Phys. Plasmas 9 (2002) 222.
[4] S.T. Wu, X.Q. Mao, S.J. Du, H. Huang, Y.T. Song, W.G. Chen, J.G. Li, Fusion Eng. Des. 63&64 (2002) 59.
[5] M. Nagase, S. Takamura, N. Ohno, H. Masuda, H. Kitahara, M. Takagi, Contrib. Plasma Phys. 46 (2006) 557.
[6] T. Yoshinaga, M. Uchida, H. Tanaka, T. Maekawa, Phys. Rev. Lett. 96 (2006) 125005.