Influence of Nitrogen Ratio on Plasma Detachment during Combined Seeding with Hydrogen on Divertor Simulation Experiment of GAMMA 10/PDX*)

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Influences of nitrogen ratio on plasma detachment and molecular activated recombination (MAR) processes during combined seeding with hydrogen have been investigated utilizing end-loss plasma in the GAMMA 10/PDX tandem mirror. Additional gases were injected under the condition that hydrogen partial pressure was fixed and nitrogen partial pressure was changed from 0% - 10% compared to that of hydrogen. Electron density and ion flux further decrease with increasing nitrogen ratio. In addition, it is suggested that the hydrogen-MAR process that begins with dissociative attachment is suppressed during combined seeding of nitrogen and hydrogen. Observed emission spectrum of NH radicals suggests that the density of NH increases as nitrogen ratio increases and nitrogen-induced MAR efficiently contributes to the reduction of particle flux.

Keywords: divertor, detached plasma, nitrogen, MAR, GAMMA 10/PDX

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1. Introduction

Formation and control of detached plasma are essential for the protection of divertor plates against huge heat and particle loads in fusion devices such as ITER and DEMO reactors. In the detached plasma, electron temperature decreases through plasma-gas interactions. Volumetric recombination processes are key reactions for reduction of particle flux, where electron temperature sufficiently decreases. Molecular activated recombination (MAR) process has a higher rate coefficient than radiative and three-body electron-ion recombination (EIR) processes at relatively high electron temperature ($T_e \sim 3\,\mathrm{eV}$) [1, 2]. A number of studies on MAR have been carried out in liner devices [3–6].

Nitrogen is a seeding impurity candidate for divertor detachment in ITER [7] and the effects of nitrogen gas seeding on divertor detachment have been investigated in ASDEX Upgrade [8, 9] and JET [10]. In addition, it was recently numerically shown that nitrogen contributes to the volumetric recombination process called "nitrogen-induced MAR (N-MAR)" [11]. The N-MAR process is a chain reaction via NH_x (x = 1, 2, and 3), consisting of ion conversion with hydrogen ions followed by dissociative recombination (DR) with electrons. The process can be described as follows:

$$H^+ + NH_x \rightarrow H + NH_x^+, \quad (1)$$

$$NH_x^+ + e^- \rightarrow NH_{(x-1)} + H. \quad (2)$$

These reactions have higher rate coefficients than hydrogen-induced MAR (H-MAR) in a wide electron temperature range [12] and have experimentally been demonstrated in Magnum-PSI at DIFFER [12, 13] and PISCES-E at UCSD [14]. In GAMMA 10/PDX, a clear particle flux reduction was also observed by combined seeding of hydrogen and nitrogen gases [15], suggesting the occurrence of N-MAR. Thus, it has been found that nitrogen contributes not only as a radiator gas but also to the reduction of heat loads through the volumetric recombination process.

H-MAR and N-MAR reaction rates and the degree of detachment are considered to be related to the ratio of hy-

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drogen and nitrogen gas pressures because those reactions are affected by each other. In this study, we investigated the influence of nitrogen ratio on plasma detachment and volumetric recombination processes during combined seeding with hydrogen achieved by changing the nitrogen partial pressure.

2. Experimental Setup

Figure 1 (a) shows a schematic view of GAMMA 10/PDX that is a large tandem mirror device [16]. GAMMA 10/PDX consists of four sections: central cell, anchor cell, plug/barrier cell, and end region. In the central cell, hydrogen plasma is generated by ion cyclotron range of frequency (ICRF) heating. The plasma that exits from mirror confinement regions, so called "end-loss plasma," flows to the end region along the open magnetic field lines. The end-loss plasma has ion and electron temperatures comparable to scrape-off layer plasma.

In order to simulate detached divertor, the divertor simulation experimental module (D-module) is installed in the west end region [17–19]. Figure 1 (b) shows a schematic view of the D-module. In this module, a V-shaped target plate made of tungsten is mounted. Additional hydrogen gas was supplied from the inlet of the D-module and nitrogen gas was supplied from the inlet and near the corner of the target. The amounts of each additional gas are adjusted by the plenum pressure in the reservoir tank. For diagnostics, Langmuir probes are mounted on the V-shaped target (#1 - 5) and upstream of the D-module. Hydrogen Balmer line emissions are measured with a low dispersion spectrometer (USB2000+, Ocean optics, now Ocean insight). NH radical emission is measured with a high dispersion spectrometer (SR500i, ANDOR). The measurement positions of the Langmuir probes and spectroscopes are shown in Fig. 1 (b). An ASDEX-type ionization gauge is installed at the top of the D-module to measure the neutral gas pressure.

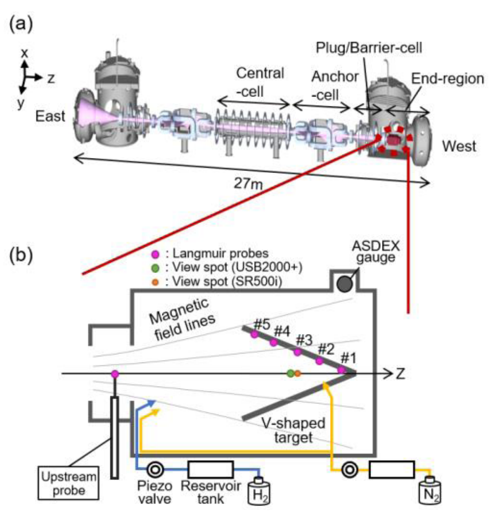

Fig. 1 Schematic views of (a) GAMMA 10/PDX and (b) the divertor simulation experimental module (D-module).

3. Results and Discussion

Hydrogen plasma is generated and sustained for 400 ms from $t = 50$ ms in the central cell by ICRF heating. Nitrogen gas seeded after $t \sim 100$ ms and additional hydrogen gas seeded after $t \sim 150$ ms into the D-module. The plenum pressure of hydrogen gas was set to 600 mbar and that of nitrogen was changed to 200 mbar, 400 mbar, and 600 mbar in each shot. Figure 2 (a) shows neutral gas pressure in the D-module when each gas was seeded independently. Nitrogen pressure just before the end of discharge is about 0% - 10% compared to that of hydrogen. Figure 2 (b) shows electron line density in the west barrier cell during combined seeding of hydrogen and nitrogen. Increase in the line density indicates the plasma just upstream of the D-module was changed by seeding of additional gases. However, there is not much difference caused by gas conditions. The diamagnetism and line density in the central cell did not changed significantly over time ($DM_{CC} \sim 0.2 \times 10^{-4}$ Wb, $NL_{CC} \sim 5.5 \times 10^{13}$ cm^{-2}). Therefore, it is considered that there was almost no effect of the seeding gases on the central cell where the plasma is produced.

Figure 3 shows the time evolution of (a) electron density (n_e) measured by the upstream probe, (b) T_e, (c) n_e, and (d) ion flux (Γ_i) measured by Probe #3 on the V-shaped target during combined seeding. n_e in the upstream region is continuously increased by mainly ionization of hydrogen. There is almost no difference for nitrogen ratio. In the downstream region, T_e decreases with additional gas seeding. Although there is a difference in the time at which T_e starts to drop, T_e (< 4 eV) after $t \sim 250$ ms is almost the same regardless of nitrogen ratio. The difference in

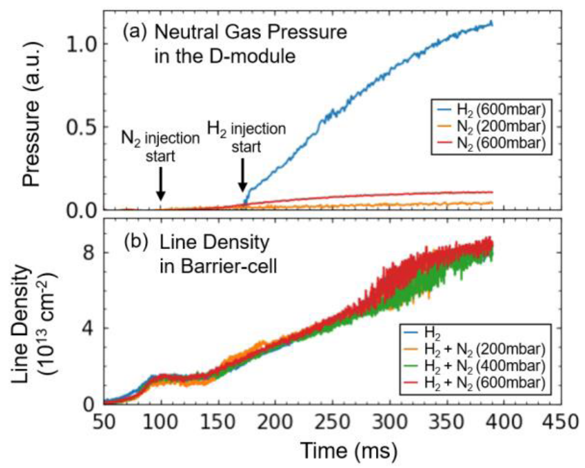

Fig. 2 Time evolution of (a) neutral gas pressure in the D-module and (b) electron line density in the west barrier cell. Gas pressure in the legend represents the plenum pressure in the reservoir tank. The plenum pressure of hydrogen is set to 600 mbar.

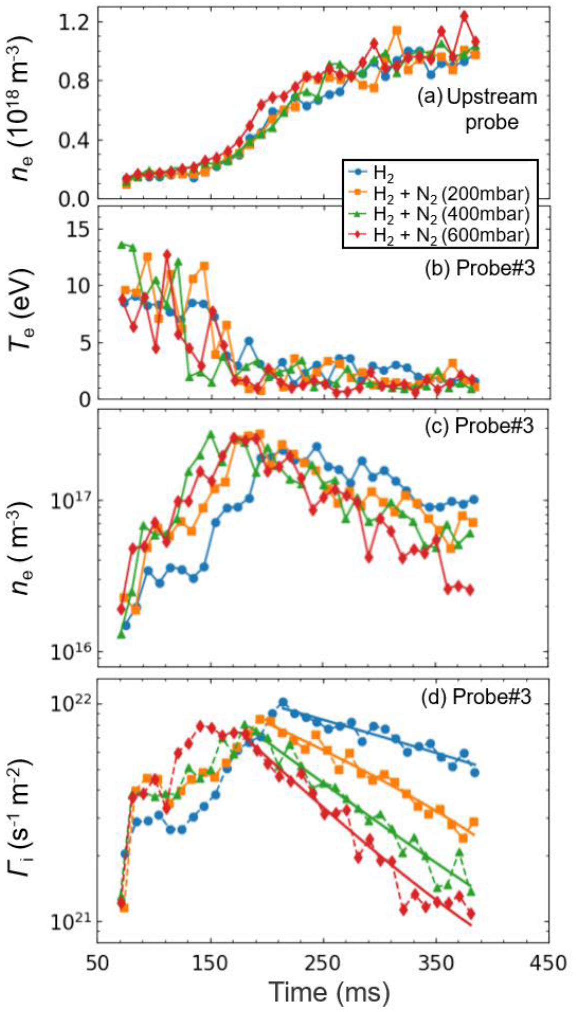

Fig. 3 Time evolution of (a) electron density measured by the upstream probe, (b) electron temperature, (c) electron density, and (d) ion flux during combined seeding. (b) - (d) Measured by Probe #3 installed on the V-shaped target. The plenum pressure of hydrogen is fixed at 600 mbar.

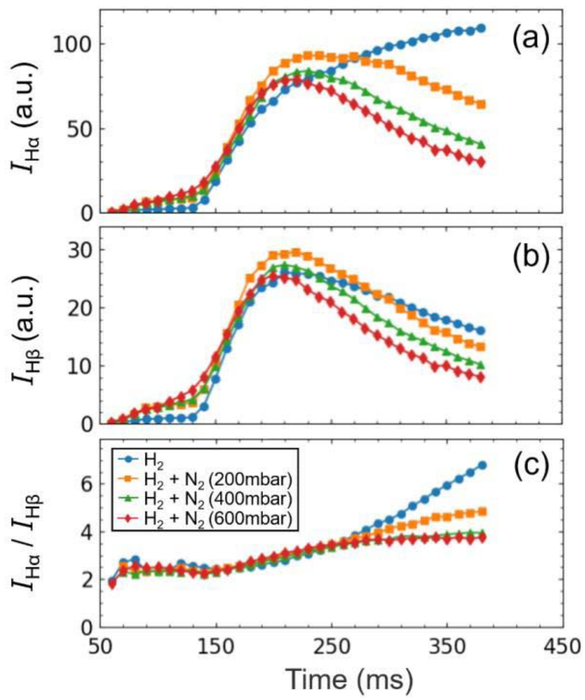

Fig. 4 Time evolution of (a) intensity of H_α emission, (b) intensity of H_β emission, and (c) intensity ratio of H_α to H_β. The plenum pressure of hydrogen is fixed at 600 mbar.

the timing of the decrease in T_e can be caused by radiation of nitrogen gas. In fact, the intensity of N_2 emission is stronger as nitrogen ratio increases (see Fig. 5 (a)). However, it does not lead to a rapid decrease in T_e, and the total radiation power is not considered to change significantly for different nitrogen ratios. n_e and Γ_i show "rollover," i.e., they first increase and then decrease. These results indicate plasma detachment occurs. As nitrogen ratio increases, n_e and Γ_i further decrease after rollover. The vertical axes of n_e and Γ_i are plotted on a log scale and Γ_i after rollover is fitted with an exponential function. With increasing nitrogen ratio, the slope becomes steeper, indicating the decay time becomes shorter. Given that T_e sufficiently decreases at this time, it is suggested that the rate of particle loss increases. The change in Γ_i is larger than that of n_e. The ion temperature (T_i) may relate to this different behavior. In GAMMA 10/PDX, the plasma that has high T_i ($> T_e$) is produced by ICRF heating. Therefore, the effect of T_i cannot be neglected. It is considered that nitrogen has different effects on T_i than hydrogen. It is also possible that heavy ion species derived from nitrogen, e.g., N_2^+, N^+, NH^+, etc., may contribute to the decrease in Γ_i. To investigate these factors in detail, we plan to evaluate T_i and the ion species by means of experiments and calculations.

In this study, nitrogen ratio to hydrogen depends on the amount of nitrogen gas, so it should be noted that total pressure increases as nitrogen ratio increases. In this experiment, the increase in total pressure due to combined seeding of nitrogen is ~10% at most. A previous study has shown that when noble gases are seeded with hydrogen and total pressure increased ~10%, the decrease in ion flux and n_e is not much different from that of only hydrogen seeding. On the other hand, when nitrogen is seeded with hydrogen at ~10%, the ion flux and n_e decrease more than those of noble gases [15]. Therefore, we consider that nitrogen ratio influences the decrease in ion flux and n_e.

Figure 4 shows the time evolution of hydrogen Balmer line emission intensities, (a) $I_{H\alpha}$, (b) $I_{H\beta}$, and (c) the ratio ($I_{H\alpha}/I_{H\beta}$) observed at the center of the V-shaped target. In the case of only hydrogen seeding, not only n_e but also $I_{H\beta}$ shows rollover, while $I_{H\alpha}$ and $I_{H\alpha}/I_{H\beta}$ continue to increase. These results are the same as that in previous studies in GAMMA 10/PDX [19–21]. These phenomena indicate dissociative attachment (DA) is a key process in H-MAR in our experimental conditions [19]. When hydrogen is seeded together with nitrogen, a different trend is

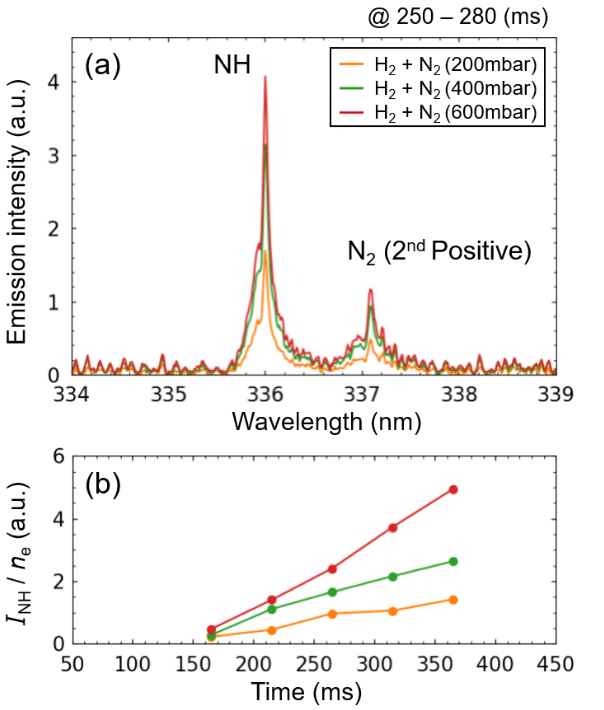

Fig. 5 (a) Emission spectrum of NH radicals observed in the D-module and (b) intensity of NH emission normalized by electron density (measured by Probe #3).

obtained. In the case of setting the nitrogen plenum pressure to 200 mbar, $I_{H\alpha}$ gradually decreases after $t \sim 250$ ms. $I_{H\beta}$ shows the same trend as that of only hydrogen seeding and $I_{H\alpha}/I_{H\beta}$ at $t \sim 390$ ms becomes two-thirds that of only hydrogen seeding. This suggests that the H-MAR process that begins with DA is suppressed by nitrogen seeding. As the plenum pressure increases further, i.e., nitrogen ratio increases, $I_{H\alpha}$, as well as $I_{H\beta}$ and n_e, shows rollover clearly. $I_{H\alpha}/I_{H\beta}$ decreases as nitrogen ratio increases, but the trend is saturated. These results suggest that the H-MAR process that begins with DA is suppressed by a small amount of nitrogen seeding and the effect is saturated as nitrogen ratio increases. However, n_e and Γ_i further decrease as nitrogen ratio increases.

A possible process for explaining Γ_i decay is N-MAR because the rate coefficient of N-MAR is higher than that of H-MAR. Figure 5 (a) shows a spectrum of the NH radical ($A^3\Pi \rightarrow X^3\Sigma$), which contributes N-MAR processes. The emission intensity (I_{NH}) becomes stronger with increasing nitrogen ratio. The time evolution of I_{NH} normalized by n_e (I_{NH}/n_e), which indicates n_{NH}, is shown in Fig. 5 (b). I_{NH}/n_e increases over time and also with increasing nitrogen ratio. Here, we discuss the processes of NH production, e.g., electron impact dissociation (EID) with NH_x, charge exchange (CX) with NH^+, DR with NH_x, and reaction between neutral particles. Figure 6 shows the rate coefficient of these reactions against T_e [11]. Below $T_e \sim 5$ eV, the rate coefficients of DR with NH_x are higher than that of EID. In this experiment, T_e on the V-

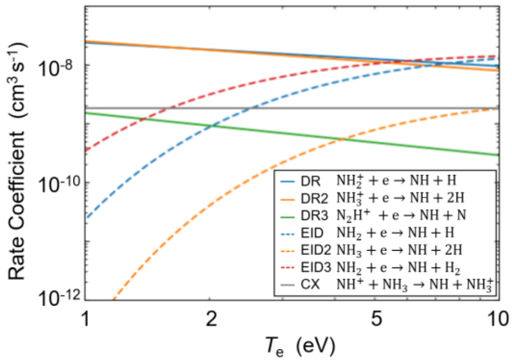

Fig. 6 Rate coefficient of the reaction processes involved in NH production versus electron temperature, which are referred from Table 2 in Ref. [11].

shaped target is sufficiently below 5 eV after $t \sim 250$ ms, which suggests that DR, one of the reactions of N-MAR, may contribute to the production of NH. However, the density of each particle needs to be considered, as well as n_e, to quantitatively discuss NH production. We also need to consider that many species, not just NH, contribute to N-MAR. Therefore, it is necessary to solve the rate equations and investigate the density of each particle and the reaction processes in detail.

4. Summary

In this study, the influence of nitrogen ratio on plasma detachment during combined seeding with hydrogen was investigated in GAMMA 10/PDX. Additional gases were seeded into the D-module under the condition that the hydrogen partial pressure was fixed and that of nitrogen was changed. In the range of this experiment, n_e and Γ_i further decrease with increasing nitrogen ratio. The change in the decay time of Γ_i suggests that the recombination rate is higher with increasing nitrogen ratio. In addition, it is suggested that the rate of the H-MAR process that begins with DA decreases by seeding of a small amount of nitrogen together with hydrogen. Observation and discussion of the emission of NH radicals suggest that the occurrence of N-MAR and its rate may be related to the degree of detachment.

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