Observation of Electron Density Rollover in Hydrogen Plasma Produced with DT-ALPHA Device

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The rollover of electron density, a common indicator for the onset of volumetric recombination, was observed in hydrogen plasma, for the first time in the DT-ALPHA. Electron density and electron temperature were measured near the plasma production region and secondary gas feeding position with various conditions regarding the amount of hydrogen secondary gas. A rollover of electron density was observed at the secondary gas feeding position, whereas electron density near the plasma production region remained nearly constant. This behavior indicates an enhancement of hydrogen molecular-activated recombination.

Keywords: divertor, molecular-activated recombination, hydrogen plasma, radio-frequency plasma, DT-ALPHA

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In magnetic fusion devices, divertor detachment is a promising solution to reduce large plasma heat loads below engineeringly acceptable levels. Divertor detachment is accompanied by an enhancement of electron-ion recombination (EIR) and molecular activated recombination (MAR). Both EIR and MAR have been studied theoretically [1] and experimentally using linear devices with direct current discharge [2–5] and tokamaks [6, 7] to reveal the underlying physics. Recently, MAR has been also reported in a tandem mirror device [8, 9] and a radio-frequency plasma device [10]. In case of pure hydrogen plasma, typical values of electron temperature (T_e) and electron density (n_e) required for the onset of MAR are approximately 10 eV and 10^{17} m^{-3}, respectively [8]. Unlike in EIR, line emissions from highly excited atoms are not observed in MAR processes. Instead, the rollover of n_e against increasing neutral pressure is a good indicator. Recently, the abovementioned parameters were achieved in a DT-ALPHA device near the plasma production region [11]. The enhancement of MAR is expected by secondary gas feeding. However, the controllability of the amount of secondary gas has been a problem because the diffusion of the secondary gas was found to increase neutral pressure near the plasma production region more than twice the optimal discharge pressure. Additionally, the measurement of T_e and n_e has not been yet performed at the secondary gas feed position. To improve the controllability of the amount of secondary gas, a mass–flow controller was introduced into the secondary gas feeding system, which enables us to measure the dependency of T_e and n_e on hydrogen neutral pressure. In this paper, observations of T_e and n_e conducted under controlled secondary gas feed are reported.

Figure 1 shows a schematic diagram of the DT-ALPHA device [12]. DT-ALPHA consists of a quartz pipe and a stainless-steel pipe. The inner diameters of the pipes were 36 and 63 mm, respectively. Plasma is produced by 13.56 MHz radio-frequency (RF) discharge. During the experiment, RF power was kept at 620 W. Two end plates are installed at the upstream and downstream edges to terminate plasma. Working gas is supplied to the device near the upstream endplate. To enhance the reaction rate of volumetric recombination, secondary gas is also supplied at the downstream of the device. Hydrogen was utilized as the working and secondary gases. Mass-flow controllers are used to control the amount of the working gas (Q_{up}) and secondary gas (Q_{down}). Three orifice units are installed inside the device to suppress the diffusion of the secondary gas. Plasma diagnostics were conducted near the plasma production region and at the secondary gas feeding position.

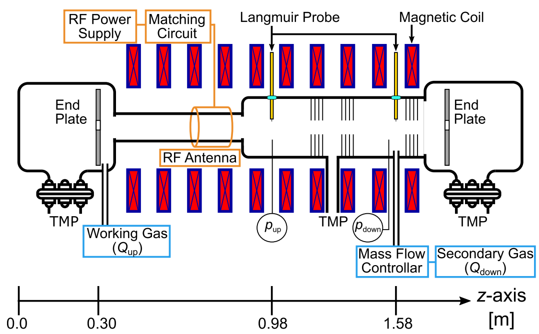

Fig. 1 Schematic diagram of the DT-ALPHA device.

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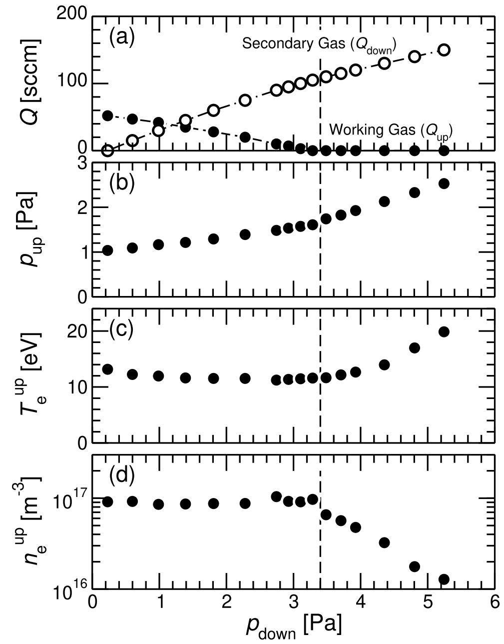

Fig. 2 (a) The amount of working and secondary gases, (b) neutral pressure, (c) electron temperature, and (d) electron density as a function of downstream pressure. Values shown in panels (b), (c), and (d) were obtained near the plasma production region.

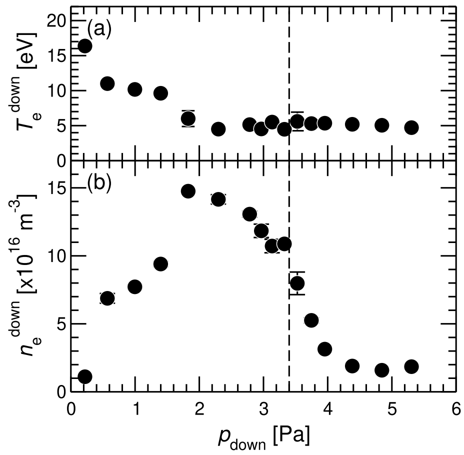

Fig. 3 (a) Electron temperature, and (b) electron density obtained at the secondary gas feeding position as a function of downstream pressure.

Like in previous work [11], a double probe was utilized near the plasma production region. An RF compensated probe was utilized at the secondary gas feeding position. T_e and n_e obtained at the two positions (plasma production region and secondary gas feeding position) are denoted below with superscripts "up" and "down", respectively. Similarly, neutral pressures at the two positions are referred to as p_{up} and p_{down}, respectively. In this experiment, plasma parameters were measured as increasing p_{down}.

Figure 2 summarizes the measurements near the plasma production region as a function of downstream pressure. As Q_{down} increases, p_{down} was increased up to 5.3 Pa, as shown in Fig. 2 (a). Since the discharge condition is sensitive to p_{up} [11], Q_{up} was simultaneously reduced to maintain the optimal discharge condition when Q_{down} was increased. Figures 2 (b) - (d) confirm that, by adjusting Q_{up} and Q_{down}, T_e^{up} and n_e^{up} of approximately 10 eV and $10^{17}\,\mathrm{m}^{-3}$, respectively, could be maintained until $p_{down} = 3.4$ Pa while the increase in p_{up} was suppressed within 40%. At $p_{down} = 3.4$ Pa, Q_{up} reached zero. The point at which the slope of p_{up} changes corresponds to this position. Optimization of p_{up} was impossible at $p_{down} > 3.4$ Pa because Q_{up} could not be reduced further. It was confirmed that p_{down} can be increased up to 3.4 Pa while the optimal discharge condition is maintained.

Figure 3 represents T_e and n_e obtained at the secondary gas feeding position. At $p_{down} = 0.2$ Pa, T_e^{down} was larger than 15 eV. In such a high–temperature region, the rate coefficient of the electron impact ionization exceeds that of MAR. Furthermore, since particle loss rate by MAR is proportional to hydrogen molecule density, neutral pressure needed to enhance MAR is typically several Pa. These indicate that the reaction rate of MAR was negligibly small at low-pressure regions. As p_{down} increased, n_e^{down} showed a rapid increase and finally exceeded $10^{17}\,\mathrm{m}^{-3}$ at 2 Pa. This trend can be interpreted as being caused by electron impact ionization. Simultaneously, T_e^{down} showed a monotonic decrease and became approximately 5 eV at 2 Pa. The decreasing electron temperature and increasing neutral pressure indicate that MAR was being gradually enhanced. When p_{down} was further increased, n_e^{down} decreased. Here, the emphasis is that a decrease in n_e^{down} started below $p_{down} = 3.4$ Pa. Therefore, the change in n_e^{down} observed below 3.4 Pa is probably caused by changes in atomic and molecular processes. This behavior is known as rollover and is typically observed when volumetric recombination is strongly enhanced, as reported in Ref. 8. The clear rollover suggests an enhancement of MAR at p_{down} of 2.0 - 3.4 Pa. A decrease in n_e^{down} above 3.4 Pa is estimated to have been caused by a change in discharge conditions due to the secondary gas in that n_e^{up} also decreases at the pressure range.

In summary, the rollover of electron density in hydrogen plasma was observed in the DT-ALPHA device, for the first time. The experimental results showed that hydrogen MAR was enhanced by secondary gas feeding. In addition to density rollover, the intensity ratio of the hydrogen Balmer series (H_α and H_β) is a good indicator of the onset of MAR. Measurement of hydrogen Balmer lines is now ongoing. In tokamaks, edge-localized modes (ELMs) associated with improved plasma confinement periodically transport energetic ions into a divertor region. However, the influence of the ions on the reaction rate of MAR is not clearly understood yet. DT-ALPHA device could study ELM-related phenomenon by injecting an energetic ion beam into a plasma [13]. Achievement of this work will enable us to study the aforementioned problem, which will be our future work.

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