# Divertor Plasma Simulation Experiment Using Hydrogen Ionizing Plasma and Helium Ion Beam in an RF Plasma Source DT-ALPHA*)

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A helium ion beam was injected into hydrogen ionizing plasma using a radio-frequency plasma source to study divertor plasma. Optical emissions from the hydrogen Balmer series and Fulcher-$\alpha$ band were collected. The emissions of the hydrogen Balmer series clearly increased following the onset of the ion beam injection. The behavior of excited hydrogen atoms slightly depend on its excitation energy. In addition to the Balmer series, the emission from hydrogen molecules increased under the existence of energetic ions. These results indicate that the energetic ion collision affects the population density of the excited hydrogen atoms and molecules.



Keywords: divertor, energetic ion, Balmer series, Fulcher-$\alpha$ band, radio-frequency

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## 1. Introduction

Detached divertor formation is a strong candidate for controlling the large plasma heat load flowing onto divertor plates, and it is recognized that plasma volumetric recombination plays an important role for plasma detachment [1]. In a molecular system, detached plasma can be formed by utilizing molecular activated recombination (MAR) [2]. The hydrogen MAR process is mediated by a vibrationally excited hydrogen molecule $H_2(v)$, and its reaction rate depends on the vibrational distribution and population density of $H_2(v)$. In a toroidal plasma device, especially in a tokamak device, energetic plasma particles are transiently exhausted from the confinement region by edge localized modes (ELM) and the particles flow into the divertor region. Experiments conducted in the conventional divertor plasma simulator indicate that energetic electrons decrease the reaction rate of the electron-ion recombination process [3]. However, the behavior of the volumetric recombination against the energetic ion inflow remains unclear because conventional linear machines have difficulties in utilizing energetic ions. The energy of the ions exhausted by the ELM events could rise to several keV. Proton impact ionization cross section for the hydrogen atom in the ground state is $\sigma \sim 10^{-21}$ m$^2$ around several keV [4]. Energetic ions have a larger influence on the Rydberg atoms because the ionization potential of the Rydberg atoms is rather smaller than that of ground state neutrals. In addition, charge-exchange interaction, which is an ion intrinsic interaction, redistributes the spatial profiles of the neutral particles through momentum transfer.

A large device that can produce reactor-relevant ion temperature and ion flux is one candidate to conduct experimental investigation [5]. However, a small linear machine with a radio-frequency (RF) plasma source is also promising because cylindrically wound RF antenna permits ion beam injection into the device. To investigate the influence of energetic ion collision on the atomic process, we perform an ion beam injection experiment using an RF plasma device and an ion beam generator [6, 7]. In these experiments, a helium ion beam and a helium ionizing/recombining plasma were utilized because helium is one of the common species in the divertor plasma and contains no molecular processes. However, helium ions in a divertor plasma collide with atomic and molecular hydrogen isotopes. The energetic ions can modulate the population balance of $H_2(v)$ when they collide with the ground state and vibrationally excited hydrogen molecules. The influence can be investigated even though we utilize an ionizing plasma. Excited hydrogen atoms $H^*$ produced by the MAR are in relatively lower excited levels. Therefore, it is also expected that influence of the energetic ion collisions on $H^*$ can be investigated with an ionizing plasma. In this study, the first results of the energetic helium ion injection experiment into hydrogen ionizing plasma are reported. The experimental setup is described in Sec. 2, and then the experimental results are presented and discussed in Sec. 3 and Sec. 4, respectively, followed by a summary

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in Sec. 5.

## 2. Experimental Setup

Experiments were conducted using the RF plasma device DT-ALPHA [8]. The schematic of the device is shown in Fig. 1. The device consists of a quartz pipe and a stainless steel (SUS) vacuum chamber. The inner diameters of the quartz pipe and vacuum chamber are 36 mm and 63 mm, respectively. An RF antenna is wound around the quartz pipe, and it is connected with an RF ($f$ = 13.56 MHz) power supply through a matching circuit. The $y$ and $z$ axes are defined as illustrated in Fig. 1. At both ends of the device, end-plates are installed to terminate the plasma. The upstream end-plate has an aperture of 10 mm diameter. The working gas is supplied near the upstream end-plate. To enhance volumetric recombination, a secondary gas puffing system is introduced at the downstream region ($z$ = 1.58 m). In this experiment, hydrogen gas was utilized as the working gas. A secondary hydrogen gas was also supplied. To prevent back flow of the secondary gas, two orifice units made by SUS were installed between the plasma production region and gas puffing region. In the present experiment, the hydrogen neutral pressure measured at $z$ = 0.98 m was approximately 1.4 Pa. At the upstream end of the device, a compact-type ion beam generator is combined with the DT-ALPHA. The details of the beam generator are described in Ref. 9. The plasma production method is a direct-current arc discharge. The extraction system consists of three electrodes, namely, the acceleration, deceleration, and grounded electrodes. An Einzel lens is equipped between the grounded electrode and the upstream end-plate to optimize ion beam transport. In this experiment, a helium ion beam of $E$ = 10 keV was produced and injected into the DT-ALPHA device.

Measurements were conducted using a Langmuir probe (LP), retarding field analyzer (RFA), and two spectroscopes. Although the RFA technique is widely utilized to obtain ion temperature [10], the technique was utilized to measure ion beam in the present study. Near the plasma production region ($z$ = 0.98 m), the electron temperature and electron density of the target plasma were measured using LP. In ion beam injection cases, the time evolutions of the emission intensity of hydrogen Balmer series

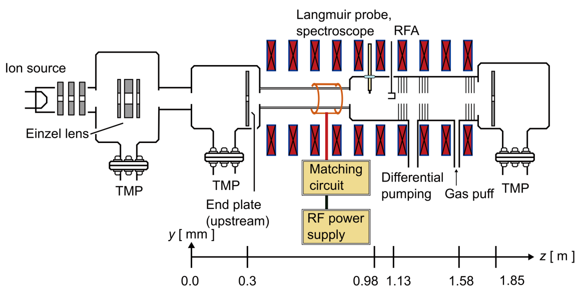


Fig. 1 Schematic of the DT-ALPHA device.

($H_\alpha$, $H_\beta$, and $H_\gamma$) were collected using bandpass filters and photomultiplier tubes. The sampling rate of the line emission was 10 kHz. At $z$ = 1.13 m, the ion beam passing through the target plasma was measured by the RFA simultaneously with an observation of atomic line emission. The RFA consists of a collector and three grids. The potential of the plasma-facing grid was maintained at floating potential to retard bulk electrons. To reduce the inflow of bulk ions, the potential of the intermediate grid was maintained at 50 V. The last grid was utilized to compensate the secondary electrons emitted form the collector, and its potential was kept at −350 V. Emissions from molecular hydrogen lines (Fulcher-$\alpha$ band) were also collected at $z$ = 0.98 m with and without beam injection cases using the Czerny-Turner polychromator with a charge-coupled device (CCD).

## 3. Experimental Results

Before conducting the ion beam injection experiment, the spatial profiles of the electron temperature and electron density near the plasma production region were measured using an LP. During the present experiment, the RF heating power was kept at approximately 10 W. After the target plasma was characterized, the energetic helium ion was then superimposed onto the target plasma. The time evolutions of optical emissions from hydrogen atomic lines were collected. Vibrational distribution can be evaluated using emission intensities from the Fulcher-$\alpha$ system, $d^3\Pi_u^- \rightarrow a^3\Sigma_g^+$ [11]. Therefore, the emission intensities from the Fulcher-$\alpha$ band were also obtained with and without beam injection.

### 3.1 Radial profile of the target plasma

Figure 2 represents the radial profile of the target plasma obtained at $z$ = 0.98 m. As shown in Fig. 2 (a), the electron temperature has a slightly hollowed profile. Around the central region of the cylindrical plasma, the electron temperature is $T_e$ = 2 - 3 eV, and it gradually increases toward the peripheral region. In addition to elec-

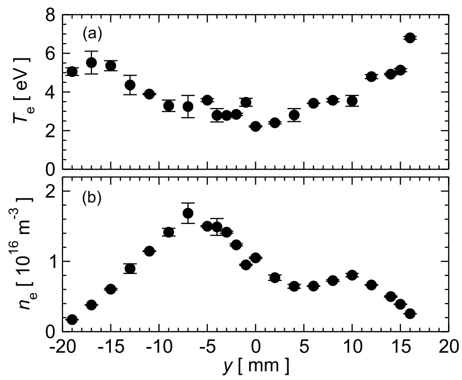


Fig. 2 Radial profile of the (a) electron temperature and (b) electron density obtained at $z$ = 0.98 m.

tron temperature, the electron density also shows a hollowed radial profile, as shown in Fig. 2 (b). The electron density peaks near $y = \pm 10$ mm, and it gradually decreases toward the plasma edge. Asymmetry in the $n_e$ profile would be due to gas puffing. The ion beam penetrates into the device through the aperture of the upstream end-plate ($\phi$ = 10 mm). Therefore, the diameter of the ion beam is considered to be approximately 10 mm. The typical values of $T_e$ and $n_e$ in $|y| \leq 5$ mm are approximately $T_e = 3$ eV and $n_e = 1 \times 10^{16}$ m$^{-3}$, respectively.

## 3.2 Time evolution of optical emission from hydrogen Balmer series

Figure 3 represents the typical time evolutions of the collector current of the RFA and the emission intensities of the hydrogen Balmer series. During $t$ = 0 - 4 s, the RF plasma was produced and the helium ion beam was extracted from $t$ = 2 s to $t$ = 5.5 s. The collector current $I_c$ obtained in the period before beam extraction ($t$ = 0 - 2 s) was approximately 2 μA. This current is caused by bulk ions, which indicates that the retardation of the bulk ion was not complete. However, $I_c$ clearly increased following the onset of beam extraction. This confirms that the helium ion beam passed through the hydrogen plasma and reached the RFA. Ion beam flux passing through the plasma evaluated from an increase in the collector current is approximately $\Gamma = 5 \times 10^{16}$ m$^{-2}$s$^{-1}$. Figure 3 (b) represents the time evolution of the H$_\alpha$ emission intensity. The emission intensity of the H$_\alpha$ line simultaneously increased with the collector current. Therefore, Fig. 3 (b) indicates that the energetic ion collision increased the population density of the excited hydrogen atoms in principal quantum number $n = 3$. On the other hand, our previous works conducted using the helium ion beam and the helium ionizing/recombining plasma indicated that emissions from the excited helium atoms decrease owing to the resonant charge-exchange interaction [6,7]. The difference in results among the present experiment and previous works is discussed in Sec. 4. The increase in the emission intensity $\Delta I$ is almost comparable to the emission obtained after plasma production $I_0$, namely $\Delta I \sim I_0$. In addition to the H$_\alpha$ line emission, emissions from H$_\beta$ and H$_\gamma$ increased with beam injection, as shown in Fig. 3 (c). Note that the time evolutions of H$_\beta$ and H$_\gamma$ emissions are running-averaged values. Figure 4 represents $I_0$ and $\Delta I$ as a function of energy of the upper excited state. The open and filled circles correspond to $I_0$ and $\Delta I$, respectively. Here, the definition of the $I_0$ and $\Delta I$ is the same as that in Fig. 3. $I$ represents emissions obtained before beam injection. As shown in Fig. 4 (a), the $\Delta I$ of each atomic line is almost comparable to each $I_0$. In the case of the H$_\alpha$ emission, an increase in the emission intensity owing to energetic ion collision is approximately 10% of the emission intensity obtained before beam injection. As the energy of the upper excited state increases, $\Delta I/I$ slightly decreases.

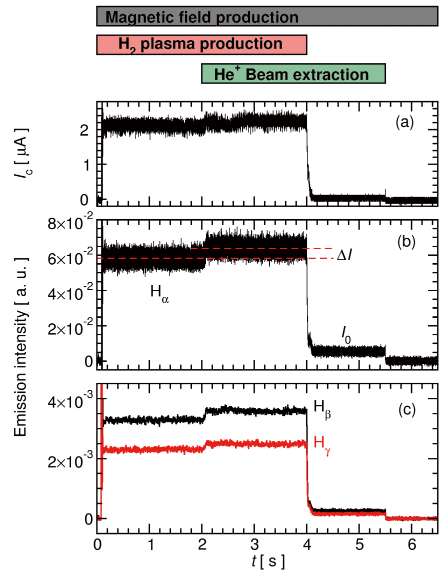


Fig. 3 Time evolution of the (a) collector current, (b) H$_\alpha$ emission intensity, and (c) H$_\beta$ and H$_\gamma$ emission intensities.

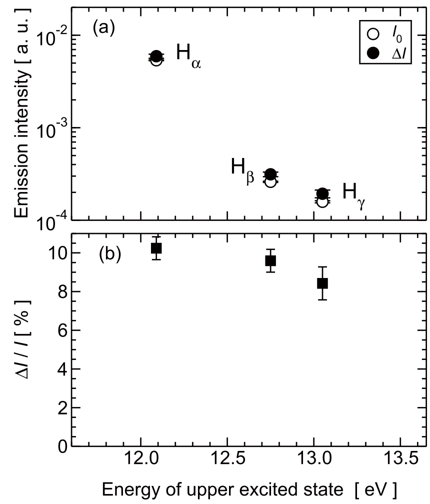


Fig. 4 (a) Emission intensity $I_0$ and $\Delta I$ and (b) intensity ratio $\Delta I/I$ as a function of energy of the upper excited state.

## 3.3 Influence of energetic ion collision on hydrogen Fulcher-$\alpha$ band

In the present experiment, the Q branch ($\Delta J = J' - J'' = 0$) of the Fulcher-$\alpha$ band was collected. Here, $J'$ and $J''$ represent the rotational quantum number of the upper and lower excited states, respectively. The horizontal axis of Fig. 5 represents the vibrational quantum number of the upper excited state. Circles, squares, and diamonds correspond to $J' = 1, 2$ and 3, respectively. The vertical axis of Fig. 5 represents the difference of emission intensities obtained without beam injection cases $I$ and with beam injection cases $I'$. As shown in Fig. 5, $\Delta I$ of each transition has a positive value, which indicates that the population density in $d^3\Pi_u^-$ state increased owing to ion collision. Therefore, hydrogen molecules and atoms behave similarly owing to

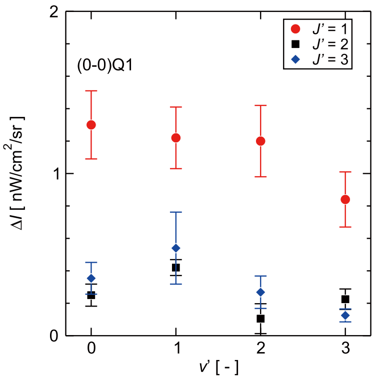


Fig. 5 Increase in the emission intensity of the Fulcher-$\alpha$ band owing to ion collision as a function of the vibrational quantum number of the upper excited state.

the ion collision. The increase in $J' = 1$ is much larger than that of other transitions. However, $\Delta I/I$ for each transition has an almost comparable value of approximately 4 %. The population density of the $d^3\Pi_u^-$ state and the $X^1\Sigma_g^+$ state would satisfy the coronal model because the present experiment utilized low electron density plasma. Therefore, a change in the population density in the $d^3\Pi_u^-$ state would reflect a change of population density and vibrational distribution in the $X^1\Sigma_g^+$ state. The present result indicates that the vibrational structure, which has an important role for MAR, could be redistributed owing to energetic ion collisions.

## 4. Discussion

As described in Sec. 3, the hydrogen atomic line intensities showed different behaviors compared to that obtained with the helium ion beam and the helium plasma. One of the possible reason to interpret this difference is the cross section of the CX interaction. For helium ions of $E = 10$ keV, the cross section of the CX interaction with helium atoms is $\sigma \sim 10^{-19}$ m$^2$. On the other hand, that becomes $\sigma \sim 10^{-20}$ m$^2$ in the case with hydrogen molecules [12]. Therefore, the non-resonant CX interaction would have a relatively smaller influence than the resonant CX interaction case. Energetic ions could dissociate the hydrogen molecule in the ground electronic state. The dissociated atoms can be excited to $n = 3$ - 5 owing to ion collision. Emissions $I_0$ observed in $t = 4$ - 5.5 s in Fig. 3 reflect this process because no electron impact dissociation can proceed in this period. The ion impact excitation of the hydrogen atom into $n = 4$ and 5 is smaller than that into $n = 3$ because excitation into an energetically higher state requires more energy than that required for a lower state, which is consistent with Fig. 4 (a). $\Delta I$ in Fig. 4 (a) has an almost comparable value to $I_0$, which indicates that $\Delta I$ also reflects ion impact dissociation and excitation. Evaluation about the contribution of dissociation and excitation on $\Delta I$ is expected to confirm this discussion and our future work. The population density of the atomic hydrogen strongly depends on the $T_e$ and $n_e$. Energetic ions also collide with bulk electrons, and their energies could be moved to the electrons. The measurement of $T_e$ and $n_e$ under the existence of energetic ion collision is necessary for detailed understanding. It is also necessary to evaluate the ion beam diameter to understand how target plasma behaves against energetic ions.

## 5. Summary

A helium ion beam injection experiment into hydrogen ionizing plasma was conducted. $H_\alpha$, $H_\beta$, and $H_\gamma$ emission intensities clearly increased with the onset of the ion beam injection. An increase in each atomic hydrogen line emission was approximately 10 % of that obtained without beam injection. These results indicate that the population density of the excited hydrogen atoms increased by approximately 10 % owing to ion collision. Although the ion impact dissociation and excitation are possible processes to interpret the results, the contributions of these processes should be evaluated. The energetic ions could transfer their energy to the bulk electrons. Therefore, $T_e$ and $n_e$ under the existence of the energetic ion collision are also required to understand the results. The observation of the hydrogen Fulcher-$\alpha$ band was also conducted. In addition to the emission from atomic hydrogen, the optical emission from the Fulcher-$\alpha$ band increased when energetic ions were superimposed. This result indicates that the vibrational distribution of the hydrogen molecule in the $X^1\Sigma_g^+$ state can be affected owing to the energetic ion collision. The results described in the present paper provide the reference data for future experiments with MAR-dominated plasma.

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