Effect of High-Energy Electrons Component on Recombination Plasma with Pulse Plasma Flow*)

Takaaki IIJIMA, Hiroaki KOBAYASHI, Suguru TANAKA, Akira TONEGAWA, Kazutaka KAWAMURA and Kohnosuke SATO[1)]

Department of Physics, School of Science, Tokai University, 4-1-1 Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan
[1)]*Chubu Electric Power Co., Inc., 20-1 Kitasekiyama, Ohdaka-cho, Midori-ku, Nagoya, Aichi 459-8522, Japan*

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Experiments on a recombination plasma with pulse plasma flow have been performed in the linear divertor simulator TPD-SheetIV. The pulse plasma flow was generated using a switching circuit controlled by the electric potential of the adjacent floating electrode in the plasma source. The duration of the pulse was 0.3 ms at a frequency of 50 Hz. The time dependence of the electron density n_e, temperature T_e, and energy distribution function $f_e(E)$ were measured using a Langmuir probe. The ionization and recombination events are analyzed using the Collisional-Radiative model, taking into account high-energy electrons.

Keywords: ELM burst, divertor plasma, recombination plasma, collisional-radiative model

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1. Introduction

A plasma detached by a divertor plays an essential role in the reduction of the heat load in a magnetically confined fusion device [1,2]. A stationary detached plasma is particularly important for efficient divertor performance. However, a detached plasma decays during the pulse plasma flow, such as due to an ELM burst. That burst leads to periodic particle and heat loads on the divertor plate, so that the electron energy distribution function is non-Maxwellian for an edge plasma [3,4]. Therefore, it is important to have diagnostics of the transient change from recombination to ionization during the pulse plasma flow. These transients have been studied by observing the short double minimum (negative) spike in D_α/H_α emission from the plasma [5]. This spike corresponds to the electron temperature increase associated with pulse plasma flow accompanied by bursts of heat and particles along the magnetic field. Experiments would aid the understanding of the high-energy electrons emitted during the plasma flow.

Here, we carry out measurements of the electron temperature T_e and density n_e, and of the hydrogen Balmer spectra in recombination plasma with pulse plasma flow in a linear device, a TPD-SheetIV [6]. The intensity of the Balmer lines are observed with a spectrometer having a photomultiplier tube. We calculate the ionization and recombination events using the Collisional-Radiative model, taking into account the high-energy electron component.

2. Experimental Setup

The experiment was performed in the linear divertor simulator TPD-SheetIV. Figure 1 sketches the device and the measuring system. The plasma was divided into two regions: that of the sheet plasma source and that of the experiment. The hydrogen plasma was produced by a modified TPD dc discharge between a LaB6 hot cathode and a hollow anode. Eleven rectangular magnetic coils produced a uniform magnetic field of 0.8 kG in the experimental re-

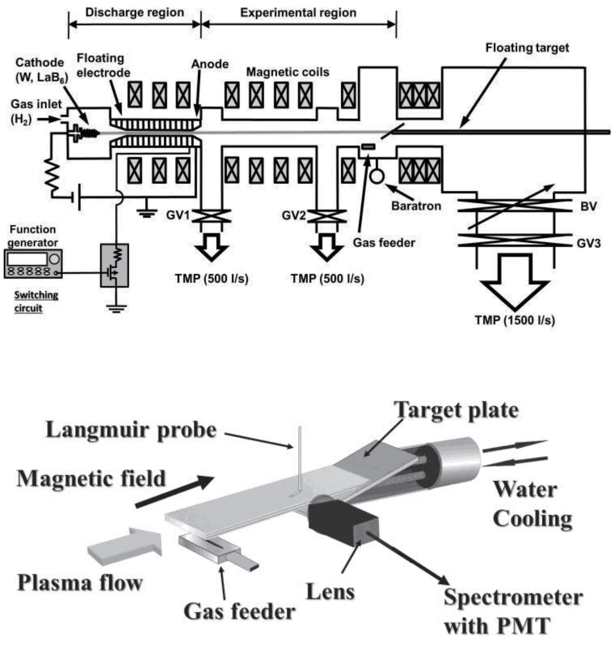

Fig. 1 Diagram of the divertor simulator TPD-SheetIV and of the measuring system.

author's e-mail: 3btad001@mail.takai-u.jp

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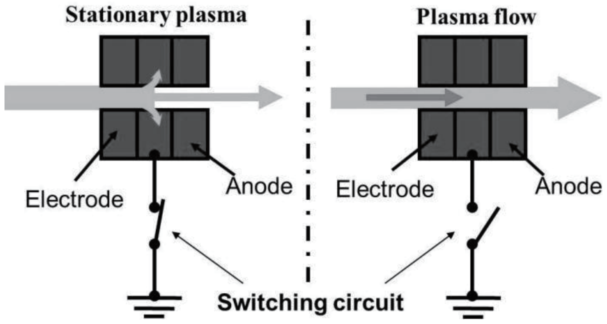

Fig. 2 Schematic of the plasma source and switching circuit.

gion. The sheet plasma was terminated by an electrically-floating, water-cooled target plate axially positioned at z = 0.7 m away from the discharge anode. The plasma was generated with a hydrogen gas flow of 75 sccm, at a discharge current of between 30 and 100 A. The neutral pressure P in the experimental region was adjusted to be between 0.05 and 3.0 Pa with a secondary gas feed. The recombination plasma with pulse plasma flow was generated by controlling the electric potential of the adjacent floating electrode in the plasma source. Figure 2 illustrates the plasma source and switching circuit.

The pulse plasma flow is introduced into the hydrogen recombination plasma in the experimental region. The duration of the pulse was 0.3 ms at a frequency of 50 Hz. The time evolution of the emission intensity of the Balmer lines was observed with a spectrometer equipped with a photomultiplier. The time evolution of the electron density n_e, temperature T_e, and elevtron energy distribution function $f_e(E)$, and of the hydrogen Balmer spectra in the recombination plasma were measured using a Langmuir probe, located 3 cm in front of the endplate.

3. Modeling

The population density of excited atoms $n(p)$ is calculated using the Collisional-Radiative model. First, $n(p)$ is described by the rate equation [7, 8]

$$\begin{aligned}\frac{\mathrm{d}n(p)}{\mathrm{d}t} = &\sum_{q<p} C(q,p) n_e n(q) \\ &- \left[\left\{ \sum_{q<p} F(p,q) + \sum_{q>p} C(p,q) + S(p) \right\} n_e \right. \\ &\left. + \sum_{q<p} A(p,q) \right] n(p) \\ &+ \sum_{q>p} \left[F(q,p) n_e + A(q,p) \right] n(q) \\ &+ \left[\alpha(p) n_e + \beta(p) \right] n_e n_i, \end{aligned} \tag{1}$$

where $n(p)$ and $n(q)$ are the excited atomic densities of hydrogen levels p and q, respectively; $C(p,q)$ and $F(q,p)$ are the rate coefficients of the electron impact excitation and de-excitation from p to q; $A(q,p)$ is the spontaneous transition probability between $p$and q; $S(p)$ is the ionization rate coefficient for p; and $\alpha(p)$ and $\beta(p)$ are the three body recombination rate and radiative recombination coefficients for$p$, respectively. Assuming the quasi-steady-state solution is valid, the time derivative of Eq. (1) can be set to zero. The coupled equations for the excited levels are then solved, so that

$$n(p) = R_0(p) n_e n_i + R_1(p) n_e n(1), \tag{2}$$

where $n(1)$ is the ground state hydrogen density, and $R_0(p)$ and $R_1(p)$ are the population coefficients as functions of the electron temperature T_e and density n_e. The first term on the right-hand side is the recombining component, and the second term is the ionizing component.

These rate coefficients depend strongly on the electron energy distribution function because the equation for the rate coefficient includes the function [3]. For example, the rate coefficient of the electron impact excitation from the p to the q state, $C(p,q)$, is calculated by

$$C(p,q) = \int_0^\infty \sqrt{\frac{2E}{m}} \sigma_{p,q}(E) f(E) dE, \tag{3}$$

where $\sigma_{p,q}$ is the cross-section.

The atomic emission intensities of the recombination and ionization plasmas are

$$I_0 = A(p.q) n_0(p) = A(p,q) R_0(p) n_e n_i, \tag{4}$$

and

$$I_1 = A(p.q) n_1(p) = A(p,q) R_1(p) n_e n(1). \tag{5}$$

Recombination rate $\Gamma_{H^+ \to H}$ and ionization rate $\Gamma_{H \to H^+}$ are

$$\Gamma_{H^+ \to H} = n(1) n_e S_{CR}, \tag{6}$$

and

$$\Gamma_{H^+ \to H} = n_i n_e \alpha_{CR}, \tag{7}$$

where S_{CR} and α_{CR} are the collisional-radiative ionization and recombination rate coefficients, respectively. S_{CR} and α_{CR} are depend strongly on electron energy distribution function. $\Gamma_{H^+ \to H}$ and $\Gamma_{H \to H^+}$ can be rewritten as

$$\frac{\Gamma_{H^+ \to H}}{I_0} = \frac{\alpha_{CR}}{R_0(p) A(p,q)}, \tag{8}$$

and

$$\frac{\Gamma_{H \to H^+}}{I_1} = \frac{S_{CR}}{R_1(p) A(p,q)}. \tag{9}$$

These equations indicate the number of recombination or ionization events per photon. Figure 3 plots the number of recombinations per H_ε photon and ionizations per H_α photon. These depend on the electron temperature T_e and density n_e.

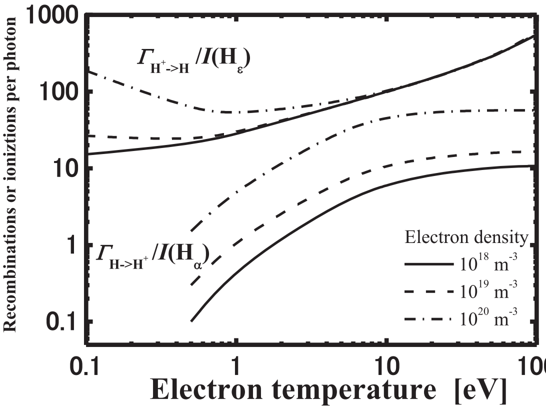

Fig. 3 The number of recombination events per H_ε photon and the number of ionization events per H_α photon.

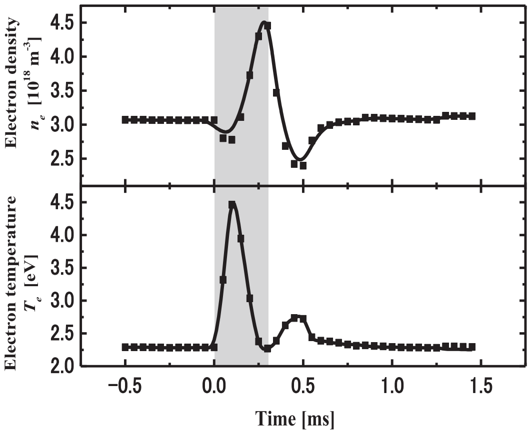

Fig. 4 Typical time evolution of the electron temperature and density at a neutral gas pressure of 1.1 Pa.

4. Experimental Results

Figure 4 graphs the typical time evolution of the electron temperature T_e and density n_e at a neutral gas pressure of 1.1 Pa (for a recombination plasma). The discharge current is 70 A in the hydrogen plasma. Both T_e and n_e increase and peak after the pulse plasma flow is introduced: T_e increases from 2.3 to 4.5 eV, and n_e increases from 3.0 $\times 10^{18}$ m^{-3} to 4.5 $\times 10^{18}$ m^{-3}.

Figure 5 plots the time evolution of the electron energy distribution function $f_e(E)$ at a neutral gas pressure of 1.1 Pa, determined from the derivative of the probe $I - V$ curve. High-energy electrons of around 40 eV appear in the recombination plasma after the pulse plasma flow is introduced.

Figure 6 graphs the typical time evolution of the line emission intensities of H_α and H_ε at a neutral gas pressure of between 0.3 and 1.0 Pa. The H_α intensity increases and peaks after the pulse plasma flow is introduced. On the other hand, the H_ε emission intensity in the recombination plasma drops, implying that the recombination becomes weaker. After the appearance of double minimum negative spikes at around 0.5 ms, the emission intensity gradually

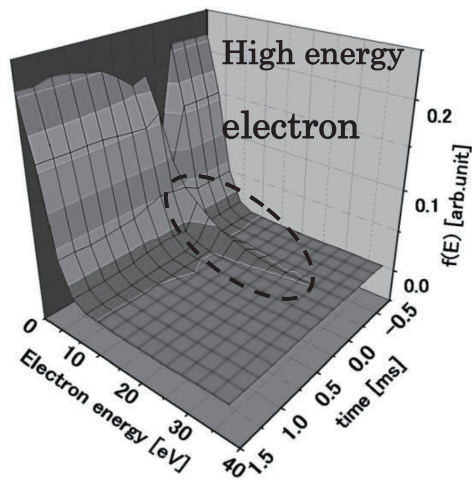

Fig. 5 Time evolution of the electron energy distribution function $f_e(E)$ at a neutral gas pressure of 1.1 Pa.

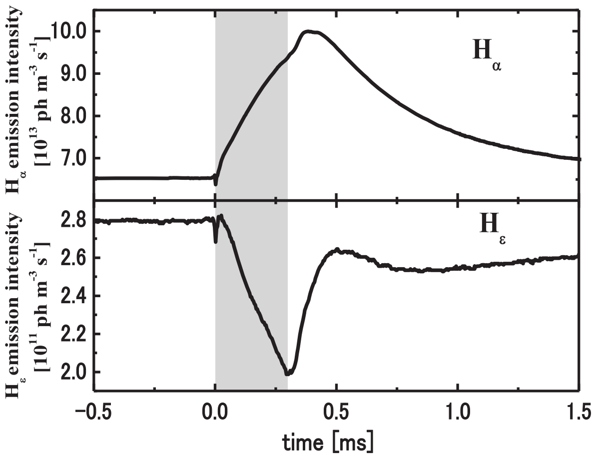

Fig. 6 Typical time evolution of the line emission intensities of H_α and H_ε at a neutral gas pressure of 1.0 Pa.

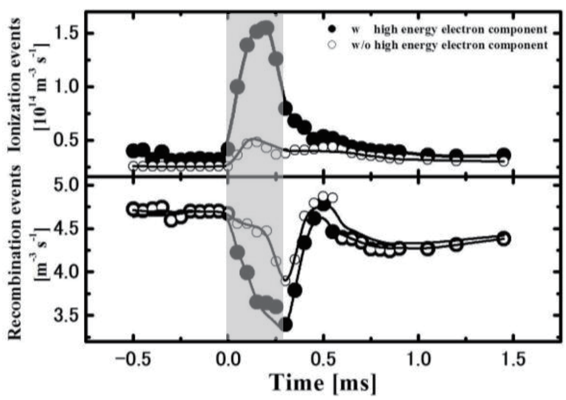

Fig. 7 Ionization and recombination according to the CR model, including high-energy electrons.

increases.

Ionization and recombination are calculated using the Collisional-Radiative (CR) model, taking into account bulk component and high-energy electrons, as plotted in Fig. 7. Ionization is increased more, and recombination is decreased more by effect of high energy electron component.

5. Conclusion

The time evolution of the electron density n_e, temperature T_e, and electron energy distribution function $f_e(E)$, and of the hydrogen Balmer spectra is found to depend on the gas pressure in the recombination plasma with pulse plasma flow. High-energy electrons in the pulse plasma flow are influenced by the time evolution of the Balmer spectra during the transition from an ionizing to a recombination plasma.

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