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

Department of Physics, School of Science, Tokai University, 4-1-1 Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan
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 $D_\alpha/H_\alpha$ 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 region.

Fig. 1 Diagram of the divertor simulator TPD-SheetIV and of the measuring system.
The population density of excited atoms \( n(p) \) is calculated using the Collisional-Radiative model. First, \( n(p) \) is described by the rate equation \([7, 8]\)

\[
\frac{dn(p)}{dt} = \sum_{q \neq p} C(q, p)n_qn_e + \sum_{q < p} F(p, q) + \sum_{q > p} C(p, q) + S(p) \right) n_e
\]

\[+ \sum_{q < p} A(p, q) \right) n(p)
\]

\[+ \sum_{q > p} \left[ F(q, p)n_e + A(q, p) \right] n(q)
\]

\[+ [\alpha(p)n_e + \beta(p)] n_e n_e, \tag{1}\]

where \( n(p) \) and \( n(q) \) are the excited atomic densities of hydrogen levels \( p \) and \( q \), respectively; \( C(q, p) \) 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 recombinating 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 \( \Gamma_{H^{-} \rightarrow H} \) and ionization rate \( \Gamma_{H \rightarrow H^+} \) are

\[\Gamma_{H^{-} \rightarrow H} = n(1)n_e S_{CR}, \tag{6}\]

and

\[\Gamma_{H \rightarrow H^+} = n_e n_e \alpha_{CR}, \tag{7}\]

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

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

and

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

These equations indicate the number of recombination or ionization events per photon. Figure 3 plots the number of recombinations per \( \text{H}_e \) photon and ionizations per \( \text{H}_a \) photon. These depend on the electron temperature \( T_e \) and density \( n_e \).
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 $f(E)$ 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 $H_\alpha$ and $H_\epsilon$ at a neutral gas pressure of between 0.3 and 1.0 Pa. The $H_\alpha$ intensity increases and peaks after the pulse plasma flow is introduced. On the other hand, the $H_\epsilon$ 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 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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