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Dynamic Behavior of Detached Recombining Plasmas for Plasma Heat Pulse in the Divertor Simulator NAGDIS-II

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Abstract

We will report on a comprehensive study of the dynamic response of the detached recombining plasma in the linear divertor plasma simulator. The plasma heat pulse was generated by rf heating, which can give a modification of the electron distribution functions. The negative spikes were appeared in the time evolution of the Balmer series spectra, which indicate the transition between ionizing plasmas and recombining plasmas. Detailed analysis on the time evolution was done with collisional-radiative code to reproduce the time evolution of the electron temperature.

Keywords:

detached recombining plasma, volumetric plasma recombination, edge localized mode, divertor

1. Introduction

In recent years, there has been a growing interest in plasma detachment in edge plasma physics of magnetically confinement fusion research, which is one of the most effective methods to reduce the plasma heat flux to plasma-facing components [1-3]. Recent studies on detached plasmas in fusion-related divertor plasma experiments make it clear that a volumetric plasma recombination in detached plasmas plays an essential role in strong reduction of ion particle flux along the magnetic field, resulting in a decrease in the heat flux to plasma-facing components. Continuum and a series of visible line emissions from highly excited levels due to the radiative and three body recombination (EIR) were clearly observed in tokamaks with a divertor configuration and linear divertor plasma simulators [4,5].

In next generation fusion devices, which are intended to have a long or steady state plasma, it is necessary to do well both in the reduction of plasma heat flux with the plasma detachment and good confinements such as H-mode. In the design activity of ITER, H-mode with Edge Localized Mode (ELMy H-mode), which brings an intermittent plasma heat pulse into the divertor plasma region, is one of the most important operation candidates as a good stationary confinement mode. Moreover, very complicated phenomena associated with the ELM were observed in the divertor plasma region [6,7], which have not been clearly understood yet. Therefore, we should understand dynamics of the detached plasma to the intermittent plasma heat pulse induced by ELM.

We will report on a comprehensive study of the dynamic behavior of the detached recombining plasma associated with EIR in the linear divertor plasma simulator, NAGDIS-II (Nagoya University Divertor

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Simulator). The plasma heat pulse was generated by the modulation of discharge currents in the dc discharge and/or rf heating.

In the case of the modulation of discharge currents, the time evolution of plasma parameters and helium Balmer series spectra is found to depend strongly on the neutral pressure in the divertor plasma test region. It is found that the EIR does not work enough to suppress an increase of ion flux to the target plate during the heat pulse for the detached recombining plasma at a relatively low neutral pressure. It is found that small concentration of the energetic electrons plays an important role in the dynamics response of the detached plasma [8].

In the case of rf heating, we can control the duration and power of the heat pulse by changing the duration and amplitude of the rf pulse. We have experiments on three different types of the heat pulse injected to the detached plasma: 1) long pulse ~ 0.5 msec, 2) short pulse ~ 0.05 msec and 3) train of short pulses, which are related to the frequency control of the ELM.

In this paper, we would like to mainly focus on the experimental results on 1) long pulse rf heating. Experimental results on 2) and 3) will be reported somewhere else.

2. Experimental Setup

The experiments were performed in the linear divertor plasma simulator, NAGDIS-II shown in Fig. 1. The maximum magnetic field strength is 0.25 T. Bulk helium plasmas were produced by the dc discharge between LaB_6 hot cathode and hollow anode. The plasma density can be controlled by changing the discharge current. The plasma column is terminated by the target plate with water cooling installed at the end of the vacuum chamber. The neutral pressure P can be controlled from 1.0 mtorr to 20.0 mtorr by feeding a secondary gas near the target plate.

Plasma heat pulse is produced by using rf generator with a frequency of 13.56 MHz and a maximum power of 10 kW .

Spectra of light emissions from helium atoms are detected at the axial positions of X = 1.06 m (Up), 1.39 m (Middle), and 1.72 m (Down) from the discharge anode electrode. Fast scanning probes are also installed at the same positions to measure plasma parameters. Time-averaged heat load to the target plate is estimated by measuring the temperature rise of the cooling water.

3. Experimental Results and Discussion

Plasma heat pulse generated by the rf heating was introduced into detached recombining plasmas in the divertor plasma test region. The duration of the pulse is 0.5 msec. The rf power is 2 kW. Figure 2 shows the typical time evolution of the line emission intensities from excited states (2p- n'd; T) of helium atom at the neutral helium pressure P of 5.85 mtorr, when the plasma was detached from the target plate. The time evolution is found to show very complicated dynamic behaviors. The T_e of the bulk plasma is estimated to be about 0.3 eV before the rf pulse is on. At the beginning of the rf pulse, all line emissions are found to drop rapidly in time, which means that the EIR becomes weak probably due to an increase in the kinetic energy of electrons. After the first negative spike, the emission intensities start to increase except for n'~10. Especially, the intensities from low excited states n' ~ 3 and 4 are increased to be larger than those before the rf pulse is on. They peak during the rf pulse, and gradually decrease in time after the rf pulse is off. It is found that the second negative spikes clearly appear at t ~ 1.6 msec for n' ~ 3 and at t ~ 1.3 msec for n' ~ 4.

In order to quantitatively specify the characteristics of dynamic behaviors of helium Balmer series emission, especially the negative spikes mentioned above, we have analyzed the emission intensities from the excited states of a helium atom by using collisional-radiative (CR) model (Goto-Fujimoto code) including recombining as well as ionizing components [9,10]. The population densities of the excited states of a helium atom are thought to be governed by i) EIR and ii) electron impact excitation from the ground state.

Figure 3 shows the dependence of emission intensities from n'~3 and 8 on the electron temperature T_e as a parameter of plasma density calculated with the CR model. It is proven that the electron temperature T_e^{eq} in which the emission intensity is minimized exists. The reason is that in the low T_e region, lower T_e gives larger emission intensities because the population densities of the excited states are governed by EIR. On the other hand, at the relatively high T_e, the emissions strengthen with the rise of T_e since the electron impact excitation is a dominating process. In short, the transition from the recombining phase to the ionizing phase and/or transition from the ionizing phase to the recombination phase give the negative spikes of emission intensities at T_e^{eq}. By comparing Fig. 3(a) and (b), the value of the T_e^{eq} depends on the excitation levels because the population densities in lower excitation levels are easy

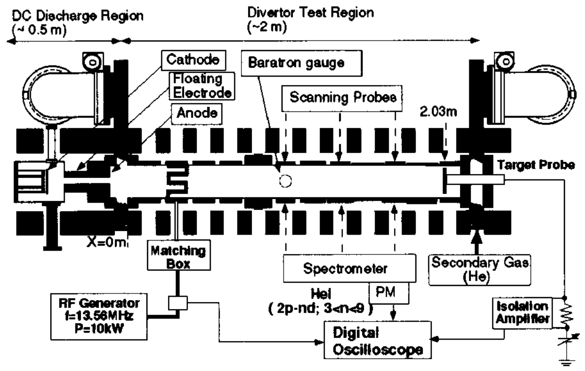

Fig. 1 Schematic of the experimental apparatus, NAGDIS-II.

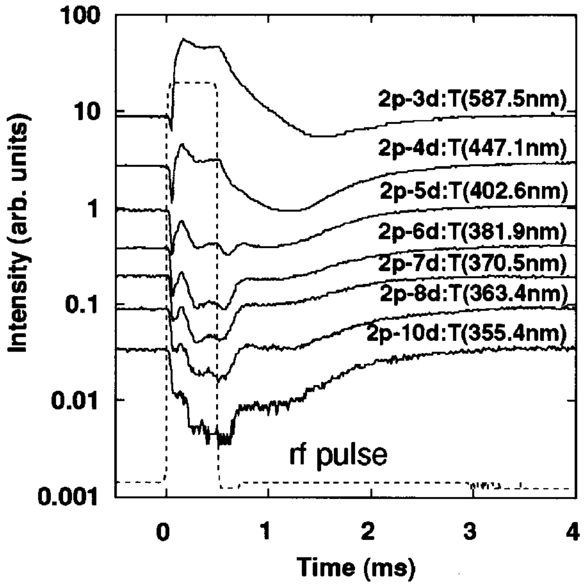

Fig. 2 Time evolution of the line emission intensities from principal quantum number n' from 3 through 10 in a fairly detached plasma at $P \sim 5.85$ mtorr.

to receive the effect of the excitation process rather than those in highly excited levels. On the recombining process, it tends to be reversed.

Based on the numerical results, we can reproduce the time evolution of the T_e by tracing back the time evolution of emission intensities from the negative spikes in Fig. 2. Figure 4 shows the reconstituted time evolution of T_e in making the second negative spikes for $n' \sim 3$ and 4 to be an origin, where the electron distribution function is assumed to be Maxwellian at any time and the plasma density is $10^{19}\mathrm{m}^{-3}$. The reconstructed time evolutions of T_e from $n' \sim 3$ and 4 match well, which means that the electron distribution

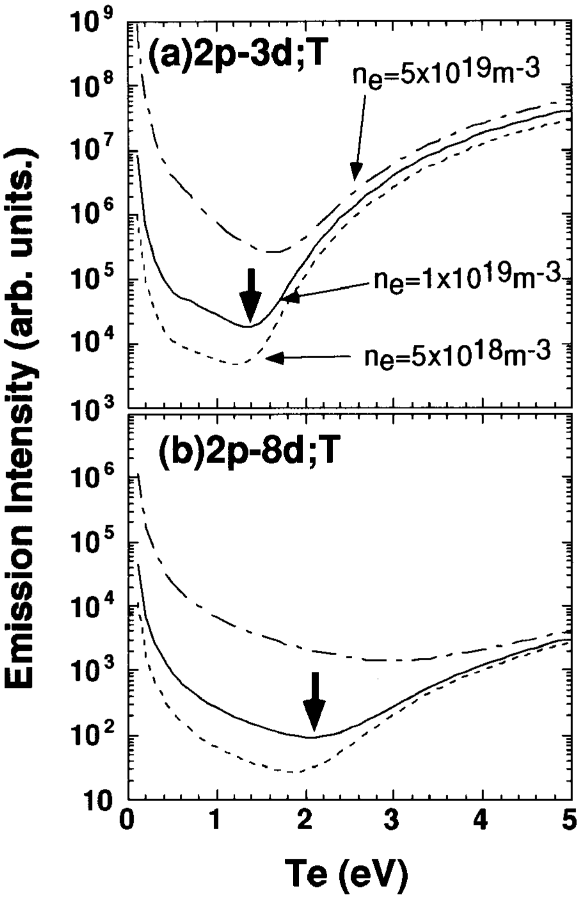

Fig. 3 Dependence of line emission intensities from principal quantum number $n' \sim 3$ and 8 on the electron temperature calculated by CR model as a parameter of plasma density.

function could be close to the Maxwellian distribution after the rf pulse. On the other hand, the first negative spikes observed at the beginning of the rf pulse can not be reproduced self-consistently, because the value of the first negative spike differs from that of second one and all the line emissions decrease simultaneously. In the case of such a rapid transition from recombining to ionizing phase observed at the beginning of the rf pulse, we should take non-equilibrium condition of atomic processes into account, in particular, non-equilibrium ionization becomes important. Usually, typical equilibrium times of ionization and recombination processes are larger than several milliseconds in our experimental conditions. The characteristic time of the first rapid transition is found to be much smaller than the equilibrium time. On the other hand, some experimental results indicate that the energetic electron could be produced at the beginning of the rf pulse probably due to the near-field acceleration. For instance, if there are assumed to be fast electrons with an energy of 25 eV and a density of $1 \times 10^{17} m^{-3}$ (0.5% of the bulk plasma density), the ionization time for an excited helium atom ($n' \sim 6$) can be estimated to be 2.0×10^{-6} s, where the cross section for the excited helium atom ($n' \sim 6$) is about $1.7 \times 10^{-10} m^2$ [8]. For helium atoms in higher excited levels, the ionization time is getting smaller, which becomes comparable to the radiative decay time for these highly excited levels. This estimation suggests that reionization due to the fast electrons is playing an important role in the net recombination, which could be related to the first negative spike. Neutral transport is also important because this reionizaiton effect depends on how fast the highly excited atoms escape from the recombining region. We should need to use the time-dependent CR model rather than the conventional CR model.

4. Conclusion

We have performed experiments on injection of a plasma heat pulse produced by rf heating to the detached recombining helium plasma to demonstrate clearly the dynamic behavior of the volumetric plasma recombination in a linear divertor plasma simulator.

The rapid transition from the recombining to ionizing plasmas at the beginning of the rf heating and slow transition from the ionizing to recombining plasmas after the rf heating were observed, both accompanied with negative spikes in Balmer series line emissions.

Time evolutions of Balmer series line emission were analyzed with collisional-radiative model, which reproduces the time evolution of the electron temperature.

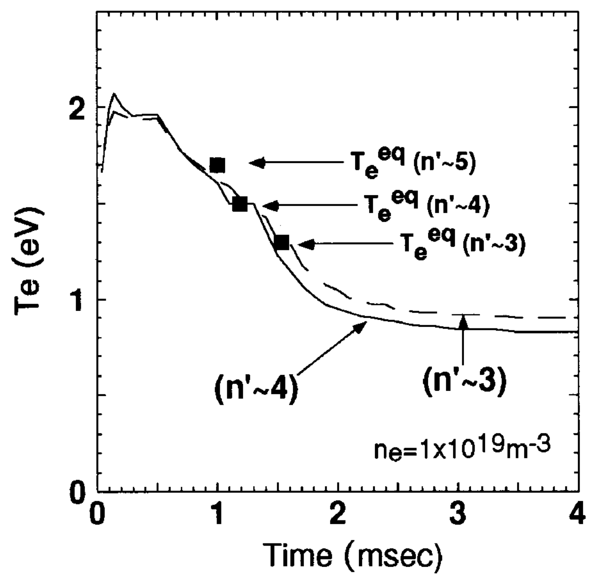

Fig. 4 Reconstructed time evolution of the electron temperature from the numerical results shown in Fig. 3.

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References

[1] D. Lumma, J. L. Terry and B. Lipshultz, Phys. Plasma, **4**, 2555 (1997).

[2] R. Isler, G. R. McKee, N. H. Brooks, *et al.*, Phys. Plasma, **4**, 2989 (1997).

[3] S. I. Krasheninnikov, A. Yu. Pigarov, D. A. Knoll *et al.*, Phys. Plasma, **4**, 1638 (1997).

[4] N. Ezumi, N. Ohno, Y. Uesugi *et al.*, in Proceedings of 24th EPS Conf. on Controlled Fusion and Plasma Physics, Berchtesgarden, (European Physical Society, Petit-Lancy) , Vol. 21A, Part III, p.1225(1997).

[5] J. L. Terry, B. Lipschults, A. Yu. Pigarov *et al.*, Phys. Plasma, **5**, 1759 (1997).

[6] A. Loarte, R. D Monk *et al.*, Nuclear Fusion, **38**, 331(1998).

[7] U. Wenzel *et al.*, J. Nucl. Mater. **266-269**, 1252 (1999).

[8] N. Ohno, M. Tanaka, N. Ezumi, D. Nishijima, S. Takamura, A. Yu. Pigarov and S. I. Krasheninnkov, Phys. Plasma, **6**, 1759 (1997).

[9] T. Fujimoto, J.Quant. Spectr. Tadi. Trans., **21**, 439 (1979).

[10] M. Goto and T. Fujimoto, NIFS-DATA-43 (1997).