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Impact of the ELM-like Heat Pulse to the Detached Recombining Plasma and its Dynamic Change Following the Heat Pulse in a Simulated Divertor Plasma

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1. Introduction

The plasma detachment is a key concept for heat and particle control in magnetically confined fusion devices. It has been recognized that the edge localized mode(ELM) associated with a good confinement at the edge region in a tokamak, such as H-mode, bring an enormous energy to the divertor target plates through the scrape off layer(SOL) and the divertor plasma. The understanding of the ELM energy transport through the SOL to the divertor plate is still poor at the moment, which leads to an ambiguous estimation of the deposited heat load on the divertor target plate in ITER[1]. We have performed a comprehensive investigation on the static and dynamic behavior of detached recombining plasmas in a linear divertor plasma simulator. The dynamic behavior of the detached recombining plasmas under ELM-like plasma heat pulse irradiation has been studied to clarify basic physical processes in the detached divertor plasmas during ELM activities.

In the present experiment the ELM-like plasma heat pulse is generated by Whistler wave heating, in which a rapid generation of energetic electrons by rf heating simulates the intermittent ELM heat pulse. The transition from detached to attached plasmas and from recombining to ionizing plasmas are identified and structural dynamics of the detached recombining plasmas along the magnetic field line is studied to understand the underlying physics.

2. Experimental Setup and Stationary Behavior of Helium Detached Plasmas

The divertor plasma simulator NAGDIS-II shown schematically in Fig. 1 has a plasma column of 2.5 m in length and about 30 mm in diameter with the magnetic field intensity up to 0.25 T. The additional gas is fed near the target plate to cool the plasma below 1 eV for plasma detachment. Fast reciprocating Langmuir probes are installed at X=0.25 m(entrance), X=1.06 m(up-stream), X=1.39 m(mid-stream) and X=1.72 m(down-stream) from the anode for DC discharge with an orifice of 24 mm. The DC discharge current of 80 A makes He plasma with n_e~4x10^{19} m^{-3} and T_e~8 eV at the entrance. With increasing the He neutral pressure around 6.5 mtorr the plasma detachment just starts as shown in Fig. 2. In the pure He plasma a low density threshold to make the plasma detachment has been identified[2] since the electron-ion energy

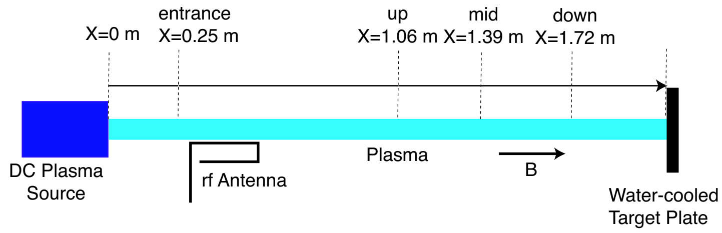

Fig. 1 Schematic configuration of the divertor simulator NAGDIS-II Axial position of probe and optical measurement and antenna position are shown.

transfer is essential for electron cooling when the ion energy is lost through the charge exchange and elastic collisions with neutrals. In the detached plasma the emission spectra show very prominent continuum radiation, connected to the He I (2^3P-n^3D) triplet series limit[3], accompanied by strong electron-ion recombination.

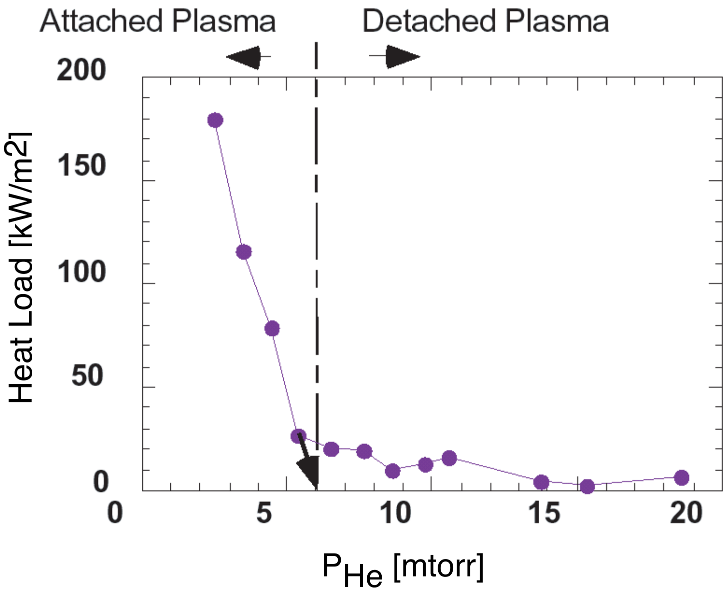

Fig. 2 Target heat flux as a function of He neutral pressure. Upstream n_e and T_e at the center are ~$2 \times 10^{19} m^{-3}$ and ~8 eV, respectively.

3. Dynamic Behavior of Plasma Detachment

3.1 Generation of the Plasma Heat Pulse

The rf heating is employed to generate the electron heat pulse. The rf antenna has 25 cmx2 folded bar along the magnetic field which is driven by 13.56 MHz in the frequency range of whistler waves[4]. In the detached plasma with $T_e < 1$ eV a strong collisional damping is expected and the most of the wave energy might be absorbed in the low T_e and high n_e detached plasma. In addition the energetic electrons must be generated by direct acceleration of the electron due to the antenna near field. The net rf power is 0.2~1 kW in the present experiment. The characteristic rise time for energetic electron generation is about 5 µs. The energetic tail formation by rf heating in the energy of 10~40 V is clearly observed in the upstream region when the detached plasma is observed.

3.2 Structural Dynamics of Detached Plasma[5]

In the following, a structural dynamics of the detached recombining plasma when the heat pulse is injected is discussed. Figure 3 shows time response of the floating voltage and ion saturation current at the plasma center, and He Balmer series emission intensity at different axial locations from upstream to the target. During the rf heating pulse both the floating voltage and emission intensity show a quick drop. The floating voltage drop usually means an increase of Te or generation of the energetic electrons if the plasma potential does not change. From the single probe measurement it has been confirmed that the plasma potential does not show such a quick and large drop. Also the emission intensity, which is mainly determined by the recombining component before the heat pulse, shows a quick drop during rf heating indicating a weakening or partial quenching of recombination in the observation region. These time response during rf heating can be explained by both the bilk electron heating in the low temperature recombining region, and the generation of the energetic hot electrons and their transport to the detached recombining region.

After the rf heat pulse, however, large reduction in both V_f and emission intensity is observed. The time corresponding to a minimum point of the floating voltage is t=0.1~0.12 ms, while the emission intensity shows much slower time behavior after the heat pulse, having the minimum point around t=0.25~0.35 ms. It seems that the floating voltage at the upstream has a minimum faster than that in the downstream, while the emission intensity has a contrary tendency as shown in Fig. 3. These complex time behavior can be explained as follows. The upstream warm plasma flows into the recombining region to compensate a partial quenching of the plasma recombination due to rf heat pulse. The time evolution of V_f and emission intensities is different because the former one is determined mainly by axial transport of the upstream hot plasmas, and the latter is determined by the balance of ionizing and recombining components of atomic level populations in collisional-radiative(CR) processes in addition to the plasma transport. On the target plate the ion flux has a large increase and a maximum corresponding to the upstream hot plasma flow in addition to the partial quenching of the detachment near the target. After the flow of the upstream hot plasma into the recombining region, a slow recovery of the plasma recombination takes place in a time scale of about 0.5~1ms.

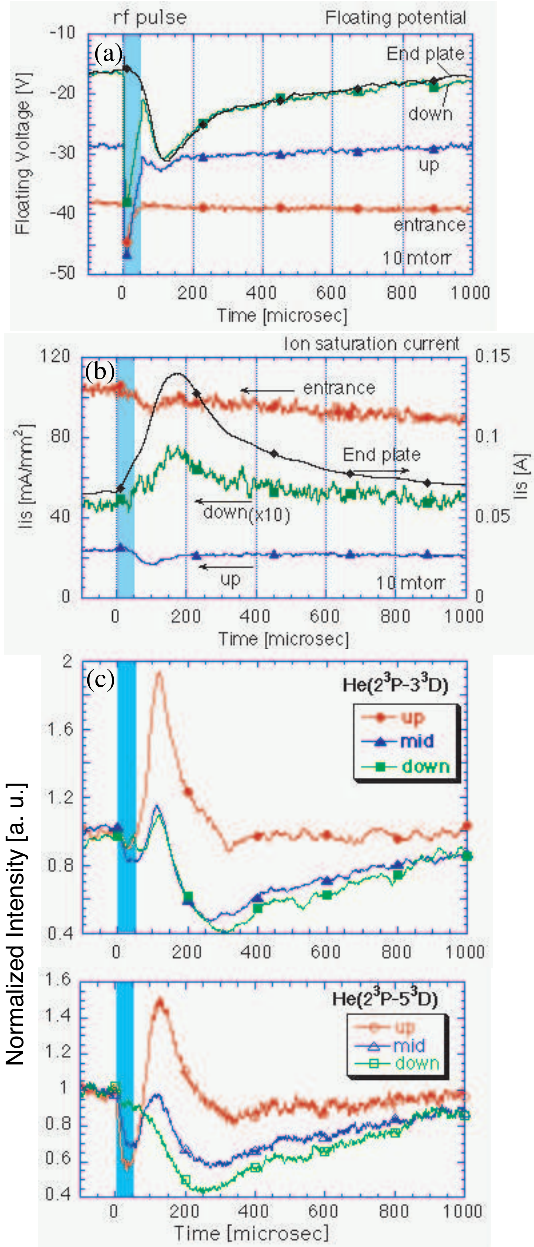

Fig. 3 Time response of the floating voltage(a), ion saturation current(b) and He Balmer series emission(c) at different axial positions. He neutral pressure is 10 mtorr and rf power and pulse duration aee 500 W and 50 µs.

Figure 4 shows a schematic structure of dynamic behavior of the electron temperature and density accompanying with the heat pulse in the detached recombining plasmas. The upstream density decreases a little due to an increase of the plasma flow velocity towards the downstream. It should be noted that a sharp drop of V_f during rf pulse comes from the arrival of energetic electrons produced by rf heating to the recombining region where the plasma density is so low that their influence for V_f appears drastically.

3.3 Response to Heat Pulse Train

A series of heat pulse with each duration of 20 µs and rf power of 200 W at a fast repetition of 10 kHz was injected to the detached recombining plasmas. The time responses of the floating potentia and ion flux to the probe are shown in Fig. 5. Slow changes in the case without rf heating in both figures come from radial movement of the probe. Even a short pulse can destroy gradually the plasma recombination, introducing the upstream warm plasma into the downstream recombining region, which appears in a floating potential drop and increase of ion flux in the downstream region. In the upstream region changes of V_f and I_s are much smaller compared with those in the downstream.

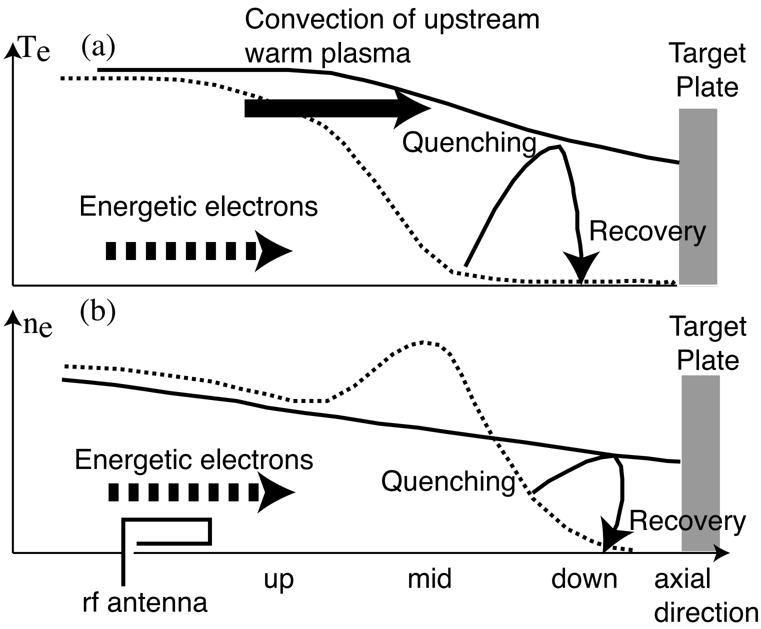

Fig. 4 Schematic structures of the dynamic behavior of the electron temperature(a) andthe electron density(b) in the detached recombining plasmas accompanying with the heat pulse along the magnetic field.

4. Summary

We have performed comprehensive studies on the dynamic behavior in detached recombining plasmas under ELM-like heat pulse irradiation. Structural dynamics were discussed based on the experimental observations. The time response of the detached recombining plasmas has quenching of the plasma recombination, compensating flow of upstream warm plasma into the recombining region and recovery of recombination. Dynamic behavior associated with the transition between recombining and ionizing plasmas was also identified. These fundamental research should contribute the further understanding of ELM activities in magnetically confined fusion devices.

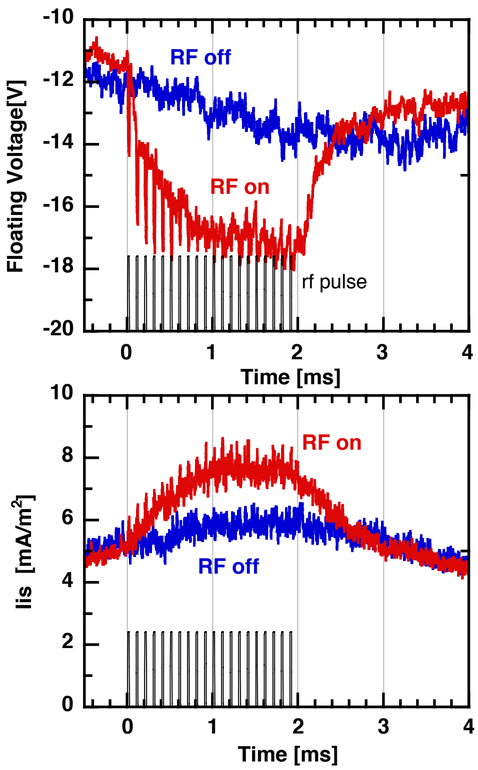

Fig. 5 Time response of V_f and ion flux of the Langmuir probe in the downstream to the heat pulse train. The rf pulse width and power are 20 μs and 200 W, respectively.

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