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Dynamic behavior of detached recombining plasmas during ELM-like plasma heat pulses in the divertor plasma simulator NAGDIS-II

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Abstract

It has been recognized that the ELMs associated with a good confinement at the edge, such as H-mode, must bring an enormous energy to the divertor target plate through SOL and detached plasmas. The understanding of the ELM energy transport through SOL to the divertor target is rather poor at the moment, which leads to an ambiguous estimation of the deposited heat load on the divertor target in ITER. In the present work the ELM-like plasma heat pulse is generated by rf heating in a linear divertor plasma simulator. Energetic electrons with an energy range 10–40 eV are effectively generated by rf heating in low temperature plasmas with $\langle T_e \rangle < \sim 1$ eV. It is observed experimentally that the energetic electrons ionize the highly excited Rydberg atoms quickly, bringing a rapid increase of the ion particle flux to the target, and make the detached plasmas attached to the target. Detailed physical processes about the interaction between the heat pulse with conduction and convection, and detached recombining plasmas are discussed.

Keywords: Divertor plasma; Divertor detachment; ELM

1. Introduction

A steady state, long pulse operation with well-confined plasma, accompanied by a reduced divertor heat load is one of the key issues in the next generation fusion devices. Particle and heat load reduction to the divertor target by forming detached recombining divertor plasmas has been investigated experimentally and substantial heat load reduction has been obtained in a quiescent H-mode plasma without edge localized modes (ELMs) or between ELMs [1,2]. It has been recognized that ELMs associated with a good confinement at the edge, such as H-mode, must bring an enormous energy to the divertor target plate through the SOL and detached plasmas. It is estimated that such a large transient heat load to the divertor target during type-I ELMs can easily exceed the heat load limit of the target evaporation in ITER. The understanding of the ELM energy transport through the SOL to the divertor target is rather poor at the moment, which leads to an ambiguous estimation of the deposited heat load on the divertor target in ITER [3,4].

So far, the transient behavior of the detached recombining plasmas during ELM activities has been studied by observing Hα/Dα and impurity line emission in addition to the divertor probe measurements. In JET [1] and ASDEX-U [5], so-called negative (or inverse) ELMs are observed in the Hα/Dα emission from the detached recombining divertor plasma responding to the ELM. This inverse response in Hα/Dα emission to the ELM is explained by the electron temperature increase associated with the ELM pulse and convective transport along the magnetic field. In the present work, the ELM-like plasma heat pulse is generated by rf heating in the frequency range of Whistler waves in the linear divertor plasma simulator NAGDIS-II. Just a small change of the electron energy distribution is

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expected to modify the properties of the detached recombining plasmas drastically as shown by a previous work [6,7].

2. Generation of energetic electrons by rf heating

In order to study the dynamic processes in the divertor plasmas with ELMs, a rapid change of the temperature and density within less than several 10 μs is required. In the present experiment, the ELM-like plasma heat pulses with a pulse duration of 20–500 μs are generated by rf heating using 13.56 MHz Whistler waves in the linear divertor plasma simulator NAGDIS-II. The electron–ion collisional damping of Whistler waves is expected to work for effective electron heating in a very low temperature plasma like a detached recombining plasma below $T_e \sim 1$ eV. The net rf power injected to the plasma is about 0.1–2 kW, and time behavior of the electron energy distribution function and visible light emission from helium atoms are measured at different axial positions by fast scanning Langmuir probes and a monochromator, respectively. A schematic diagram of the heat pulse experiment is shown in Fig. 1. A single turn loop antenna is located at an upstream region about 1.5 m away from the end plate. With increasing the helium neutral pressure P_n from about 0.4–0.8 Pa the electron temperature decreases from about 6 eV to below 1 eV near the target end plate and the plasma becomes marginally detached from the target as shown in Fig. 2. In a relatively low neutral pressure plasma of about 0.4 Pa the generation of the energetic electrons is weak since the electron temperature is too high for collisional damping. By increasing the neutral pressure to 0.8 Pa, however, it becomes significant. In Fig. 3 the electron current density obtained from single probe *V–I* characteristic curves is shown at different times. A spectroscopic measurement of detached recombining plasmas shows that the electron temperature is about 0.2 eV at the downstream region [7], which is low enough for effective collisional damping. The energetic electrons with an energy of 10–40 eV are generated by rf heating in a helium neutral pressure range above $P_n = 0.8$ Pa. The characteristic rise time for energetic electron generation by rf heating is about 5 μs. The energetic tail formation by rf heating is clearly observed in the upstream region. In the downstream region the energetic electrons seem to be thermalized. In the present rf heating experiment the wave dispersion and damping have not been measured yet. Both, the electron collisional damping of the excited waves and the near field excitation of the antenna might be related to the energetic electron production in the present rf heating experiment.

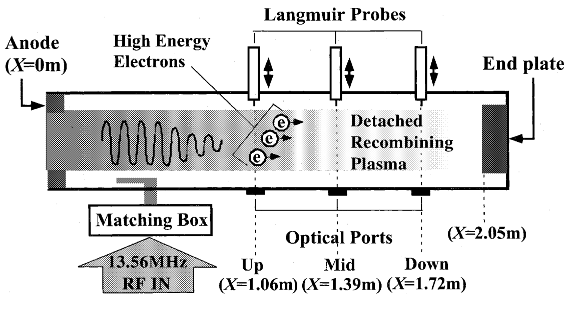

Fig. 1. Schematic diagram of the ELM-like heat pulse experiment in NAGDIS-II.

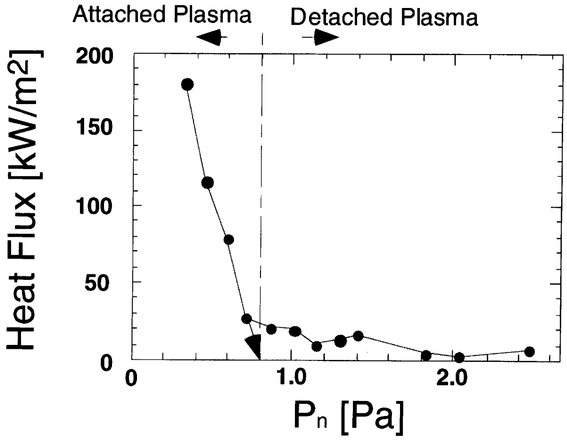

Fig. 2. Target heat flux as a function of the helium neutral pressure. The electron temperature and density in the upstream region is about 5 eV and $1\text{–}2 \times 10^{19}$ m^{-3}, respectively.

3. Dynamic response of the detached recombining plasmas

The dynamic behavior of the detached recombining plasmas to the ELM-like heat pulse is studied by observing the time response of the ion particle flux and floating potential using Langmuir probes, and visible light emission from helium neutral atoms. In Fig. 4 emission spectra from attached and detached helium plasmas in a steady-state condition are shown. When the plasma is detached series spectra from highly excited helium atoms and continuum are clearly observed as shown in the figure. The dynamic response of the light emission from helium atoms to the heat pulse irradiation at different axial positions is shown in Fig. 5. At $P_n = 1.1$ Pa the downstream region is deeply detached, but the upstream region is away from detached recombining plasmas. When the heat pulse comes to upstream region the emission from low excited neutrals (2p–3d;*T*) is increased by an enhanced excitation from the ground state due to electron temperature rise. In the detached

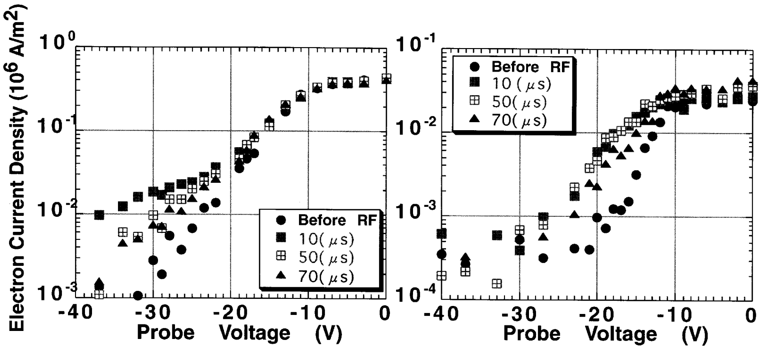

Fig. 3. Electron current as a function of the probe biasing voltage in the upstream and downstream regions. The rf power is about 200 W with a duration of 50 μs. The neutral pressure is about 1.1 Pa.

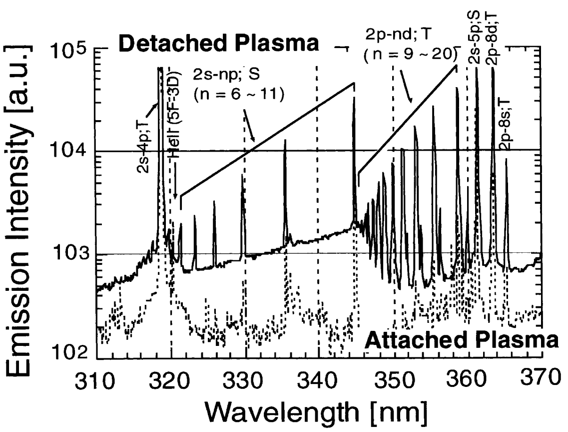

Fig. 4. Visible light emission from attached (dotted line) and detached (solid line) helium plasmas in a steady-state condition.

downstream region the emission from low excited and highly (2p–9d;T) excited atoms is reduced significantly due to suppression of the recombination by energetic electron irradiation. These in-phase and out-of-phase changes of the emission intensity have been observed in Hα emission in ASDEX-U [5]. It is also shown that the time behavior of the emission from the upstream (2p–3d;T) has a different time scale from that in downstream. The minimum and maximum points of the emission intensity have significant time delay about 0.1–0.2 ms from a switch-off of the rf pulse. The reason for this time delay is not clear.

Fig. 6 shows the response of the detached recombining plasmas to the heat pulse generated by rf heating. The inverse ELMs which have been observed in JET [1] and ASDEX-U [5] for Dα emission are also found here to have a double minimum in time for the Balmer series emission from low excited levels and strong reductions of spectral intensities from highly excited levels. This time behavior shows the transition from recombining to ionizing plasma with rf heating and again back to recombining plasma after switch-off of the rf pulse. From Fig. 6 it is indicated that the heat pulse, mainly due to energetic electrons, first ionizes the highly excited Rydberg atoms making the target ion flux increase, but no energetic electrons can reach the target due to a large ionization cross-section of Rydberg atoms. The increase of the target ion flux must be related to the density of Rydberg atoms in the detached recombining plasmas. After most of Rydberg atoms are re-ionized, then the excitation from the ground state starts after 50 μs, and

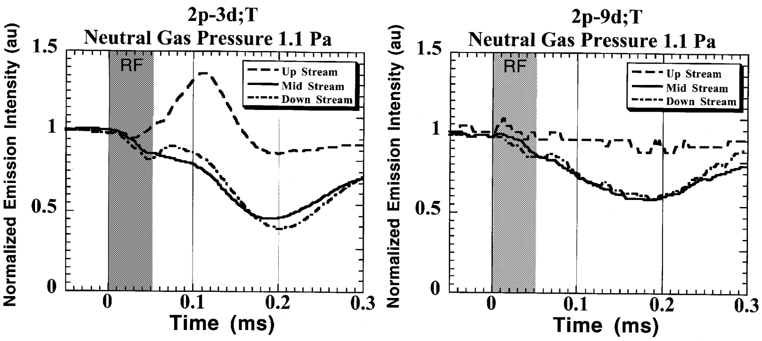

Fig. 5. Time behavior of the helium neutral line emission from different axial positions. The applied rf power is about 200 W.

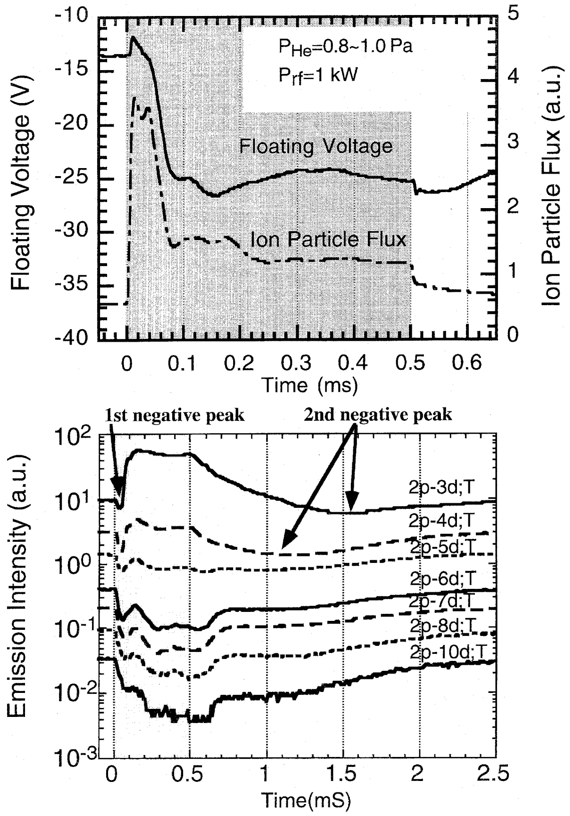

Fig. 6. Time behavior of the target ion particle flux and floating voltage (top) and helium Balmer line intensity observed in the downstream region (bottom). The rf power of about 1 kW is injected in the shaded region.

the energetic electrons arrive at the target, decreasing substantially its floating potential.

4. Summary

The rf heating at a frequency range of Whistler wave can effectively generate energetic electrons in a very low temperature plasma with $T_e < 1$ eV, such as the detached recombining plasmas. The energetic electron irradiation to the detached recombining plasmas strongly modifies the recombination processes in detached plasmas. It is indicated experimentally that the heat pulse, mainly due to energetic electrons, first re-ionizes the highly excited Rydberg atoms making the target ion flux increase, but no energetic electrons can reach the target due to a large ionization cross-section of Rydberg atoms. After re-ionizing most of Rydberg atoms the energetic electrons can reach the target. During the heat pulse irradiation, highly excited Rydberg atoms absorb the energy of energetic electrons, transferring the electron kinetic energy to the ion internal energy. The dynamic behavior of the light emission from the detached recombining plasmas during ELM-like heat pulse irradiation cannot be explained by the conventional collisional radiative model but motivates us to develop a time-dependent CR modeling. The detailed physical processes about the interaction between the heat pulse with conduction and convection, and detached recombining plasmas provide the ideas about the energy dissipation of ELMs through SOL including the detached region.

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