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Detached plasma control by negative ion in divertor simulator

M. Ono [a,*], A. Tonegawa [a], K. Kumita [a], T. Shibuya [b], K. Kawamura [b]

[a] *Department of Physics, School of Science, Tokai University, 1117, Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan*
[b] *Course of Applied Science, Graduate School of Engineering, Tokai University, Japan*

Abstract

We have developed a new way to stably maintain a detached plasma based on feedback control of the negative hydrogen ion (H^-) density in the linear divertor plasma simulator, TPD-SheetIV. Measurements of the negative hydrogen ion density, n_{H^-}, the heat load to the target plate, Q, and the secondary gas-flow rate, G_{Div}, were carried out as a function of neutral pressure in the plasma. A small amount of secondary gas puffing strongly reduced Q and rapidly increased n_{H^-} in the periphery of the plasma without increased radiative and three-body recombination. The detached plasma is steadily maintained in the region of the target plate by rapidly varying G_{Div} so as to maximize the value of n_{H^-} and keep P_{Div} constant. The new system has achieved the goal of reducing both Q and amount of G_{Div} in a detached plasma.

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Keywords: Divertor diagnostic; Heat load reduction; Volume recombination; H_2 flow rate

1. Introduction

Volumetric recombination in detached plasmas is expected to play an essential role in strongly reducing the heat flux to the divertor plates [1,2]. Stable maintenance of a detached plasma, then, is a key issue associated with reducing the heat flux on to the divertor plates. The most attractive feature of the divertors has been the expected capability to create a dense and cold detached plasma with low neutral back flow to the main plasma. It was discovered empirically that the transition to an X-point MARFE could be prevented by feedback control of the gas injector on the pressure in the pumped W-shaped divertor of JT-60U [3]. However, a loss of plasma pressure often only occurs along a narrow flux surface region of a few millimeters width and often occurs only near the separatrix. This partially detached plasma is produced in a narrow zone between the high and low temperature divertor regions [4]. The partially detached plasma is a very complex phenomenon with atomic and molecular collision processes. It is difficult to control the detached and partially detached plasmas by commonly used diagnostics, such as heat loads, langmuir probes, etc.

In tokamaks with a divertor configuration, electron-ion recombination (EIR) has been clearly identified in detached plasmas by measurements of high-n Balmer series spectral lines [5]. On the other hand, another recombination process associated with molecular reactions, such as the molecular assisted recombination (MAR) involving a vibrationally excited hydrogen

* Corresponding author. Tel.: +81 463 58 1211x3710; fax: +81 463 50 2013.
E-mail address: tone@keyaki.cc.u-tokai.ac.jp (M. Ono).

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molecule $H_2(v)$, has been emphasized in theoretical investigation and modeling [6,7]. In detached and partially detached divertor conditions with low plasma temperature, $H_2(v)$ contributes via dissociation and ionization processes to plasma volume recombination. Thus, the plasma volume recombination associated with $H_2(v)$, that is MAR, is effective in the divertor plasma to enhance the reduction of ion particle flux over EIR. However, the role of the MAR in fusion experiments is still under discussion and different conclusions have been derived from the analysis of different experiments [8–12].

Recently, we have presented the experimental observation of the spatial structure of MAR (including both the mutual neutralization and dissociative recombination channels) in the detached hydrogen plasma at the periphery of the plasma in the linear divertor plasma simulator, TPD-SheetIV [12]. It is shown from the results of mass-analysis (H^+, H_2^+, H_3^+) that dissociative recombination is dominant in the center of the plasma over a range of low gas pressures [13]. At the same time, it is observed that the mutual neutralization in MAR via H^- ion formation, which is produced by dissociative electron attachment to $H_2(v)$, occurs in the periphery of the plasma where cold electrons ($\sim$1 eV) are found [14]. In other words, H^- ions play an important role in the mutual neutralization of MAR, providing a new method of controlling detached plasmas.

In this paper, we have developed a new method to control a detached plasma based on utilizing H^- ions which are formed as part of the MAR mutual neutralization process occurring in the periphery of the plasma on the linear divertor plasma simulator, TPD-SheetIV.

2. Experimental apparatus and method

The experiment was performed in the linear divertor plasma simulator TPD-SheetIV as shown in Fig. 1. Ten rectangular magnetic coils formed a uniform magnetic field of 0.04 T in the experimental region. The hydrogen plasma was generated at a hydrogen gas flow of 70 sccm, with a discharge current of 100 A. The neutral pressure $P_{\rm Div}$ in the divertor test region was controlled between 0.1 and 20 mtorr with a secondary gas feed. Electron temperature and electron density were measured by a planar Langmuir probe located 3 cm in front of the target. The heat load on the target plate Q was measured by a calorimeter. At a discharge current of 100 A, the value of Q reaches about 1 MW/m^2. A cylindrical probe made of tungsten ($0.4\phi \times 2$ cm) was used to measure the spatial profiles of the negative hydrogen ion density (n_{H^-}) by a probe-assisted laser photodetachment method at a repetition rate of 50 Hz. The Nd-YAG laser had an energy per pulse of 100 mJ at its fundamental wavelength

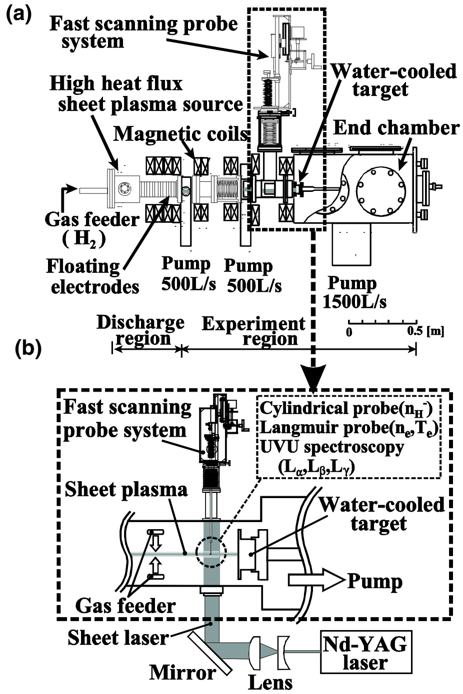

Fig. 1. Schematic diagram of (a) the divertor simulator, TPD-SheetIV and (b) schematic of a divertor controlling system.

of 1064 nm. A combination of spherical and cylindrical optics was used to produce a laser sheet having typical dimensions of 4.0 cm in width and 1.0 cm in thickness at the vacuum chamber as shown in Fig. 1(b). The value of n_{H^-} was determined from the photodetached electron current measured with a cylindrical probe. The spatial profile of the negative ions was measured by moving the probe across the laser sheet which is incident perpendicular to the sheet plasma. The Lyman Rydberg series lines of neutral hydrogen were measured at an axial distance of 3 cm in front of the target with a CCD camera-equipped VUV spectrometer coupled with a differential pumping system to a side port on the target vacuum chamber. The brightness of the high-n Lyman series lines, such as L_γ, are directly related to the recombination rate of EIR. Therefore the ratio of L_γ(4–1) to L_α(2–1) line intensities can be used as an indicator of EIR.

The concept of control of a detached plasma using negative ions can be illustrated through the following steps: (1) determine the minimum and maximum basic parameters (gas pressure $P_{\rm Div}$, heat load Q) required to control the MAR, (2) control the secondary gas-flow rate $G_{\rm Div}$ rapidly so as to maximize the value of the negative ion density n_{H^-}, (3) carry out a real time feedback control of n_{H^-} in order to maintain a steadily detached plasma in the neighborhood of the target plate.

3. Experimental results

Fig. 2 shows the effect of hydrogen neutral gas pressure, P_{Div}, on the heat to the target plate, Q, the hydrogen Lyman spectrum ratio, L_γ/L_α, the maximum value in the plasma of the hydrogen negative ion density, n_{H^-}, the electron density, n_e, and electron temperature, T_e, at a discharge current of 50 A. The electron density, n_{ec}, n_{ef}, and temperature, T_{ec}, T_{ef}, in the center and at the periphery of the sheet plasma respectively, were measured by Langmuir probes. The electron density has a hill-shaped profile with a half width of about 5.0 mm in the sheet plasma. Also, the sheet plasma has a steep electron temperature gradient over a plasma thickness of several millimeters: a hot plasma (~15 eV) in the central region and a cold plasma (1–2 eV) in the periphery region [12–14]. In the center of the plasma, the value of n_{ec} increases slightly, and T_{ec} decreases rapidly from 15 to 10 eV due to ionization, until $P_{Div} \sim 2$ mtorr. Above $P_{Div} \sim 2$ mtorr, T_{ec} falls below less than 5 eV, and n_{ec} gradually decreases. On the other hand, in the periphery of the plasma, n_{ef} has a lower value and T_{ef} is less than 1–2 eV. The H^- ions of the periphery are localized in a circumferential region of about 10–20 mm distance from the center in the direction of thickness of the sheet plasma. Using a small amount of secondary hydrogen gas puffing into a hydrogen plasma, n_{H^-} has a maximum value of 1.0×10^{17} m^{-3} at $P_{Div} \sim 3.0$ mtorr. With an increase in P_{Div}, the value of Q is found to decrease rapidly from 0.32 to 0.1 MW/m^2, a value less than 30% of the initial value in the attached plasma for $P_{Div} < 3.0$ mtorr, while the hydrogen Lyman spectrum ratio L_γ/L_α of VUV emission remains nearly constant. With an increase of P_{Div} to ~4 mtorr, n_{H^-} disappears and L_γ/L_α is observed in front of the target plate. The ratio L_γ/L_α rapidly increases above $P_{Div} \sim 6$ mtorr. At the same time, the intensities of the hydrogen Lyman series from $n = 3$ to 6 due to the EIR were observed in front of the target (full detachment region), that is, the radiative and three-body recombination processes have appeared. It is found that feedback control on the negative ion density is the only process allowing a factor of two reduction of the initial heat flux onto the target without strong radiation loss from EIR.

By defining Q_{att} as the heat load in attached plasma and Q_{pm} as the heat load at the maximum negative ion density for a particular pressure $n_{H^-_{max}}$, we can express the reduction of the heat load as the ratio of Q_{att} to Q_{pm}, that is, $\Delta Q = Q_{pm}/Q_{att}$. The variations of $n_{H^-_{max}}$, heat load Q_{att}, Q_{pm}, and the head load radio ΔQ with the discharge current I_d is shown in Fig. 3. As I_d changes from 50 to 100 A, Q_{att} increases from 0.32 to 1.1 MW/m^2. At the same time, $n_{H^-_{max}}$ increases linearly from 1.8

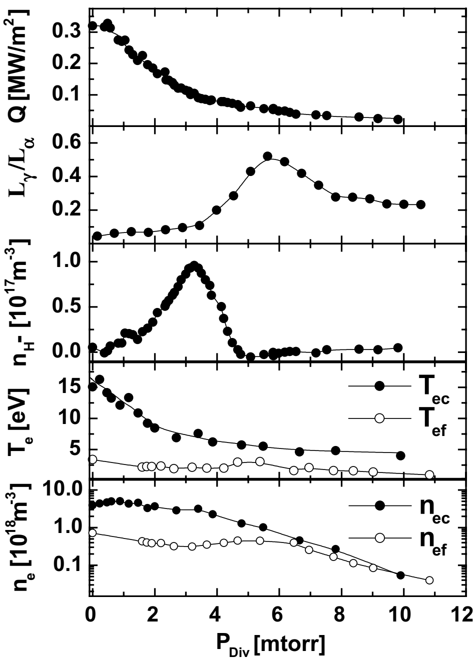

Fig. 2. The effect of hydrogen neutral gas pressure P_{Div} on heat load to the target plate Q, the hydrogen Lyman spectrum ratio L_γ/L_α of VUV light emission and the maximum value across the column of the negative ion density of hydrogen atom, n_{H^-}, the electron density, n_e, and electron temperature, T_e, at a discharge current of 50 A.

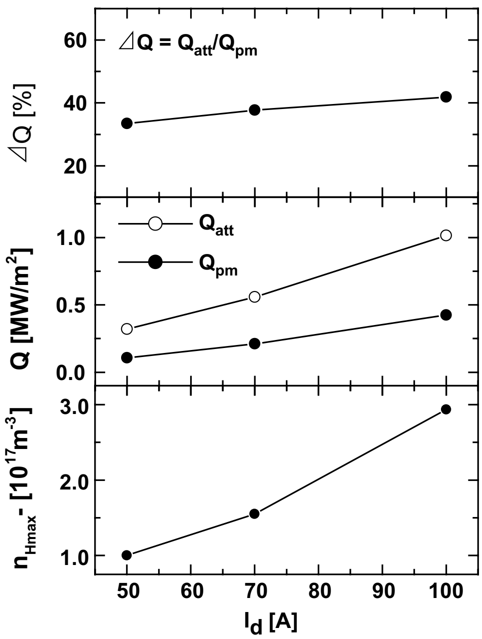

Fig. 3. The variations of $n_{H^-_{max}}$, heat load Q_{att}, Q_{pm}, and the heat load ratio ΔQ with the discharge current I_d. The efficiency of the reduction of the heat load is defined as $\Delta Q = Q_{pm}/Q_{att}$.

to $5.1 \times 10^{16}\,\mathrm{m}^{-3}$ and Q_{pm} increases from 0.1 to 0.4 MW/m^2. Therefore, ΔQ remains nearly constant at around 30–40% with increasing heat load to the target. The negative hydrogen ions are produced by the dissociative electron attachment to $H_2(v)$ in the periphery of the high density plasma. These results indicate that this new way of controlling a detached plasma, based on the feedback control of the negative hydrogen ion density in the high density part of the plasma, is promising.

Fig. 4 shows the time traces of the secondary gas-flow rate, G_{Div}, the neutral gas pressure, P_{Div}, the negative ion density of hydrogen atom, n_{H^-}, the heat load to the target, Q, and discharge current, I_d, using feedback control of the divertor plasma. At 480 and 960 s, the value of I_d changes from 50 to 70 A and from 70 to 100 A, respectively. Both Q and P_{Div} are depressed by feedback control of the detached plasma based on negative ion formation in the periphery of this plasma. The value of Q and P_{Div} stay low at around 0.2–0.3 MW/m^2 and 3–4 mtorr, respectively, with increasing I_d. It is found from this experiment that the detached plasma is maintained steadily in the region of the target plate under feedback control using the secondary gas-flow rate so as to maximize the value of the negative ion density and keep the neutral pressure constant. Also, it is found that this system adapts well to rapid changes of the discharge current. This new system has achieved the goal of reducing both heat flux and gas flow rate in a detached plasma.

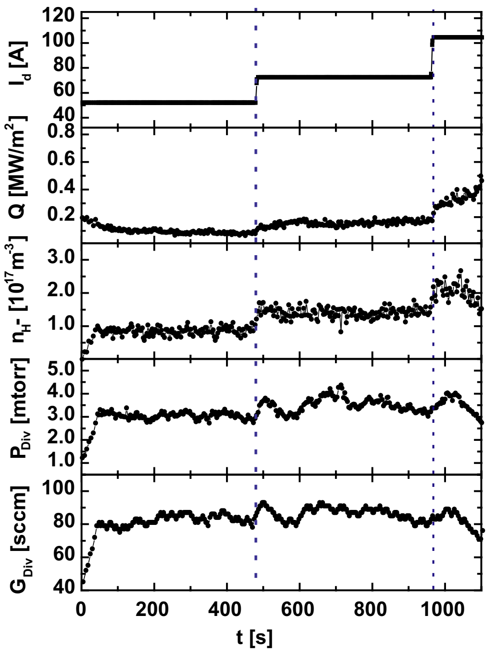

Fig. 4. Temporal behaviors of the secondary gas-flow rate, G_{Div}, the neutral gas pressure, P_{Div}, the negative ion density of hydrogen atoms n_{H^-}, the heat load to the target, Q, and discharge current, I_d, under feedback control of the divertor plasma.

4. Summary

We have developed a new way to stably maintain a detached plasma based on the feedback on the level of H^- which is produced in the course of the mutual neutralization of MAR in the periphery of the plasma on the linear divertor plasma simulator, TPD-SheetIV. It is found from the experiment that the detached plasma is steadily maintained in the neighborhood of the target plate under feedback control of the secondary gas-flow rate so as to maximize the value of the negative ion density at constant neutral pressure. The new system has achieved the goal of reducing the target heat flux while simultaneously minimizing the amount of gas puffed in a detached plasma without radiative and three-body recombination processes.

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