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Modification of hydrogen recycling due to edge ergodic magnetic layer in long tokamak discharge with high duty

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Abstract

The effect of ergodic divertor (ED) on the particle balance in the plasma–wall system is investigated. It is found that in the short timescale 2–3 s at the beginning ED effectively increases the recycling wall area and enhances wall pumping by connecting the field lines to the wall. But in long timescale greater than several seconds ED brings an early termination of wall pumping due to the localization of recycling area around the X-region. A zero-dimensional model reproduces the observed behavior on the particle balance over the long timescale.

Keywords: Ergodic divertor; Hydrogen recycling; Modeling wall pumping

1. Introduction

Experiments on long timescale tokamak discharge becomes increasingly important for the future long pulse operation in fusion devices. Particularly in a timescale longer than the wall retention time, the neutrals thermally released from the wall would considerably affect the history of discharge. However, since such a long timescale experiment under the condition of wall saturation has not been brought about so far, except for a few experiments in Tore Supra [1–3] and TRIAM-1M [4], the behavior of plasma–wall system over such a long duration is not well understood. The concept of the dynamic ergodic divertor (DED) [5,6] has the potential to control SOL characteristics in terms of hydrogen recycling due to the rotation of an edge plasma associated with a pump limiter. Therefore, the effect of DED on the behavior of long tokamak discharge is one of the attractive topics in tokamak physics. But the fundamental understanding of the effect of ergodic divertor (ED) on the particle balance in the plasma–wall system has not been established particularly in the long timescale. In this paper we focus our interests on the effect of ED to the particle balance. Particularly, the long timescale effects of its near field are studied because the helical field coils give rise to the periodic magnetic field structure near the wall, and such a structure would considerably affect the recycling and particle balance between the plasma–wall system. In addition to that, the numerical analysis using a simple zero-dimensional model is attempted to describe the long timescale behavior of particle balance.

2. Experimental setup

CSTN-III has the major radius of 0.4 m and the minor radius of 0.1 m. A turbomolecular pump evacuates the vacuum chamber with the pumping speed of 244 l/s at the operating pressure range. The mass flow controller keeps the hydrogen gas feed rate constant at around 6 ccm (cm^3/min). Both Joule and vertical field coils are powered independently by the pulse width modulation (PWM) invertor power supply which is controlled with LabVIEW (National Instruments) on a personal computer [7–9]. Such a system gives us a flexible control of the plasma current and its equilibrium position, by carefully adjusting the supply current waveforms. The machine has no limiter and the plasma mainly contacts on the outerboard wall. The local helical field coils are

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installed on the vacuum vessel at eight toroidal sections among 16 with poloidal and toroidal mode number $(m, n) = (6, 1)$ [5]. In the present experiments, the helical coil current was set to 42 A for the whole ED discharge. The toroidal magnetic field is kept at around 0.09 T in steady state, and the initial neutral gas pressure around 3.0×10^{-4} Torr. The electron density and temperature at the edge were measured with a triple probe and the line-averaged electron density with microwave interferometer. The time evolution of neutral gas pressure was measured with a baratron pressure sensor (whose time constant is less than 20 m) as well as an ionization gauge, and the wall temperature with the infrared TV (IRTV) camera (Thermovision 900, AGEMA).

In a series of experiments we employed the high-repetition high-duty tokamak operation, which simulates the long pulse discharge, by integrating 4000 tokamak shots over 60 s [10]. Fig. 2(d)–(g) shows the first six shots of the high repetition discharge with a duty factor of 50%, $I_p \sim$ 960 A, flat top ~6 m. Plasma current and loop voltage do not change when ED is applied while T_e increases and n_e decreases at $(x, z) = (9, 1)$ cm.

A simple but effective wall conditioning was carried out before each long discharge, and we have confirmed that the results obtained in the present experiment are reproducible with such a conditioning.

3. Results and discussion

3.1. Modification of edge plasma structure due to ED

A resonant helical magnetic perturbation breaks the magnetic surface at the edge and makes the field line structure stochastic [5]. But at the region very close to the wall there appears a periodic structure made of the regions where the dots become dense (X-region) or thin (O-region) [5]. It means that the field line coming from the interior connects to the wall at the X-region. Therefore, the hydrogen recycling is expected to be enhanced at X-regions.

There has been a comprehensive analysis of the heat deposition with considering the connection length of the field lines and the energy transport in the stochastic boundary [11]. But in the present case we have already found a good correspondence between the maximum points of ion particle flux and X-regions [5], where it was observed that the ion saturation current at the X-region much exceeds that at the O-region. It is confirmed from the IR camera measurements of the wall temperature as shown in Fig. 1 The points SP01 and SP02 correspond to the O-region and SP03 does to the X-region. It is observed that the wall temperature at the X-region becomes higher than those at the other regions when ED is applied. The temperature modulation on the wall comes from the localization of plasma heat flux at X-region.

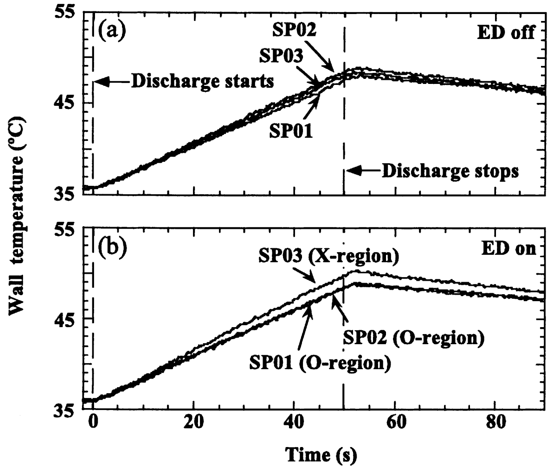

Fig. 1. Temporal evolutions of wall temperature at the three points, SP01, SP02 and SP03 during the whole duration of discharge in the case with (b) and without (a) ED. SP01, 02 correspond to O-region, SP03 X-region respectively on the outer wall at the #9 section. The increase in wall temperature is around 15°C/min.

3.2. Effects of ED on particle balance

Fig. 2(a)–(c) displays the change of various parameters at the first 2 s of the long pulse discharge. The gas pressure which was measured with the baratron rapidly decreases at the first 200 m and comes to increase slowly after that. T_e, n_e at the edge and the averaged density $\langle n_e \rangle$ behave in the similar timescales as the gas pressure. The number of atoms absorbed on the wall, $N_w - N_{w_0}$, was estimated with

$$N_w - N_{w_0} = (N_{n_0} + N_{p_0}) - (N_n + N_p) + \int_0^t (\Gamma_{in} - \Gamma_{out})\, dt, \tag{1}$$

where N_w, N_n and N_p are the numbers of atoms at the wall, of neutrals in the vacuum chamber, and of plasma particles, respectively. Γ_{in} and Γ_{out} are the gas feed rate and the pumping rate, respectively. The latter is given by $(N_n/V) \times 244$ l/s where V is the inner volume of vacuum chamber. N_{w_0}, N_{n_0} and N_{p_0} mean initial values at $t = 0$. There is a strong wall pumping at the first 200 m, and 5.0×10^{18} atoms are absorbed on the wall during first 2 s.

In this first stage of long duration, it is observed that in the case with ED the gas pressure shows a little bit deep drop compared to the normal discharge as shown in Fig. 3. It implies that the wall pumps more particles in the ED discharges than in the normal ones. This is considered to come from the increase in the area of the wall pumping at the inboard side due to ED. Since the plasma is usually located at 2 cm outside from the center

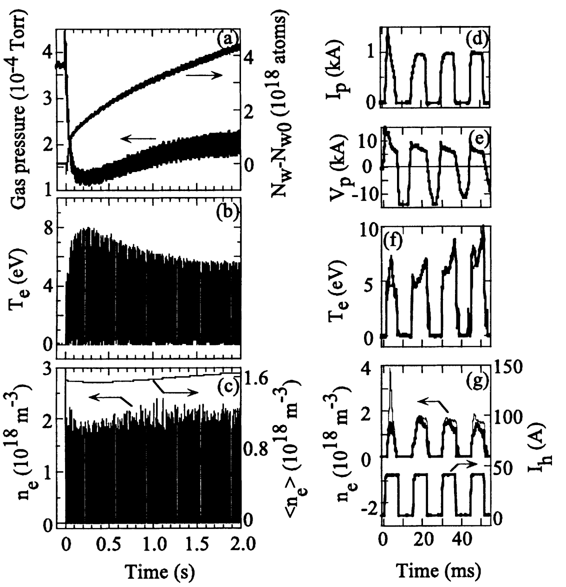

Fig. 2. (a)–(c) Traces of gas pressure, number of neutrals absorbed on the wall, electron temperature, electron density at (9, 1) cm and averaged electron density $\langle n_e \rangle$. (d)–(g) Traces of plasma current, loop voltage, electron temperature, electron density and helical coil current for first six shots. Thick lines for ED on and thin lines for ED off. Triple probe is located at (x, z) = (9, 1) cm which corresponds to the O-region.

of chamber and does not interact with the inboard side compared with outerboard if ED does not work, the field line connection to the inboard with the application of ED results in the increase of wall pumping. In the first 1 s, there is no difference in $\langle n_e \rangle$ between both cases of ED on and off. This is considered due to the strong wall pumping in both cases, so that the effect of ED on $\langle n_e \rangle$ may not come out at the moment. But, as the wall saturates in the normal discharge after $t = 1$ s, then the neutral supply is enough to increase the plasma density.

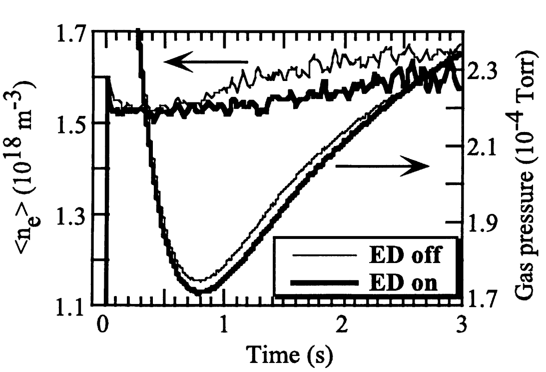

Fig. 3. Traces of $\langle n_e \rangle$ and gas pressure at the initial 3 s in both cases with and without ED.

On the other hand, the discharge with ED needs a longer time to have a enough neutral supply from the wall because of an enhanced wall pumping.

Fig. 4(a) and (b) shows the temporal evolutions of gas pressure, $\langle n_e \rangle$ and number of atoms absorbed on the wall during the whole duration of the long discharge in both cases with and without ED. The jump of gas pressure observed at around the instant of discharge termination $t = 50$ s is caused by a large amount of neutral gas desorption from the wall. From Fig. 4(a) it is seen that the wall absorbs the hydrogen up to 1.2×10^{19} atoms which corresponds to the one mono layer on the wall of CSTN-III vacuum chamber, and that the hydrogen on the wall saturates at around $t = 25$ s. Thereafter, the wall starts to desorb the neutrals which is due to the decrease of wall retention time coming from the wall temperature evolution (Fig. 1), and continues to desorb the neutrals after the discharge termination. The gas pressure rises to 3.0×10^{-4} Torr in the similar timescale as the wall inventory after the strong wall pumping and thereafter gradually increases according to the neutral desorption from the wall. The electron den-

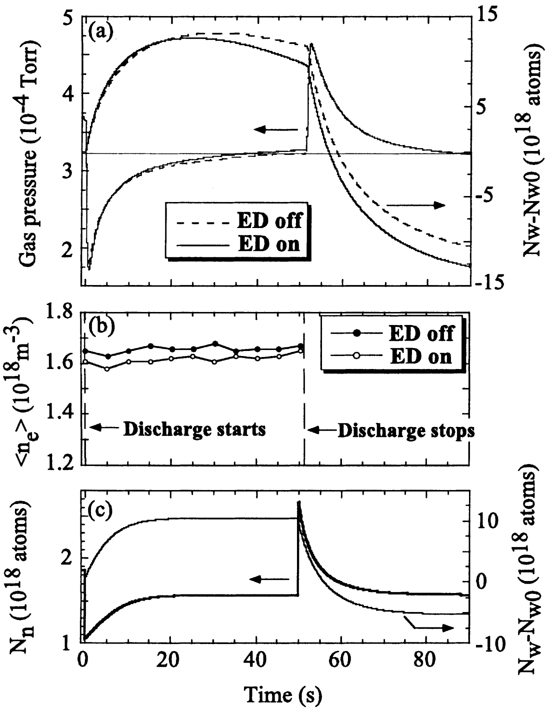

Fig. 4. (a) Temporal evolutions of gas pressure, number of neutrals absorbed on the wall and (b) $\langle n_e \rangle$ during the whole duration of discharge, where the peaks of $\langle n_e \rangle$ at every shot are plotted. (c) Evolutions of gas pressure (corresponds to N_n) and wall retention ($N_w - N_{w_0}$) obtained by numerical analysis, which reproduce the experimental results of gas pressure (i.e. N_n) and ($N_w - N_{w_0}$) well.

sity is almost constant around 1.65×10^{18} m^{-3} (and 3% decreases due to ED) at each discharge shot during the whole duration.

It should be noted that after $t = 3$ s the gas pressure in the case with ED becomes high relative to the one without ED. It is considered due to the hydrogen saturation at the wall around X-region, where the enhanced recycling due to shortening of particle confinement time results in the early wall saturation. Therefore it can be said that ED enhances the wall pumping by increasing the effective wall area at early stage during relatively short time 2 or 3 s, but in the long timescale ED gives rise to the localized wall saturation and results in the early termination of wall pumping. Such a result suggests that the DED may keep a good wall pumping capability for a long timescale by rotating the magnetic structure poloidally, which will give the fresh wall to the plasma constantly. This is a very important and new insight on the future DED operation in terms of the basic understanding of the modification of the particle balance due to ED.

The particle balance in the plasma–wall system is analyzed, using the following zero-dimensional equations for the particle numbers N_p, N_n and N_w:

$$\frac{\partial N_p}{\partial t} = -\frac{N_p}{\tau_p} + \frac{N_n}{\tau_{ion}}, \tag{2}$$

$$\begin{aligned}\frac{\partial N_n}{\partial t} = & -\underset{\text{(ionization)}}{\frac{N_n}{\tau_{ion}}} - \underset{\text{(absorption)}}{\frac{N_n}{\tau_{ab}}\left(1 - C_2\frac{N_w}{N_{ws}}\right)} \\ & + \underset{\text{(reflection)}}{r\frac{N_p}{\tau_p}\left(1 - \frac{N_w}{N_{ws}}\right)} + \frac{N_p}{\tau_p}\frac{N_w}{N_{ws}} \\ & + \underset{\text{(plasma desorption)}}{C_1\frac{N_p}{\tau_p}\frac{N_w}{N_{ws}}} + \underset{\text{(desorption)}}{\frac{N_w}{\tau_w}} + \Gamma_{in} - \Gamma_{out},\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{\partial N_w}{\partial t} = & -\underset{\text{(desorption)}}{\frac{N_w}{\tau_w}} + \underset{\text{(plasma flux)}}{(1-r)\frac{N_p}{\tau_p}\left(1 - \frac{N_w}{N_{ws}}\right)} - \underset{\text{(plasma desorption)}}{C_1\frac{N_p}{\tau_p}\frac{N_w}{N_{ws}}} \\ & + \underset{\text{(absorption)}}{\frac{N_n}{\tau_{ab}}\left(1 - C_2\frac{N_w}{N_{ws}}\right)},\end{aligned} \tag{4}$$

where N_{ws} is the maximum number of neutrals in the wall, and C_2 represents the ratio of N_{ws} coming from the ions to that from the neutrals. The ions are accelerated in the sheath before arriving at the wall and impinge deeper in the wall than neutrals so that the ions may have a larger N_{ws} than the neutrals have. τ_p, τ_{ab}, τ_w are the particle confinement time in the plasma, the neutral resident time in the vacuum chamber and the retention time at the wall, respectively.

In the present calculations the plasma density is assumed to be constant during the whole duration of discharge which can be confirmed from the micro-wave measurements so that N_p is fixed to 1.3×10^{17}. Then, we put $\partial N_p/\partial t = 0$ which implies $N_n/\tau_{ion} = N_p/\tau_p$ and the ionization term in Eq. (3) is replaced with N_p/τ_p. We have chosen the various constants as follows: $\tau_p = 1.0$ m, $\tau_{ab} = 0.2$ m, $\tau_w = 10$ s, $r = 0.3$, $N_{ws} = 2 \times 10^{22}$, $C_1 = 0.7$, $C_2 = 12$, $\Gamma_{in} = 5.90$ ccm. The values of τ_p and τ_{ab} are determined from the Bhom diffusion at $T_e = 7$ eV and the thermal velocity of neutrals at 0.03 eV respectively. The N_{ws} of 2×10^{22} (atoms) corresponds to neutrals contained in the depth of 3×10^2–4×10^2 nm in the chamber wall of CSTN-III. It is a reasonable value as the maximum range that the implanted ions can reach [12]. The value of τ_w was estimated as follows. In general the diffusion coefficient D of the hydrogen in the metal wall is given by the formula $D = D_0 \exp(-U_d/kT)$ [12–14], where D_0 is set to 4.7×10^{-3} cm^2/s, U_d is the activation energy of diffusion process which is now estimated at 8.64×10^{-20} J in the case with the hydrogen diffusing in the 304 stainless steels, T is the wall temperature and k the Boltzmann constant. The wall retention time can be estimated as $\tau_w = d^2/D$, where the d is the typical distance over which the hydrogen diffuses until desorbed from the wall. In the present case, $D \sim 5.0 \times 10^{-12}$ cm^2/s at $T = 316$ K and $d \sim 10^{-5}$ cm, which results in $\tau_w \sim 10$ s. N_{w_0} are determined by the fact that the N_w and N_n are under the equilibrium before the discharge starts. Further C_1 and C_2 are adjusted so that the calculation matches to the experimental results. In these calculations it is assumed that the high repetition discharges would be analyzed with such steady state model equations (2)–(4) in terms of the particle balance because the repetition period is much smaller than τ_w.

Using the above model, we could reproduce the temporal evolutions of gas pressure and the number of particles absorbed on the wall as shown in Fig. 4(c). The jump in gas pressure at the end of the discharge comes from the neutral desorption from the wall which has been canceled by the plasma flux to the wall during the discharge. We found that the timescale of gas pressure evolution from $t = 1$ to 20 s observed in the experiment is almost determined by N_{ws} and C_2, that is, wall condition and energy of impinging ions. The larger N_{ws} or smaller C_2 elongates the timescale. The desorption of particle from the wall is not reproduced completely because this model does not take into account the temporal change in wall retention time due to the wall temperature increase. But it was found that the smaller τ_w reduced the equilibrium wall inventory, which is in accord with the experimental results.

Fig. 5(a) displays the change of gas pressure due to 10 s pulse ED during a normal discharge. It is considered that such a decrease of gas pressure comes from the wall pumping enhancement due to the effective expansion of the wall area. The model analysis also reproduces such a parametric change by increasing the wall area pumping the plasma particles by 10% (Fig. 5(b)).

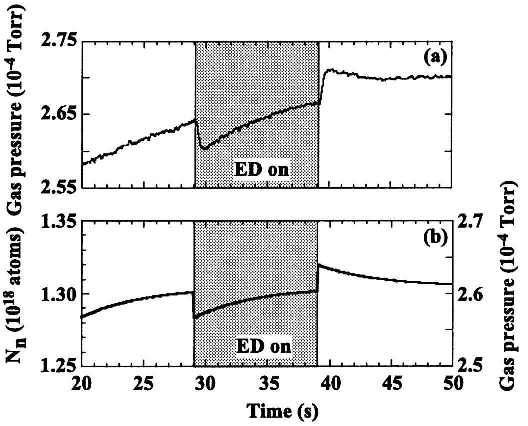

Fig. 5. Gas pressure change due to ED: (a) experimental result and (b) numerical modeling.

4. Summary

Using the high-repetition high-duty discharge the effect of ED on particle balance was investigated. ED increases effectively the wall area pumping the particles by connecting the field line to the wall where the particle normally does not recycle so much. But in the long timescale greater than several seconds ED gives rise to the early termination of wall pumping due to the localization of recycling area around X-region. However, since the DED rotates such a magnetic structure poloidally [5], it will keep the good pumping capability for a long timescale by giving the fresh wall to the plasma continuously, as well as smearing out the localization of the heat load. The model constructed in this work can simulate the behavior of gas pressure and hydrogen contents at the wall including the effect of ED by increasing the wall capacity. Therefore, the present model will be useful in analyzing the particle balance in a long timescale which will be more and more important in long pulse or steady state fusion devices.

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