Global particle balance and wall recycling properties of long duration discharges on TRIAM-1M

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Abstract. The longest tokamak discharge with the duration of 11406 s (3 h 10 min) was achieved. The global particle balance has been investigated. In the longest discharge, the global balance between the particle absorption and release of the wall was achieved around t~30 min and then the fueling was automatically stopped. After that the plasma density was maintained by the recycling flux alone until the end of the discharge. The maximum wall inventory is about 3.6×10^{20} H at t ~ 30 min but it is finally released from the wall at the end of the discharge. The global balance seems to be caused by the increase in the hydrogen release from the main chamber resulting from its temperature rise. Moreover, it has been observed a large difference between properties of wall recycling in the continuous gas feed case (i.e. static condition) and the additional gas puff case (i.e. dynamic condition). In the static condition, the effective particle confinement time increases almost linearly to about 10 s during the one-minute discharge. In the dynamic condition, the decay time of the electron density just after the gas puff, i.e. the effective particle confinement time, is 0.2 to 0.3 s during the one-minute discharge. The large difference was also reproduced in the longest discharge. It is considered that the enhanced wall pumping is caused by the increase in fluxes of the diffused ions and charge exchange neutrals due to the additional gas puff.

1. Introduction

The achievement of stable long pulse operation is one of the requirements for the future fusion reactor. The global particle balance and its control are critical in achieving the steady state operation (SSO). Many studies on the global particle balance have been carried out, for example in the references [1-6]. The wall recycling is a key to understand the global particle balance. Recently, the importance of the main chamber recycling in diverted plasmas has been pointed out in Alcator C-Mod [7,8]. The wall recycling changes with a long time constant depending on the wall condition, which continues to change during the discharge. The effect of the wall conditioning done before the discharge cannot be expected in the SSO. It is necessary to obtain the database from the long pulse experiments.

The wall recycling depends on not only the wall condition but also the particle flux out of the plasma. In transient phenomena such as edge localized modes (ELMs) or the pellet injection, the wall would contribute considerably to the pumping of the transient particle flux out of the plasma. Such dynamic responses of the wall recycling is considered to play an important role in the operation of ELMy H-mode, which is an essential operation in ITER [9]. The understanding of the dynamic response of the wall recycling is important for the SSO as well as the static response.

In the superconducting tokamak TRIAM-1M, ultra-long discharges with the duration of longer than 3 hours have been obtained. In this paper, the global particle balance in the longest duration discharge (τ_D ~ 11406 s) and the static and dynamic responses of the wall recycling will be presented.

2. Experimental Results

TRIAM-1M (R_{major} ~ 0.8 m, $a \times b$ = 0.12 m x 0.18 m) is a superconducting tokamak. All of the plasma facing components are made of high Z materials: the poloidal limiters and the divertor plates are made of molybdenum, and the main chamber is made of stainless steel. A low *Z* material coating has never been done. All results reported in this paper were obtained with hydrogen discharges with a limiter configuration. The fueling is feedback controlled to match the H_α line intensity at the center chord with the reference signal.

The waveforms of the discharge with the duration of 11406 s are shown in Fig.1. The plasma current was almost constant of ~20 kA during the discharge and was sustained by 2.45 GHz LHCD. The electron density is deduced to be ~10^{18} m^{-3}. The RF power decreased from 7.5 kW to 6.9 kW at t ~ 46.6 min to reduce the heat load to the limiter. The reference level for the fueling was decreased about 6.5 % at t ~ 26.5 min to examine the static response of the wall recycling. The additional gas puff was carried out twice as shown in Fig.1 (f) to examine the dynamic response of the wall recycling.

The H_α line intensity spontaneously increased around t ~ 30 min and the piezoelectric valve for the fueling was automatically closed. At t~ 30 min, the global balance between the hydrogen absorption and release of the wall was achieved, and then the plasma density was maintained by the recycling flux alone until the end of the discharge. The OV (278 nm) and MoI (386 nm) line intensities were almost constant during the discharge as shown in Fig.1 (c) and (d). No impurity accumulation was observed. The time evolution of the neutral gas pressure at the pump duct (Fig.1 (e)) suggests that the neutral pressure in the main chamber increased after the global balance resulting from increase in the hydrogen release from the wall.

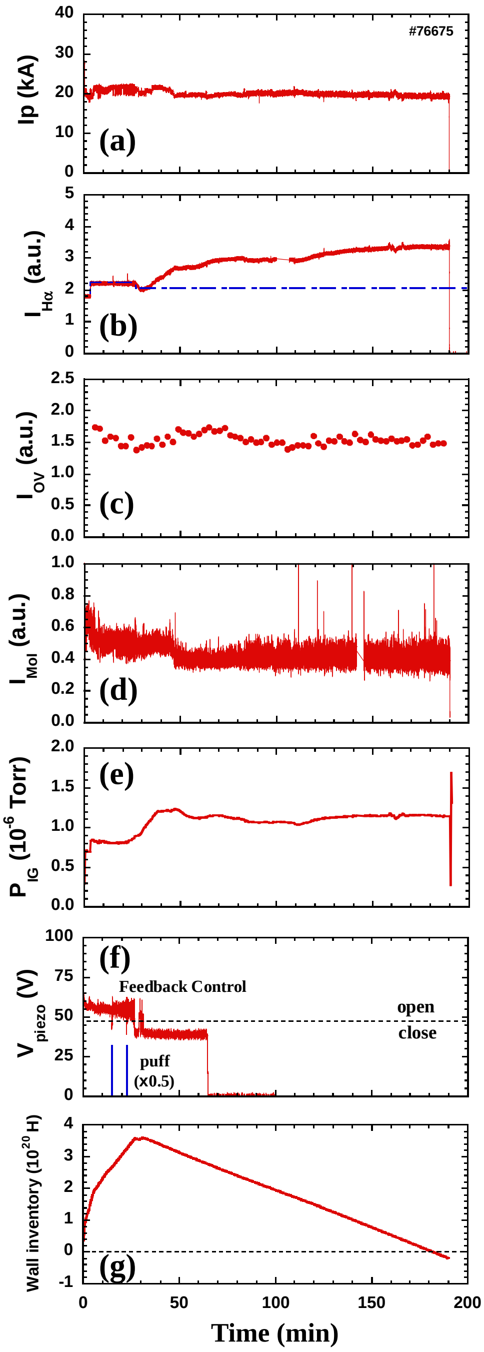

Fig.1 Time evolution of (a) plasma current, (b) H_α line intensity, (c) OV line intensity, (d) MoI line intensity, (e) neutral pressure at the pump duct, (f) voltage of the piezoelectric valve and (g) wall inventory in the longest discharge.

2.1 Global Particle Balance

A simple particle balance in the main chamber can be written by

$$dN_H^0/dt + dN_H^p/dt = \Gamma_{fuel} - \Gamma_{pump} - \Gamma_{wall} \qquad (1)$$

where N_H^0 is the total number of hydrogen neutral atoms in the chamber, N_H^p the total number of hydrogen ions in the plasma, Γ_{fuel} the fueling rate, Γ_{pump} the pumping rate by the external pump-unit and Γ_{wall} the net wall pumping rate, which means the balance between absorption rate and release rate of the wall. Namely, Γ_{wall} is positive when the total amount of hydrogen absorbed by the wall is larger than that of hydrogen released from the wall. This means that the wall plays a role of the particle sink. When Γ_{wall} is negative, the wall plays a role of the particle source. The first term of the left hand side of eqn. (1) is deduced from the data of the ionization gauge at the pump duct. N_H^p is assumed to be the same as N_e, namely, Z_{eff} = 1 is assumed. Γ_{fuel} is estimated from the voltage applied to the piezoelectric valve. Γ_{pump} is the product of the neutral pressure and the pump speed of the external pump-unit. The unknown parameter Γ_{wall} can be obtained from the above equation. In the steady state condition, the net wall pumping rate is written by

$$\Gamma_{wall} = \Gamma_{fuel} - \Gamma_{pump} \quad (2)$$

since the left hand side of eqn. (1) is negligibly small.

The averaged wall pumping rate from t ~ 10 to 20 min is estimated to be 2.4 x 10^{16} atoms m^{-2} s^{-1}. In this period, the wall played a role of the particle sink. After t ~ 30 min, Γ_{wall} = $-\Gamma_{pump}$ ~ -8 x 10^{15} atoms m^{-2} s^{-1}, since the fueling was stopped (Γ_{fuel} = 0). In this period, the wall played a role of the particle source and the effective particle confinement time, τ_p^*, is infinite. The whole surface area (S~5m^2) of the wall is used for calculation of the wall pumping rate although unevenness due to the limiters, the divertor plates, the cooling pipes and so on is not taken into account. The time evolution of the wall inventory is shown in Fig.3 (g). The maximum wall inventory is ~ 3.6 x 10^{20} hydrogen atoms. The total amount of wall-pumped hydrogen was finally released from the wall until the end of the discharge.

The H_α line intensity was measured at four different toroidal positions as shown in Fig.2 (a). The signal at the port D is about twice higher than the others as shown in Fig.2 (b) due to the strong interaction between the plasma and the #9 limiter. All of the signals increased at the same rate after the global balance. This suggests that the increase in the H_α line intensity (i.e. influx to the plasma) was caused by the contribution from the whole toroidal area.

Time evolution of the temperature of the plasma facing components is shown in Fig. 3. The temperature is measured with thermocouples. The temperature of the main chamber increased partly up to ~120 ^oC and it depends on the distance of the measuring point from the cooling pipe. The range of the limiter surface temperature measured with an infrared camera is about 600 to 800 ^oC provided that the emissivity of molybdenum is unity. The characteristic time of the temperature rise of the limiter is ~ 5 min and that of the main chamber including the divertor plate is about 10 to 35 min. The results of Fig. 2 and Fig. 3 suggest that one candidate of the causes of the global balance is the increase in hydrogen release from the main chamber due to its temperature increase.

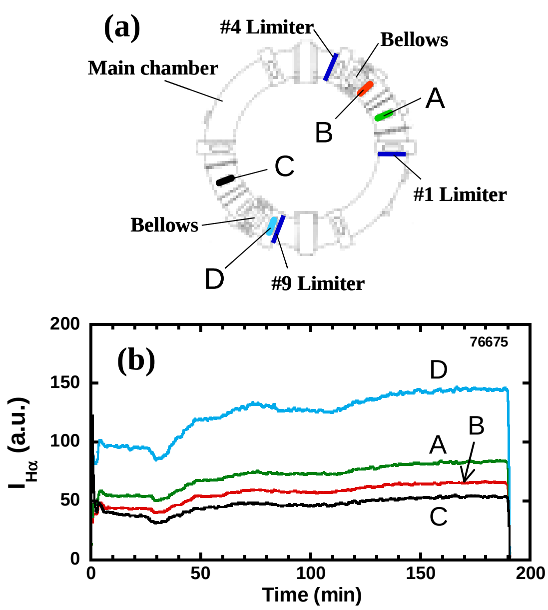

Fig.2 (a) Top view of the main chamber of TRIAM-1M. Three sets of the poloidal limiters (#1, #4, #9) are installed. The H_α line intensity is vertically measured at the ports A, B, C and D. (b) The time evolution of the H_α line intensity at the ports A, B, C and D.

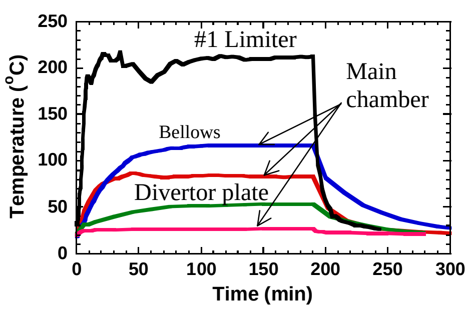

Fig.3 Time evolution of the temperature of the #1 poloidal limiter, the divertor plate, the main chamber.

2.2 Static and Dynamic Properties of Wall Recycling

To investigate the dynamic property of wall recycling, we carried out the additional gas puffs in the 2.45 GHz LHCD plasma. The decay time, τ_D, of the electron density just after the gas puff, i.e. the effective particle confinement time, is ~ 0.27 s and τ_D of the H_α line intensity is ~ 0.33 s as shown in Fig.4. It is found that the decay time agrees well with each other. The time evolution of τ_p^* in the dynamic condition (i.e. additional gas puff case) is shown in Fig.5. The data were obtained by that many gas puffs were carried out in three one-minute discharges. τ_p^* is almost constant with a value of 0.2 s to 0.3 s during the one-minute discharge.

τ_p^* in the static condition is evaluated from the following equation:

$$\tau_p^* = \tau_p/(1-R) \qquad (3)$$

where τ_p is a global particle confinement time and R is a recycling coefficient. It is known that R increases with time in a static condition in which the plasma density is kept constant by continuous fueling [1]. This means that the wall pumping rate gradually decreases and τ_p^* increases with time. In the 2.45 GHz LHCD discharge ($\bar{n}_e$ ~ 0.2 x 10^{19} m^{-3}), τ_p^* increases almost linearly to about 10 s during the one-minute discharge as shown in Fig.5. The decay time of $\bar{n}_e$ after the fueling is stopped at t ~ 33 s during the discharge is also shown in Fig.5 and it is consistent with the value of τ_p^* evaluated from eqn. (3). It is found that τ_p^* in the static condition is one order of magnitude higher than that of the dynamic condition.

In the longest discharge, moreover, the static and dynamic properties of wall recycling were also investigated. Additional gas puffs were carried out at t ~ 900 s and 1350 s as shown in Fig.1 (f). The value of τ_D of the H_α line intensity are 0.24 s at t ~ 900 s and 0.33 s at t ~ 1350 s as shown in Fig.6 (a) and (b). We do not have $\bar{n}_e$ data for this discharge but τ_p^* is expected to be similar to τ_D of the H_α line intensity from the result of Fig.4. It is found that τ_p^* deduced from the result of Fig.6 (a) and (b) is the same as that of the initial phase of the discharge shown in Fig.5 even though the wall inventory increases with time as shown in Fig.1 (g). On the other hand, τ_p^* in the static condition is deduced to be on the order of 100 s at t ~ 1600 s from Fig.6 (c). It changes with time (i.e. the wall inventory) in contrast to the dynamic property.

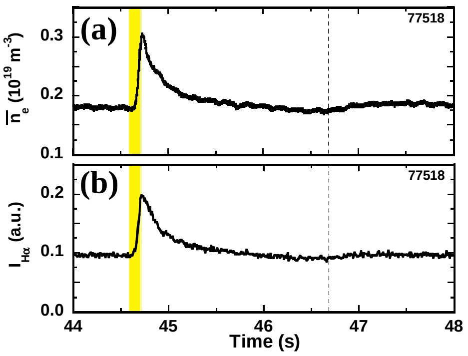

Fig.4 Time evolution of (a) line averaged electron density and (b) H_α line intensity at the additional gas puff (hatch). The fueling is automatically stopped just after the gas puff and restarts at the time indicated by the dashed line.

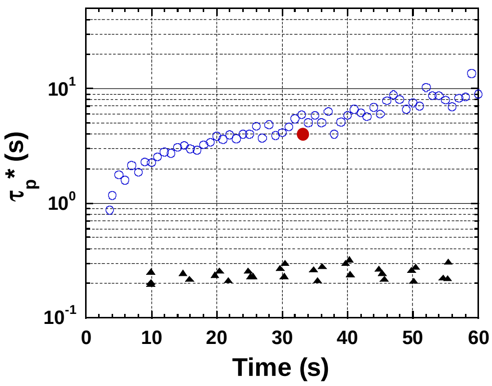

Fig.5 Comparison of the effective particle confinement times between the static (open circle) and dynamic (closed triangle) conditions. The closed circle is the decay time of $\bar{n}_e$ after the fueling is stopped.

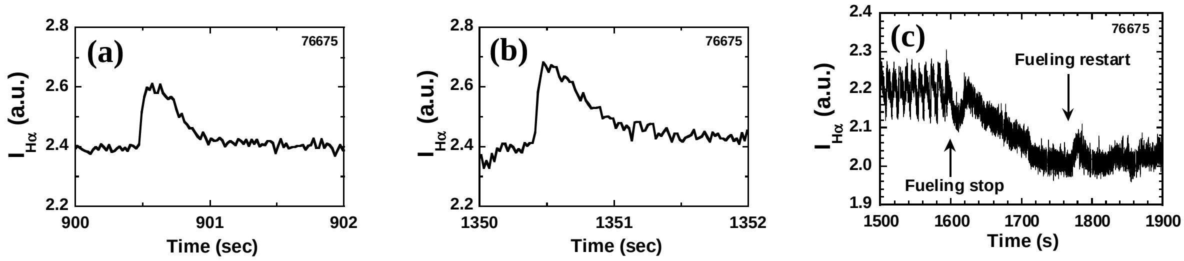

Fig.6 (a), (b) H_α line intensity at the additional gas puff with the duration of 0.1 s and (c) H_α line intensity when the fueling is stopped in the longest duration shown in Fig.1.

This large difference between τ_p^* in the static and dynamic conditions suggests that the recycling coefficient decreases just after the gas puff, i.e. the wall pumping is enhanced by the additional gas puff, since the reduction of τ_p due to the density increase by the gas puff is evaluated to be about 30%. It is considered that the enhanced wall pumping is caused by the increase in fluxes of the diffused ions and charge exchange neutrals from the plasma to the wall due to the additional gas puff.

4. Summary

In TRIAM-1M, wall recycling experiments have been carried out intensively. In this paper, the global particle balance of the longest discharge with the duration of 11406 s (3 h 10 min) and the wall recycling properties of the static and dynamic conditions are presented. During the longest discharge, the net wall pumping rate became zero (i.e. the global balance between the particle absorption and release of the wall was achieved) and then negative. The wall played a role of a particle sink until t ~30min and afterwards it played a role of a particle source. The total amount of wall-pumped hydrogen was finally released from the wall until the end of the discharge. The maximum wall inventory is about 3.6 x 10^{20} hydrogen atoms. The global balance seems to be caused by the increase in the hydrogen release from the main chamber resulting from its temperature rise.

In the static condition, the effective particle confinement time increases almost linearly to about 10 s during the one-minute discharge. On the other hand, the decay time of the electron density just after the gas puff, i.e. the effective particle confinement time, is 0.2 to 0.3 s during the one-minute discharge in the dynamic condition. This large difference of the wall recycling properties between the static and dynamic conditions is also reproduced in the longest discharge. It is considered that the enhanced wall pumping is caused by the increase in fluxes of the diffused ions and charge exchange neutrals from the plasma to the wall due to the additional gas puff.

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