20th IAEA Fusion Energy Conference
Vilamoura, Portugal, 1-6 November 2004

IAEA-CN-116/ EX / 10-3

Impact of nearly-saturated divertor plates on particle control in long and high-power heated discharges in JT-60U

T. Nakano, N. Asakura, H. Takenaga, H. Kubo, Y. Miura, S. Konoshima, K. Masaki, S. Higashijima and the JT-60Team

Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken, 311-0193 Japan.

Impact of nearly-saturated divertor plates on particle control in long and high-power heated discharges of JT-60U

T. Nakano, N. Asakura, H. Takenaga, H. Kubo, Y. Miura, S. Konoshima, K. Masaki, S. Higashijima and the JT-60Team

Japan Atomic Energy Research Institute, Ibaraki, Japan.

e-mail contact of main author: nakanot@fusion.naka.jaeri.go.jp

Abstract. In order to understand plasma-wall interactions in a long time scale, the discharge pulse length has been extended from 15 s to 65 s with the NB heating duration extended to 30 s. The divertor plates were nearly-saturated in the latter half of long pulse ELMy H-mode discharges, where reduction of particle sink into the divertor plates, and subsequently, increase of particle release from them became significant, resulting in a rise of the main plasma density without any auxiliary gas fuelling besides the NB fuelling even with the divertor exhaust. No negative effects on impurity behavior were observed in the long pulse discharges with the divertor plates nearly-saturated. ELMy H-mode plasmas were sustained for about ~ 30 s without sudden increase of carbon generation such as "carbon bloom" [1], even when the total injected energy reached up to about ~ 360 MJ in a discharge (~ 12 MW x 30 s), and dilution of the main plasma was not seen.

1. Introduction

In JT-60U, high performance plasmas have been developed to provide a physics basis for ITER [1] and advanced steady-state tokamak reactors such as SSTR [2]. The equivalent break-even condition (equivalent DT fusion gain of 1.25) has been demonstrated in the reversed magnetic shear configuration with an internal transport barrier [3]. For realizing a steady-state operation in a fusion reactor, another research direction towards the performance prolongation is important in addition to the performance extension. For the performance prolongation, sustainment of high performance plasmas longer than a time scale of variation of plasma-wall interaction is one of the key issues. In the short pulse discharge, the particle absorption at the wall (wall pumping) largely contributes to the density control. High confinement plasmas have been achieved by avoiding confinement degradation at high density using the wall pumping. However, the wall pumping is expected to be less effective in the long pulse discharge due to the saturation of the wall inventory (wall saturation). It is important to understand a time scale of the wall saturation and to develop the particle control during the wall saturation. In JT-60U, no wall saturation was observed during the 15 s discharges [4]. In order to address the new research direction towards the performance prolongation, JT-60U discharge pulse length has been recently extended from 15 s to 65 s together with the extension of the NB heating pulse length from 10 s to 30 s.

In the long pulse discharge, increase in time-integrated particle flux to the divertor plates and higher plate temperature attained by a larger energy input help the wall saturation. The wall inventory decreases with increasing the wall temperature in the range of >150-200 oC [5]. On the other hand, co-deposition with carbon impurity delays the wall saturation, because carbon impurity deposition to the wall surface generates the new fresh surface. In long pulse discharges of TRIAM-1M, wall saturation and wall pumping were repeated with a time scale of several tens minute, and the discharge duration of high density plasmas (>2.5 1019 m-3) were limited to about 10 s due to the wall saturation [6]. In long pulse discharges of Tore Supra, wall saturation was not observed for more than 4 minute after installation of the cooling system [7], although the density was increased before the installation [8]. In divertor

plasmas of JET, the density increased in the latter phase of 1 minute discharge [9]. It is important to understand key parameters for the wall saturation and its impacts on the plasma performance. In this paper, the time scale and the key parameters of the wall saturation, and impacts of the wall saturation on particle balance, pedestal and ELM characteristics and particle behavior of deuterium and carbon impurity are investigated. It is noted that the wall pumping includes the particle absorption at both divertor plates and first wall, and the wall saturation means that net wall pumping rate is equal to zero in this paper.
In section 2, the modification for the long pulse discharge and initial results are briefly described. In section 3, the particle balance is quantitatively analyzed in the long pulse discharges. The main plasma performance and the particle behavior of deuterium and carbon impurities under the wall saturation are investigated in Section 4, followed by a summary in section 5.

2. Extension of discharge and heating pulse length

In JT-60U, the W-shaped divertor formed by the inner and outer inclined divertor plates and the dome in the private flux region was installed with the divertor pumping from both inner and outer private flux regions. The divertor pumping rate can be controlled with shutters during the discharge. CFC tiles are used for the divertor plates, the dome top and the outer dome wing, and graphite tiles are used for the inner dome wing, the baffle plates and the first wall around the main plasma. Previously the discharge duration was limited to 15 s with a plasma current (Ip) of 3 MA and a toroidal magnetic field (BT) of 4 T. Recently, the discharge duration has been extended up to 65 s with Ip~1 MA and BT=2.7 T. The NB heating duration has also been extended from 10 s with the heating power (PNB) of ~30 MW to 30 s with PNB=14 MW.
The long pulse experiments was performed in 2003 JT-60U experiment campaign with the wall baking temperature of 150 oC. A 65 s tokamak discharge of Ip=0.7 MA and 59.8 s flat top with divertor configuration was obtained with NB pulse length fully extended to 30 s of the positive-ion source based NB (P-NB). The total input energy of 360 MJ, including the negative-ion source based NB (N-NB) and ECRF powers which are still under conditioning, has been achieved with 10-14 MW heating power. No sudden increase of carbon generation such as carbon bloom was observed even with this energy input in the W-shaped divertor, while the sudden increase of the carbon generation was observed with 70 MJ input in the JT-60U open divertor [10]. ELMy H-mode plasmas were successfully sustained for about 30 s, and a value of normalized beta (bN) of 1.9, which is comparable to the ITER standard operation, is sustained for ~24 s with ITER relevant safety factor at normalized radius of 0.95 (~ 3.2). In the latter phase of this discharge, the current profile reached a steady-state. However, Da emission intensity between ELMs and the electron density increased, and energy confinement enhancement factor (H89PL) decreased from 1.9 to 1.7. This indicates that the plasma-wall interaction is a critical issue for sustainment of high confinement.

3. Experimental

3.1 Identification of wall-saturation

3.1.1 ELMy H-mode discharge with the first walls/divertor plates nearly-saturated

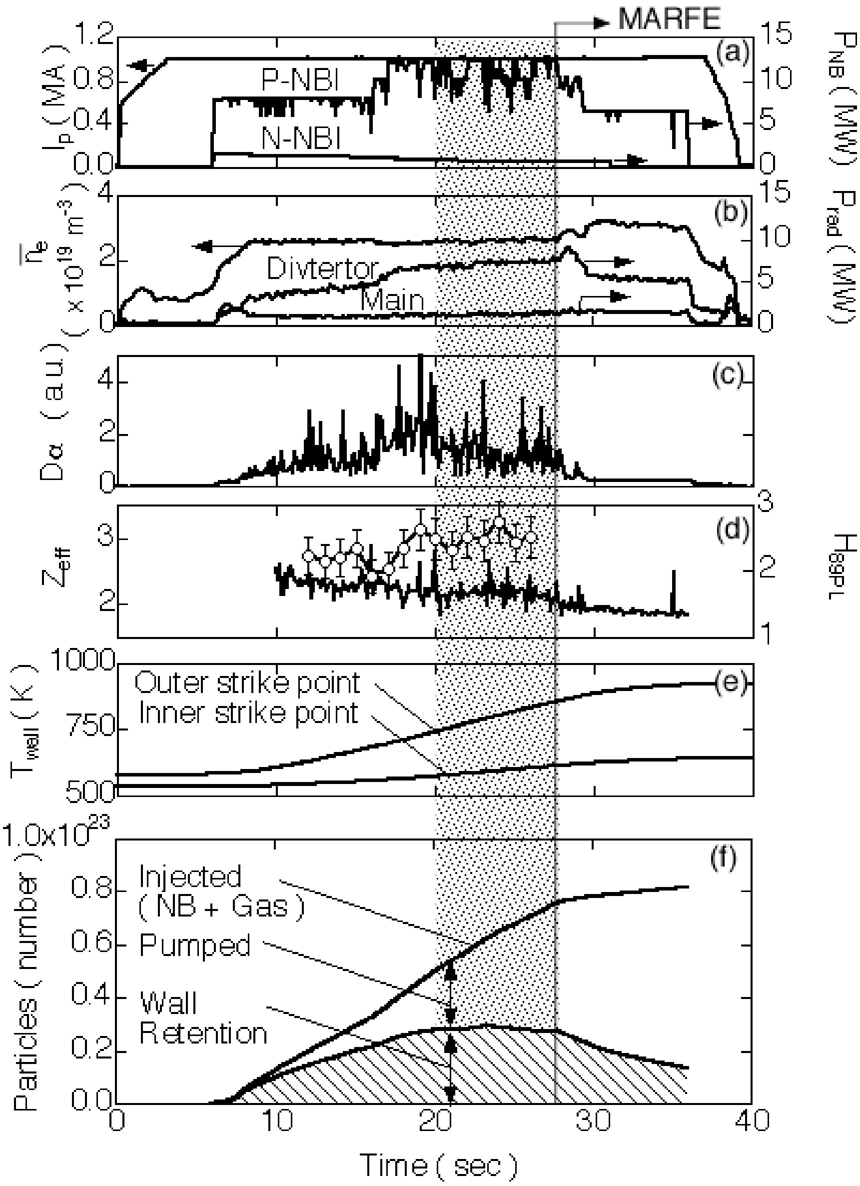

Fig 1 Waveforms of long pulse, ELMy H-mode plasma. (a) plasma current (Ip), positive- and negative-ion based neutral beam heating power (PNB), (b) line-averaged electron density (ne), radiation from the main and the divertor plasma (Prad), (c) Da emission intensity from the divertor plasma, (d) plasma effective charge (Zeff), H factor (H89PL), (e) temperature around the strike points beneath 4 mm, and (f) number of injected particles, pumped particles and retained in the first walls/divertor plates.

Figure 1 shows typical waveforms of an ELMy H-mode discharge with the first walls/divertor plates nearly-saturated. At a toroidal magnetic field of 2.7 T, the flat-top of the plasma current (1 MA) was maintained for 34 s and the plasma was diverted for 36 s. The positive-ion based neutral beam was injected for 30 s with a heating power of 7-12 MW and the negative-ion based neutral beam for 25 s with a heating power of 0.6 – 1.5 MW. The line-averaged electron density was controlled at 66% of the Greenwald density by a feedback control system of a gas-puff rate. The radiation power from the main plasma remained constant while that from the divertor plasma increased. As the waveform of D_α line emitted from the divertor plasma shows, ELMy H-mode was sustained until t = 28 s. During the H-mode phase, a plasma effective charge (Z_{eff} ~ 3) and an H factor (H_{89PL} ~ 1.7) were kept constant. The temperature of the divertor plates at the inner strike point was always lower than that at the outer strike point because the innder divertor plasma was detached and the outer attached. Figure 1 (f) shows the particle balance of this pulse on the assumption that the number of injected particles (NBI + Gas) is equal to that of pumped by the divertor-pumping system and retained in the first walls/divertor plates. From this analysis, the number of retained particles (wall retention) can be invoked. As the figure shows, the wall retention increases until 20s.

This increase means that a wall-pumping is effective because particles continued to be sinked during the increase. After 20 s, on the contrary, the wall retention is constant. This situation means that a wall-pumping is not effective. Hereafter, this situation is called “wall-saturation”. Even under the condition of the wall-saturation, the ELMy H-mode plasma with Z_{eff} and H_{89PL} constant was sustained. But the line-averaged electron density and the radiation from the divertor plasma gradually increased (hard to see from Fig. 1 (b)) . Finally, the divetor plasma evolved into the X-point MARFE, and H_{89PL} dropped to 1.3. This fact indicates that the number of injected particles is slightly larger than that of pumped. The controllability of the plasma density with the divertor-pumping rate is discussed later.

3.1.2 Particle Balance Analysis between discharges

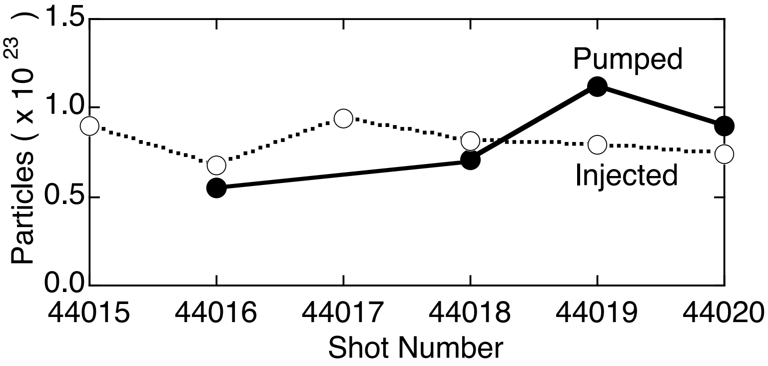

Fig. 2 number of pumped and injected particles from the breakdown of a discharge until the breakdown of the next discharge, as a function of shot number.

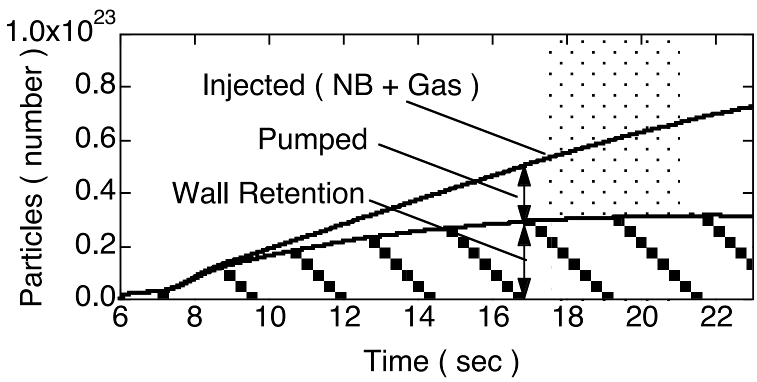

Fig. 3 particle balance of E044020, at a first wall temperature of 440 K. Meanings of the lines are the same as Fig. 1 (f).

In order to confirm the wall-saturation, defined in the above subsection, the particle balance analysis was performed between discharges. As Figure 2 shows, the number of injected particles is larger than that of pumped at fore part of a series of the discharges. This indicates that particles are accumulating in the vacuum vessel, specifically, the first walls/divertor plates. But the number of pumped particles increased and went over that of injected particles after the shot of 44019. This situation means that some of retained particles in the wall are released between discharges. The difference between the number of pumped and injected particles is 3 x 10^{22}, and, this number agreed with the number of retained particles during the next shot (*E044020*) as shown in Fig. 3. As shown in Fig. 1 (f), the wall retention at the wall-saturation is also 3 x 10^{22}. Provided that the effective wall-pumping area is 1/5 of the area of the first walls/divertor plates (160 m^2), 1 x 10^{21} /m^2 is obtained, and this value agrees with the saturated wall retention in the case that D+ is injected at an energy of 300 eV. In other words, 1/5 of the first wall/divertor plates is saturated in average.

3.2 Comparison of wall retention at different wall temeprature

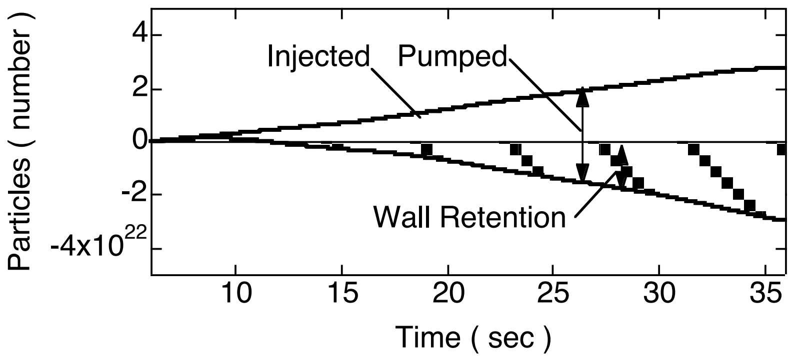

Fig. 4 particle balance of E043581, at a first wall temperature of 540 K. Meanings of the lines are the same as Fig. 1 (f).

Figure 4 shows the particle balance of the discharge performed at a first wall temperature of 540 K (*E043581*). In this pulse, the first walls/divertor plates played a role opposite to those of the pulse at a fist wall temperature of 440 K (*E044020*). After t= 10 s, the wall retention continued to decrease. This decrease means that particles are supplied from the first walls/divertor plates and probably, fueled the plasma. By this mechanism, the same line-averaged electron density as the pulse *E044020* (66% of Greenwald density) was kept without any gas-puff.

This significant difference is considered to come from the difference of the temperature of the first walls between the two pulses. These two pulses have almost the same parameters ; a plasma current, a toroidal magnetic field, a neutral beam heating power, a line-averaged electron density, H factor, and so on. This is also the case for the temperature of the divertor plates. In *E044020*, although the first walls/divertor plates were set at a temperature of 420 K by a baking system, the divertor plates did not cool down to 420 K between pulses. As a result, the temperature of the divertor plates gradually increased in the series of pulses while the temperature of the first walls remained ~ 420 K. From this reason, the temperature of the divertor plates happened to be close between *E044020* and *E043581* as shown in Fig. 5, even if the baking temperature was set at 420 K and 520 K, respectively. This coincidence is the case not only at the beginning of the pulse but also during the discharge. Hence the only difference between the two pulses is the temperature of the first walls. This result suggests that it is important to control the temperature of the first walls for the purpose of particle control including particles retained in the walls.

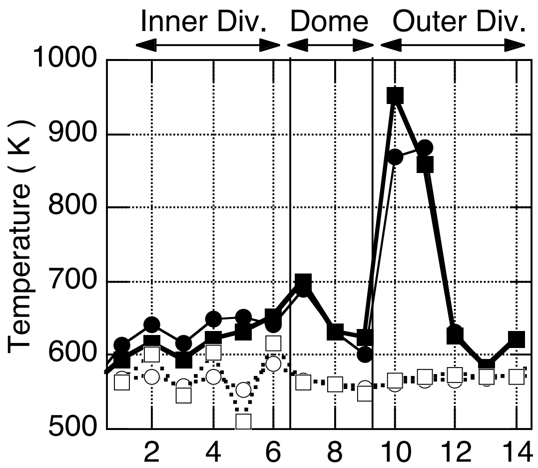

Fig. 5 Temperature of the divertor plates beneath ~ 4 mm from the surface. Circels and squares indicate temperature of E043581 and E044020, respectively. Open and close symbols indicate temperature at the breakdown and at the end of the discharge, respectively.

Additionally, Because at a temperature of < 700 K, D_2 does not interact with carbon materials [14], D^+ and/or D^0 are considered to interact with the first walls.

3.3. Controllability of the plasma density

As already described, it is difficult to control the balance of pumping and fueling, under the condition of the wall-saturation. In this condition, because the first walls/divertor plates do not work as a pump, the divertor-pumping rate is required to be high enough to exhaust an excess of particles for maintaining a plasma density. For this reason, the divertor magnetic configurations were scanned to obtain the highest efficiency of the divertor-pumping.

Figure 6 shows the divertor magnetic configurations investigated here. The high triangularity plasma (δ = 0.36) has a large gap between the inner strike point and the inner pumping-slot. This large gap results in a lower pumping rate. On the contrary, the low triangularity plasma (δ = 0.27) has small gaps between the strike points and the pumping slots, resulting in a higher pumping rate [15]. Furthermore, to enhance the pumping efficiency more, the X-point is lowered by 2 cm.

Figure 7 summarizes the controllability of plasma particles by the divertor-pumping. Comparison of the high and the low triangularity plasma at the same Greenwald density (66%) indicates that the high triangularity plasma has lower efficiency in controlling the plasma particles due to the lower pumping-rate. From the same reason, the low triangularity plasma with the X point height lower by 2 cm has the highest efficiency in the data.

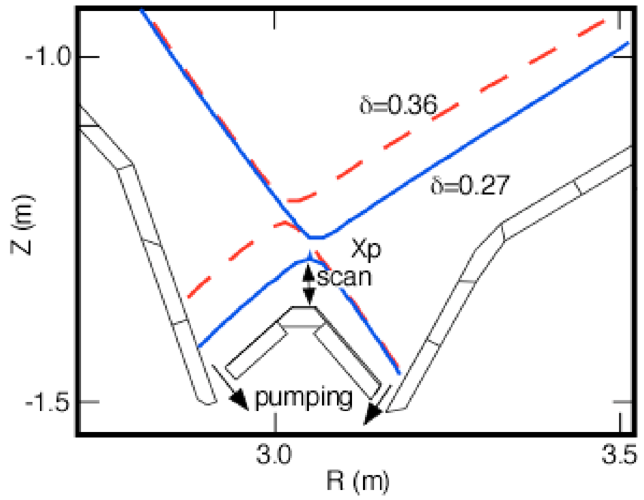

Fig. 6 Magnetic configurations around the divertor of a high (0.36) and a low (0.27) trangurality plasma, shown by a solid and a broken line, respectively. Xp indicates an X-point.

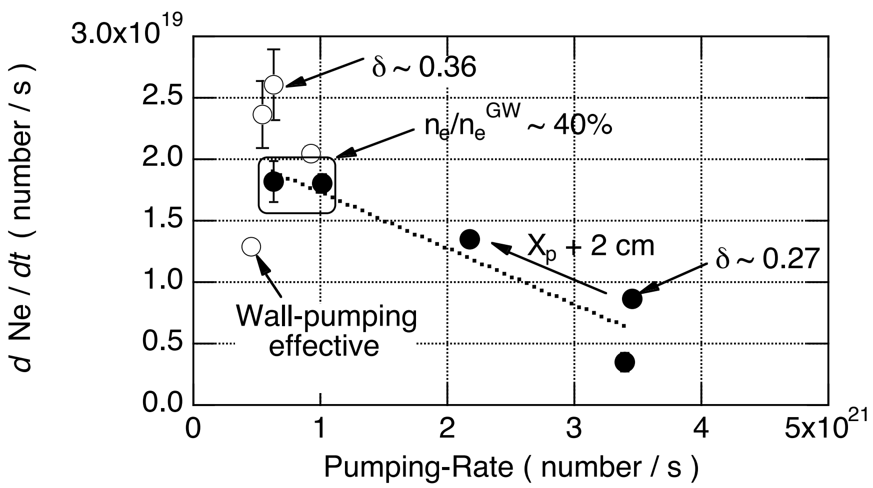

Fig. 7 Increase rate of number of electron in the main plasma as a function of the divertor-pumpig rate. The data are obtained under the condition of wall-saturation at a 66% of Greenwald density. For comparison, The data obtained at different density and under the condition of non-wall-saturation are also shown.

From above discussion, it is difficult to keep the plasma density constant for the high triangularity plasma due to the insufficient pumping-rate. With this configuration, even if the first walls/divertor plates are not saturated, it is difficult to avoid the increase of the plasma density. Thus, it is considered that the plasma with high normalized beta (β_n) was sustained for a limited period; for example, 15 s for $\beta_n \sim 2.5$ [14]. To obtain longer duration of the high β_n plasmas, modification of the divertor structures is required to fit the magnetic configuration for the high pumping-rate.

3.4. Temperature dependence of chemical sputtering yield

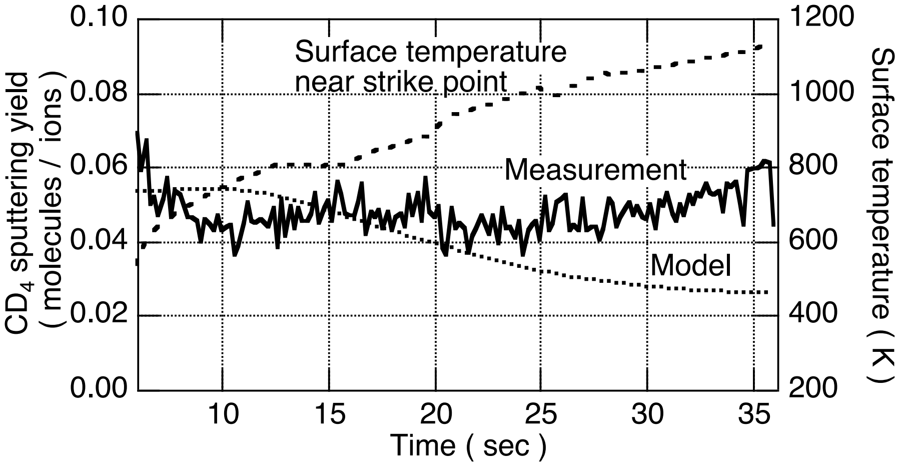

Fig. 8 Chemical sputtering yield measured at the outer divertor plates under attached divertor condition. Dotted lines shows the chemical sputtering yield calculated with consideration of temperature dependence [17]. Broken line indicate the surface temperature around the strike point calculated by heat transfer analysis [13].

4. Summary

JT-60U research has been expanded to the new area towards the steady-state operation by utilizing the long pulse operation extended to 65 s and NB heating pulse length extended to 30 s. The particle balance analysis in the long pulse discharge indicates that wall is not saturated even with a high divertor plate temperature around the strike points. However, the wall is saturated by repeating the several long pulse discharges. The density increases without gas-puffing in the latter phase of the wall saturated discharge. These results indicate that the absorption area with the low wall temperature is dominant for wall pumping rather than the co-deposition. During the wall saturation, the edge pressure is reduced and the ELMs become close to type III regime. Increase in Da emission intensity is not observed around the main plasma, but observed at upstream of the outer divertor under the wall saturation. The intensities of C II emission near the X-point and CD band emission in the inner divertor start to increase before the wall saturation, and they continue to increase. This could be related to the surface temperature dependence of the chemical sputtering yeild.

Acknowledgement

The authors wish to thank the members who have contributed to the JT-60U project especially for modification to the long pulse operation.

[1] H. Takenaga, A. Sakasai et al., Nucl. Fusion, 41 (2001) 1777.
[2] W. Moller, J. Nucl. Mater., 162 -164 (1989) 138.
[3] ITER Technical Basis, ITER EDA Documentation Series No. 24, IAEA, Vienna, 2002.
[4] S. Nishio et al., Fusion Energy 2000, Sorrento, Italy, 2000, FTP2/14, International Atomic Energy Agency (2000).
[5] T. Fujita et al., Nucl. Fusion 39 (1999) 1627.
[6] W. Moller, J. Nucl. Mater. 162-164 (1989) 138.
[7] M. Sakamoto et al., Nucl. Fusion 42 (2002) 165.
[8] J. Jacquinot, Nucl. Fusion 43 (2003) 1583.

[9] Equipe Tore Supra (prepared by F. Saint-Laurent), Nucl. Fusion 40 (2000) 1047.
[10] J. Jacquinot et al., Plasma Phys. Control. Fusion 35 (1993) A35.
[11] Y. Kamada et al., Nucl. Fusion 39 (1999) 1845.
[12] K. Masaki et al., in this conference.
[13] W. Moller, J. Nucl. Mater., 162 -164 (1989) 138.
[14] H. Takenaga et al., Nucl. Fusion 41 (2001) 1777.
[15] T. Suzuki et al., EX/1-3 in this conference.
[16] T. Nakano et al., Nucl. Fusion 42 (2002) 689.