STEADY-STATE EXHAUST OF HELIUM ASH IN THE W-SHAPED DIVERTOR OF JT-60U

A. SAKASAI, H. TAKENAGA, N. HOSOGANE, H. KUBO, S. SAKURAI, N. AKINO, T. FUJITA, S. HIGASHIJIMA, H. TAMAI, N. ASAKURA, K. ITAMI, K. SHIMIZU AND THE JT-60 TEAM

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

Abstract

STEADY-STATE EXHAUST OF HELIUM ASH IN THE W-SHAPED DIVERTOR OF JT-60U

By injecting a neutral beam of 60 keV helium (He) atoms as central fueling of helium into the ELMy H-mode plasmas, helium exhaust has been studied in the W-shaped pumped divertor on JT-60U. Efficient He exhaust was realized by He pumping using argon frosted cryopumps in the JT-60U new divertor. In steady state, good He exhaust capability (τ^*_{He}/τ_E=4 and high enrichment factor, where τ^*_{He} is a global particle confinement time of helium and τ_E is the energy confinement time) was successfully demonstrated in attached ELMy H-mode plasmas. Good He exhaust capability was also obtained in detached ELMy H-mode plasmas, which was comparable to one in attached plasmas. This result of the helium exhaust is sufficient to support a detached divertor operation on ITER. After the divertor modification, helium exhaust in reversed shear plasmas has been investigated using He gas puff. Helium removal inside the internal transport barrier (ITB) is about two times as difficult as that outside the ITB in reversed shear discharges.

1. INTRODUCTION

Control of helium (He) ash is one of the key issues in future tokamak reactors, such as ITER and SSTR (Steady State Tokamak Reactor) [1]. ITER is designed to operate in H-modes with partially-detached divertor or some other enhanced confinement regime for helium ash exhaust [2]. A detailed experimental data base related to He level regulation and He ash removal should be developed to contribute to the determination of the device size and to the evaluation of the margin to ignition achievement. ELMy H-mode is attractive because of its capability of steady-state operation and particle exhaust by MHD relaxation at the plasma peripheral region.

Using a neutral beam of helium atoms as central fueling of helium or a short pulsed He gas puff as peripheral fueling, helium exhaust characteristics (He flux and neutral particle pressure in the divertor) have been studied to simulate He ash removal on TEXTOR [3] and JT-60 [4] in L-mode plasmas, and on JT-60U [5-7], DIII-D [8,9] and ASDEX-U [10] in ELMy H-mode plasmas. The previous study on JT-60U with He beam fueling indicated that He ash could be easily exhausted in ELMy H-mode and L-mode discharges with an open divertor configuration without pumping [6]. The deuterium flux is larger on the inner target than on the outer target on JT-60U [11]. The in-out asymmetry of He and deuterium flux in the divertor was studied in L-mode and ELMy H-mode plasmas [7]. The in-out asymmetry of He flux in the divertor during ELMy H-mode has been successfully controlled by changing neutral beam (NB) power and plasma current (I_P). Its characteristics are an important issue for He ash control.

Helium exhaust was performed by wall pumping due to gettering by solid target boronization (STB) in low density H-mode plasmas and low recycling divertor so far [5]. In STB discharges, τ^*_{He}/τ_E = 8 (τ^*_{He} : the global particle confinement time of helium, τ_E : the energy confinement time) was successfully obtained [12]. The JT-60U divertor was modified from the open divertor to the W-shaped pumped divertor in Feb.-May, 1997 [13]. The divertor modification enabled helium exhaust in high density H-mode plasmas and high recycling divertor with the divertor pumping. Helium exhaust experiments were performed to investigate the efficiency of helium exhaust with the W-shaped pumped divertor in attached and detached divertor discharges, and I_p and B_t reversed discharges.

In reversed shear modes, the electron density in the central region is peaked and the confinement is remarkably enhanced inside the internal transport barrier (ITB), which is formed near the position of minimum q. Electron density, electron temperature and ion temperature profiles (n_e(r), T_e(r), T_i(r)) inside the ITB are peaked in JT-60U [14]. Then reversed shear mode is attractive because of improvements of particle and energy confinement at the core region as a new operation scenario for ITER. Helium ash exhaust from the revered shear plasma is a matter of concern. A previous study of He transport in reversed shear plasmas indicated the improvement of the He particle confinement inside the ITB without He pumping [7]. It is very important to make clear He exhaust characteristics of reversed shear plasma because of an enhancement of He particle confinement.

2. W-SHAPED PUMPED DIVERTOR

Figure 1 shows the poloidal cross section of an ELMy H-mode discharge in JT-60U after the installation of the new divertor (a) and the structure of the W-shaped pumped divertor (b). The new divertor consists of inclined divertor plates (vertical divertor) and a dome arranged in a W-shaped configuration, as well as inner baffles and outer baffles for pumping duct [13]. The inclined target type divertor with a dome was adopted because of its effectiveness in achieving dense and cold divertor plasmas and baffling the back flow of neutral particles towards the boundary of main plasma. The dome is also expected to increase the pumping efficiency from the private flux region by compressing the deuterium molecule density and to function as a baffle for reducing the neutral particle flux to the X-point region at the same time. Carbon fiber composite (CFC) tiles are used for divertor plates, top tiles of the dome and baffling tiles at the divertor throat. For the other parts, graphite tiles are used.

An exhaust slot is located between the inner target plate and the dome. Three units of NBI cryopumps for divertor pumping are used to exhaust the gas through the slot. Fast movable shutter valves were installed in front of each cryopump to control timing and pumping speed of the divertor pump, which depends on opening rate of the valves.

The pumping speed was determined by measuring the neutral pressure without plasma. After deuterium gas was enclosed in the JT-60U vacuum vessel, pumping was started by opening the fast movable shutter valves of the divertor pump. The time evolution of neutral pressure at the main plasma and divertor (below the baffle plates, P_{baffle}) regions was measured with ionization gauges and Penning gauges. The effective pumping speed was estimated to be 13 m^3/s at P_{baffle} = 0.06 Pa for D_2. It was also estimated to be 13-15 m^3/s from the particle balance keeping the same density with and without pump by D_2 gas puff in ELMy H-mode discharges.

Helium exhaust is accomplished by condensing an argon (Ar) frost layer on the liquid helium cooled surface of three NBI cryopumps for divertor pumping between successive plasma discharges by injecting a known amount of Ar gas into the port chambers. Helium neutral particles accumulated in the private region are exhausted through the inner exhaust slot. Actually, the effective pumping speed is determined by the conductance of the exhaust slot and the under the dome. Therefore the effective pumping speed for He was experimentally evaluated to be 13 m^3/s. A total pumping capacity of the three Ar frosted NBI cryopumps was estimated to be 2325 $Pa \cdot m^3$ from the measurement.

3. EXPERIMENTAL SETUP

JT-60U is a single-null semi-closed divertor tokamak with a major radius of 3.2 m, a minor radius of 1 m, plasma current up to 6 MA and toroidal field up to 4 T. A tangential viewing charge-exchange recombination spectroscopy (CXRS) system provides radial density profiles of fully ionized helium as shown in Fig. 1(a). CXR emission of He II 468.52 nm (n = 4-3) is led to 0.5-m and 1.0-m Czerny-Turner spectrometers through 80-m pure quartz optical fibers. The detection system for He density profile measurement consists of image-intensified double linear photodiode arrays. The calibration of the CXRS system was performed by using an integrating sphere.

A set of spectrometers, a Langmuir probe array and an infrared television (IRTV) camera are used to measure the divertor characteristics. Recycling influx profiles of deuterium and He ions were derived, from the measured line intensities of D_α and He I (667.8 nm) with a 60-channel optical fiber array coupled to visible spectrometers as shown in Fig. 1(b). The neutral pressure of He and D_2 in the divertor region linked to the exhaust ports was measured by a Penning gauge below the outer baffles.

4. HELIUM EXHAUST IN ELMy H-MODE PLASMAS

The helium exhaust experiments were made possible with the JT-60U neutral beam system allowing 6.0-s steady-state He-NBI. Delivered powers on the order of 0.7-0.8 MW per unit (at 60 keV injection energy) are routinely available for up to 6.0-s pulses. Four units of NBI system, each consisting of 11 positive-ion source NBI units, are available for He-NBI.

In a situation with a simultaneous source and sink of helium, the global He particle balance equation is described by

$$dN_{He}/dt = S_{He} - Q_{He} \tag{1}$$

where N_{He} is the total number of He ions in the plasma, S_{He} and Q_{He} are the instantaneous He source and exhaust rates, respectively. The He exhaust rate can be written as N_{He}/τ_{He} - $R_{He}N_{He}/\tau_{He}$, where R_{He} is the global He recycling coefficient and $R_{He}N_{He}/\tau_{He}$ includes the recycling flux returning to the plasma and the exhausted flux. Then this equation takes on the familiar form:

$$dN_{He}/dt = S_{He} - N_{He} / \tau^*_{He} \tag{2}$$

where $\tau^*_{He} = \tau_{He}/ (1 - R_{He})$. The general solution to this equation for a source turning on at time t_0 is:

$$N_{He}(t) = N_{He}(t_0) + \left[S_{He}\tau^*_{He} - N_{He}(t_0)\right]\left\{1 - exp\left[-\left[\frac{(t - t_0)}{\tau^*_{He}}\right]\right]\right\} \tag{3}$$

provided S_{He} and τ^*_{He} are constant for $t > t_0$.

The enrichment factor of He was defined by $\eta_{He} = [P_{He}/2P_{D2}]_{div}/[n_{He}/n_e]_{main}$, where $[P_{He}/2P_{D2}]_{div}$ is the ratio of the He neutral pressure to the deuterium neutral pressure in the divertor and $[n_{He}/n_e]_{main}$ is the ratio of the He density to the electron density in the main plasma. It is a key parameter to reduce pumping speed of divertor pumping for future fusion reactors (i.e., $\eta_{He} \geq 0.2$), such as ITER. Both helium and fuel particles are simultaneously exhausted with divertor pumping. The higher He enrichment factor means that the required pumping speed is lower and leads to reduce tritium inventory.

4.1. Attached plasmas

In the new divertor, effective He exhaust was demonstrated with He beam injection of $P_{He\text{-}NB}$ = 1.4 MW, which corresponds to He fueling rate of 1.5×10^{20}/s (equivalent to 85 MW a heating) for 6 s into ELMy H-mode discharges. Figure 2 shows the time evolution of the electron density, the fueled D_2 gas, total injected NB power, He density, He I and D_α intensities in the divertor, the neutral pressure of He and D_2 below the outer baffles in an ELMy H-mode discharge (I_P = 1.4 MA, B_t = 3.5 T, P_{NB} = 13 MW, $q_{95\%}$ = 4.0, V_P = 58 m^3). The line-averaged electron density in the main plasma is $\overline{n}_e = 3.4\times10^{19}$ m^{-3}, which corresponds to 0.5 of Greenwald density limit, and the central ion and electron temperatures are $T_i(0)$ = 3.2 keV and $T_e(0)$ = 3.1 keV in the ELMy H-mode plasma. Deuterium gas of about 30 Pa·m^3/s is puffed to keep the electron density constant by a density feedback control. With He pumping, the He density measured by CXRS reached a steady state at 1.2 s after the start of the He beam injection, which was $n_{He} = 1.4\times10^{18}$ m^{-3} (r/a = 0.24) at t = 12 s. The He concentration reached 4% of the electron density in the main plasma and was kept constant for 4 s. This indicates that the He source rate (equivalent to 0.6 Pa·m^3/s) from the He beam injection is balanced by the exhaust rate with He pumping. In this discharge, τ^*_{He} = 0.7 s and τ^*_{He}/τ_E = 4 with τ_E = 0.18 s and an H-factor($\equiv\tau_E/\tau_E^{ITER\text{-}89P}$) = 1.3 were achieved, well within the range generally considered necessary for successful operation of future fusion reactors (i.e., $\tau^*_{He}/\tau_E \leq 10$), such as ITER.

The D_2 neutral pressure below the outer baffles reached a steady-state level of $P_{baffle\text{-}D2}$ = 0.35 Pa at t = 9 s. The He neutral pressure gradually increased and reached a steady-state level of $P_{baffle\text{-}He}$ = 0.03 Pa at t = 11 s. The He enrichment factor was estimated to be 1.0±0.2 from the He and D_2 neutral pressure at t = 12 s, which is 5 times larger than the ITER requirement of η_{He} = 0.2.

A similar ELMy H-mode discharge was performed closing the shutter valves in front of cryopumps. This condition of closed shutter valves is called "without He pumping". Without He pumping, the He concentration linearly increased up to 10% at 5 s after the start of the He beam

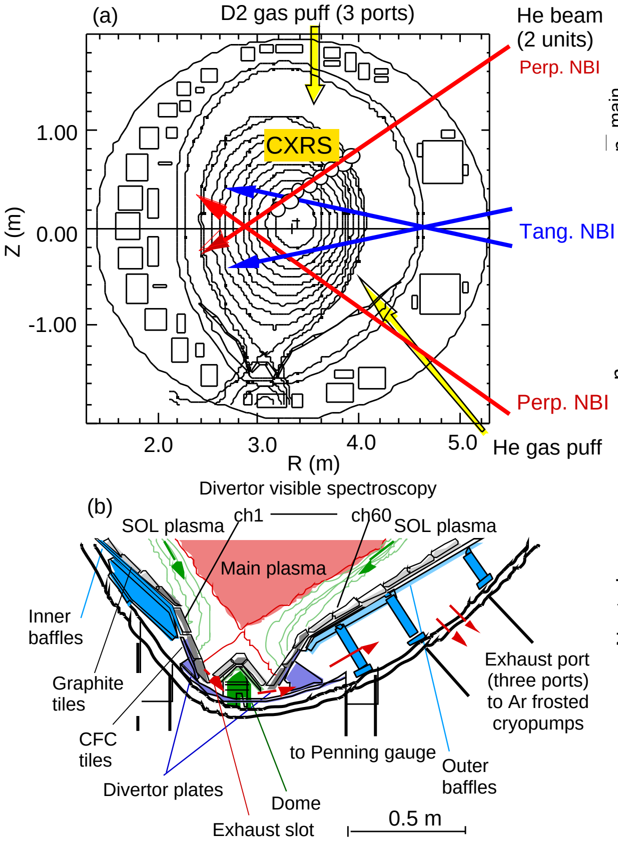

FIG. 1. (a) The cross section of an ELMy H-mode plasma in He exhaust experiments. The directions of He-NBI and heating NBI, the locations of He and D2 gas puff, and the viewing position of CXRS for the He density measurement are shown. (b) The structure of W-shaped pumped divertor of JT-60U after the divertor modification.

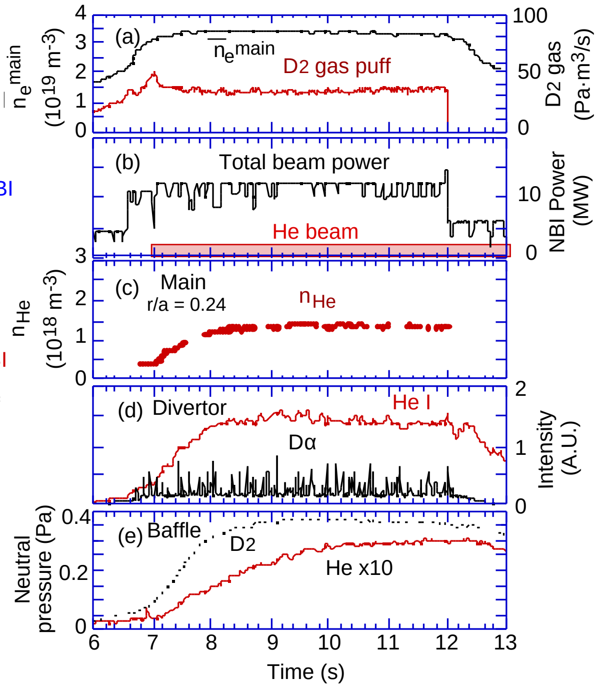

FIG. 2. Time evolution of the (a) plasma density and fueled D2 gas, (b) total injected beam power and He beam power, (c) He density at r/a = 0.24, (d) He I and Dα intensities in the divertor, and (e) neutral pressure of He and D2 below the outer baffles in an ELMy H-mode plasma. In steady state, the He source rate from the He beam injection is balanced by the exhaust rate.

injection, which was 2.5 times as much as that with pump in Fig. 3. Without He pumping, τ^*_{He} = 3.7 s and τ^*_{He}/τ_E = 21 were obtained. However, a good enrichment factor of η_{He} = 0.5 was obtained without He pumping.

Helium exhaust experiments using a short He gas puff were performed to compare with those using He beam injection. Figure 4 shows the time evolution of He density at r/a = 0.66 with and without He pumping using a short He gas puff. The line-averaged electron density of $\overline{n_e}$ = 2.7×10^{19} m^{-3} is lower than the one in the above discharges. With and without He pumping, τ^*_{He} = 1.2 s and τ^*_{He} = 10.2 s were obtained, respectively. The time evolution of He density without pumping has two decay characteristics just after the He gas puff and later at t = 9.0 s by detailed viewing. This implies that helium exhaust by "the reservoir effect" is slightly observed even though without He pumping. The vacuum space of V_{baffle} = 20 m^3 below the outer baffles is filled with helium even when the pumping is not active, so that this space acts like a helium reservoir. Actually, helium exhaust is accomplished by the He pumping capability including the reservoir effect.

4.2. Detached plasmas

Effective He exhaust was also demonstrated with He beam injection into an ELMy H-mode discharge (I_P = 1.7 MA, B_t = 3.5 T, P_{NB} = 12 MW) with detachment. The line-averaged electron density in the main plasma is $\overline{n_e}$ = 6.7×10^{19} m^{-3}, which corresponds to 0.8 of Greenwald density limit, the central ion and electron temperatures are $T_i(0)$ = 2.5 keV and $T_e(0)$ = 2.3 keV in the

ELMy H-mode plasma. Deuterium gas of about 100 Pa·m^3/s is puffed to keep the electron density constant. The He density reached a steady state (n_{He} = 8.3×10^{17} m^{-3} at r/a = 0.66) at 1.0 s after the start of the He beam injection with He pumping. The He concentration reached 1.3% of the electron density in the main plasma and was kept constant. In this discharge, τ^*_{He} = 0.5 s and τ^*_{He}/τ_E = 3 (H-factor = 1.0) were achieved. In the other discharge (I_P=1.4 MA, B_t = 3.5 T, P_{NB} = 12 MW, $\overline{n}_e$ = 5.8×10^{19} m^{-3}, $\overline{n}_e/n^{Gr}$ = 0.8), τ^*_{He} = 0.6 s and τ^*_{He}/τ_E = 4 (H-factor = 1.0) were achieved. The He density with He pumping reached a steady state (n_{He} = 9×10^{17} m^{-3} at r/a = 0.66) and the He concentration reached 1.6% of the electron density in the main plasma. This result of the helium exhaust is sufficient to support a detached divertor operation on ITER.

In attached plasmas, an inboard-enhanced He flux and D flux profiles were observed. After a divertor detachment occurred, however, the inboard He and D fluxes decreased and the outboard fluxes increased, and then those flux profiles were almost in-out symmetry.

4.3. Helium exhaust capability

The He exhaust capability was investigated in attached and detached plasmas. Figure 4 shows the ratio of τ^*_{He}/τ_E as a function of the line-averaged electron density $\overline{n}_e$ in the main plasma. In attached plasmas, τ^*_{He} decreases and therefore the exhaust efficiency of τ^*_{He}/τ_E increases with increasing $\overline{n}_e$. The recycling flux of deuterium is not enhanced in low density ELMy H-mode discharges. Indeed, the enhancement of the recycling flux of He is difficult at $\overline{n}_e$ = 2-3×10^{19} m^{-3}. The He recycling flux is exponentially enhanced with increasing $\overline{n}_e$. In detached plasmas, the in-out asymmetry with deuterium and He flux was relaxed. However, τ^*_{He}/τ_E is comparable to the one in attached plasmas because of high recycling particle flux at the inner strike point in high density operation. In JT-60U, good confinement (H ≥ 2) is incompatible with high density ELMy H-mode plasmas by using D2 gas puff. However, the He exhaust capability of τ^*_{He}/τ_E = 3 in detached plasma seem to be sufficient to apply in future reactors.

At reversed I_P and B_t, τ^*_{He} is 2-3 times as long as compared to normal I_P and B_t. The inner He flux and D flux were higher than the outer flux at normal I_P and B_t (the ion grad-B drift direction towards the target) in an ELMy H-mode discharge. On the other hand, an outboard-enhanced He flux and D flux were observed at reversed I_P and B_t (the ion grad-B drift away from the target) in an ELMy H-mode discharge. The in-out asymmetry of the He and D flux profiles depends on the ion grad-B drift direction in these discharges. The He exhaust efficiency at reversed I_P and B_t was low because of the in-out asymmetry of the He flux and D flux profiles. The neutral pressure below the outer baffles was low as expected because of the outboard enhanced particle flux profiles.

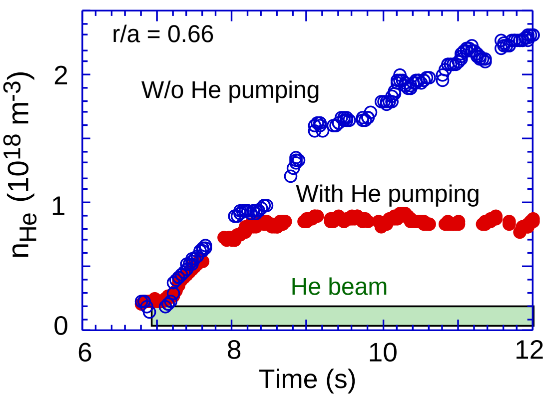

FIG. 3. Time evolution of the measured He density with and without He pumping. The He density with He pumping reaches a steady state at 1.2 s after the start of the He beam injection.

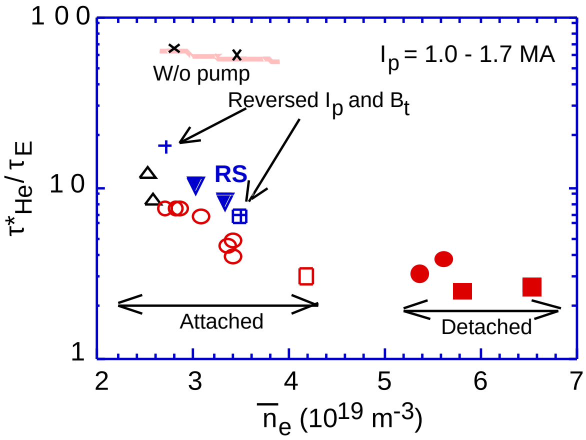

FIG. 4. The ratio of τ^*_{He}/τ_E confinement time of helium as a function of the line-averaged electron density in the main plasma in various operation modes (attached and detached divertor, reversed I_P and B_t, with and without He pumping).

5. HELIUM EXHAUST IN REVERSED SHEAR PLASMA

In reversed shear plasmas of JT-60U, the profiles of $n_e(r)$, $T_e(r)$ and $T_i(r)$ inside the ITB are peaked and the confinement inside the ITB is remarkably enhanced. The He particle confinement inside the ITB was improved. He density profile depends on a strength of ITB. Helium particle confinement is enhanced by ITB formation [7]. Helium removal from the central region of reversed shear plasmas is an important issue for advanced tokamak reactors.

Helium exhaust characteristics in the reversed shear plasma (I_P = 1.7 MA, B_t = 3.7 T and $\overline{n}_e = 3\times10^{19}$ m^{-3}) were investigated by using a short pulsed He gas puff (edge fueling) as shown in Fig. 5. In this discharge, the ITB was sustained with P_{NB} = 6 MW until the end of NB heating (t = 8.0 s). The line averaged electron density at the central region gradually increased. The central ion temperature of 8-10 keV was kept and H-factor of 1.6 - 2.0 were achieved during the NB heating with the constant NB power. The profiles of $T_i(r)$, $T_e(r)$ and $n_e(r)$ in the reversed shear discharge have steep gradients at the ITB region (r/a = 0.5 - 0.6) as shown in Fig. 6. The He density profiles changed with time by He gas puff (Fig. 6 (c)). The He density profile at t = 5.7 s after the He gas puff (t = 5.4 - 5.6 s) is broad by the He fueling from the edge plasma. Then the He density profile became peak due to the transport characteristics at t = 6.3 s. After that, the $n_{He}(r)$ profile became similar to the $n_e(r)$ profile with He pumping.

Figure 7 shows the time evolution of the He density at r/a = 0.21 and r/a = 0.64 in the reversed shear plasma. The decay time of the He density (equivalent to the local τ^*_{He}) at r/a = 0.21 inside the ITB is τ = 4.2 s. While the decay time at r/a = 0.64 outside the ITB is τ = 2.2 s. The He residence time inside the ITB is 1.9 times as long as that outside the ITB. This result indicates that it is difficult to remove helium particles inside the ITB as compared with those outside the ITB as predicted from the previous result. This is due to the improvement of He particle confinement inside the ITB. If the decay time of the He density inside the ITB is assumed as the local τ^*_{He}, the ratio of τ^*_{He}/τ_E = 8 - 10 were achieved, within the range generally considered necessary for successful operation of future fusion reactors. In reversed shear plasmas, efficient He exhaust was realized at the first time.

The He exhaust efficiency depends on the ITB formation. When a strong ITB was formed, the central electron density increased with time and a partial collapse or a major collapse

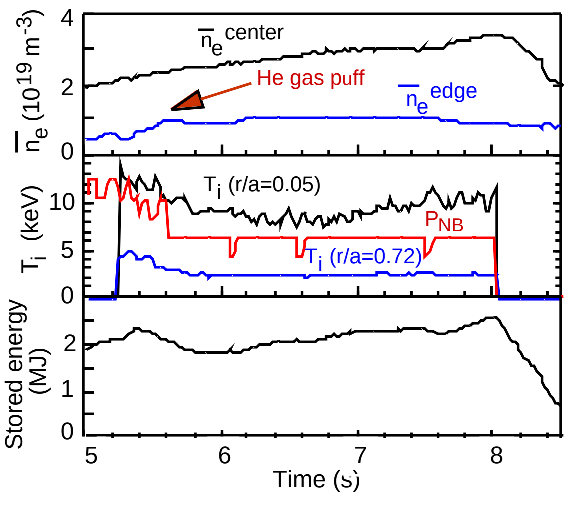

FIG. 5. Time evolution of a typical reversed shear discharge (I_P = 1.7 MA, B_t = 3.73 T, vol. = 65 m^3, P_{NB} = 6 MW) with He pumping.

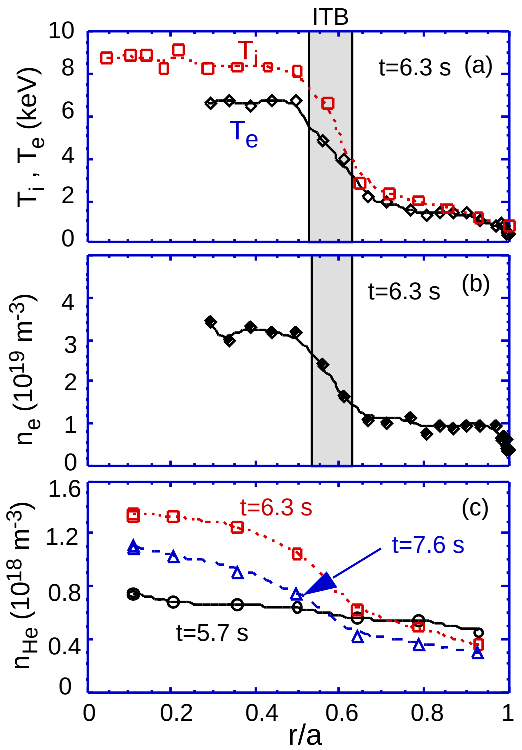

FIG. 6. (a) Ion and electron temperature profiles, (b) electron density profile and (c) He density profile in reversed shear plasma. He gas was puffed at t = 5.4 - 5.6 s.

occurred because of the MHD instability. In this discharge, a steeper pressure gradient at the ITB position was formed and helium particle confinement was enhanced. In the case of a strong ITB, the He density inside the ITB was not reduced and increased even though with He pumping. While He removal outside the ITB was observed and the decay time is τ = 2.2 s. Comparing the case of no pump, He removal inside the ITB was not clearly observed. The He density outside the ITB was almost kept constant without He pumping. It was found that He removal inside the ITB was difficult in this type of reversed shear discharges. Helium transport is not sufficient to remove He particles inside the ITB. High efficient He exhaust outside the ITB is required in order to obtain good He exhaust efficiency inside the ITB.

Helium exhaust in the reversed shear plasma of hydrogen (I_P = 1.2 MA and B_t = 3.5 T, $\overline{n_e}$ = 2.4×10^{19} m^{-3}) were also performed. Figure 8 shows the time evolution of the He density at r/a = 0.13 and r/a = 0.81 in the reversed shear mode. The decay time of the He density at r/a = 0.13 inside the ITB (r/a = 0.4- 0.5) is τ = 5.5 s. While the decay time at r/a = 0.81 outside the ITB is τ = 1.9 s. The He residence time inside the ITB is 2.9 times as long as that outside the ITB. In this case, the He exhaust efficiency was not favorable to remove helium inside the ITB.

This behavior of helium in reversed shear modes is clearly different from that in ELMy H-modes. The decay time is almost constant at the center and the peripheral region in ELMy H-modes. In general, τ^*_{He} is defined as the global residence time from the decay time of total helium particles. However, the He residence time in reversed shear plasmas should be newly expressed as the local residence time. In a fusion reactor, the burning efficiency is large near the central core plasma due to high temperature and high density. Therefore, it is necessary to consider the local weight of the burning efficiency for a reversed shear operation.

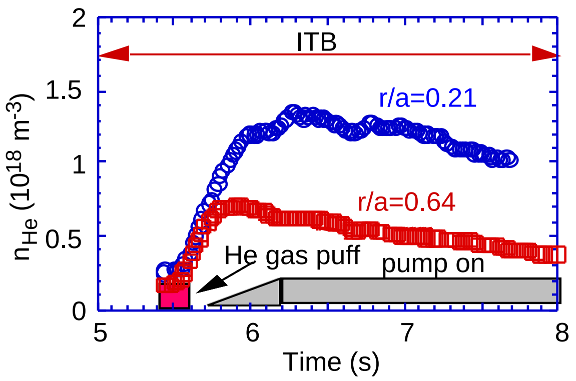

FIG. 7. Comparison of the time evolution of the He density at r/a = 0.21 inside the ITB and r/a = 0.64 outside the ITB in a reversed shear plasma (I_P = 1.7 MA, B_t = 3.73 T, vol.= 65 m^3, P_{NB} = 6 MW, deuterium) with He pumping.

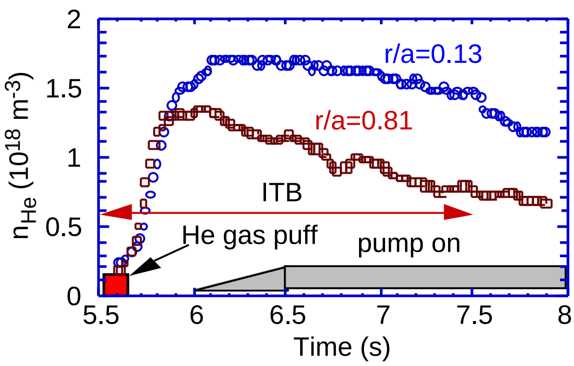

FIG. 8. Comparison of the time evolution of the He density at r/a = 0.13 inside the ITB and r/a = 0.81 outside the ITB in a reversed shear plasma (I_P = 1.2 MA, B_t = 3.5 T, vol.= 60 m^3, P_{NB}=8 MW, hydrogen) with He pumping.

6. CONCLUSIONS

Efficient He exhaust was realized with He pumping using Ar frosted NBI cryopumps and the W-shaped pumped divertor on JT-60U. Neutral beams of 60 keV helium atoms were injected into ELMy H-mode plasmas for 6 s. In these discharges, the He source rate (equivalent to 0.6 $Pa{\cdot}m^3/s$) is balanced by the exhaust rate with He pumping. In steady state, good He exhaust capability (τ^*_{He}/τ_E = 4) was successfully demonstrated in ELMy H-mode plasmas. The enrichment factor of He was estimated to be about 1.0, which is 5 times larger than the ITER requirement of 0.2. The exhaust rate increased with the line averaged electron density. Even without He pumping, an enrichment factor of 0.5 was obtained by the geometry effect of the W-shaped divertor. It seems that the reflection of He neutral particles near the inner strike point is enhanced by the vertical divertor and the dome. These results strongly support the existing divertor designs of ITER.

In detached ELMy H-mode plasmas, τ^*_{He} is comparable to the one in attached plasmas because recycling particle flux is enhanced at the inner strike point in high density operation. Helium exhaust capability of τ^*_{He}/τ_E = 3 in detached plasmas enables an ITER divertor operation scenario. The inner leg pumping worked well for He exhaust because of the inboard-enhanced He flux and D flux at normal I_P and B_t (the ion grad-B drift direction towards the target). The in-out asymmetry with He and deuterium flux profiles strongly affects the He exhaust capability.

Helium exhaust characteristics of reversed shear plasmas has been studied by using a short pulsed He gas puff in the W-shaped divertor of JT-60U. Helium removal inside the ITB is about two times as difficult as that outside the ITB in reversed shear discharges. If the decay time of the He density inside the ITB is assumed as the local τ^*_{He}, the ratio of τ^*_{He}/τ_E = 8 - 10 were achieved and efficient He exhaust was realized with He pumping and the W-shaped divertor. The He residence time in reversed shear plasmas should be newly considered as the local residence time.

ACKNOWLEDGMENTS

The authors would like to thank the members of the Japan Atomic Energy Research Institute who have contributed to the JT-60 project.

REFERENCES

[1] Kikuchi, M., Nuclear Fusion **30** (1990) 265.
[2] ITER Detail Design Report (Nov. 1996).
[3] Hillis, D.L. et al., Phys. Rev. Lett. **65** (1990) 2382.
[4] Nakamura , H. et al., Phys. Rev. Lett. **67** (1991) 2658.
[5] Sakasai, A. et al., Proc. 15th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research (Seville, 1994), IAEA, Vienna, Vol. **2** (1995) 95.
[6] Sakasai, A. et al., J. Nucl. Mater. **220-222** (1995) 405.
[7] Sakasai, A. et al., Proc. of the 16th Int. Conf. on Fusion Energy (Montreal, 1996), IAEA, Vienna, Vol. **1** (1997) 789.
[8] Wade , M.R. et al., J. Nucl. Mater. **220-222** (1995) 178.
[9] Wade, M.R. et al., Proc. of the 16th Int. Conf. on Fusion Energy (Montreal, 1996), IAEA, Vienna, Vol. **1** (1997) 801.
[10] Bosh, H.-S. et al., Proc. of the 16th Int. Conf. on Fusion Energy (Montreal, 1996), IAEA, Vienna, Vol. **1** (1997) 809.
[11] Asakura, N. et al., Nucl. Fusion **37** (1996) 795.
[12] Reiter, D. et al., Nuclear Fusion 30 (1990) 2141.
[13] Hosogane, N. et al., Proc. of the 16th Int. Conf. on Fusion Energy (Montreal, 1996), IAEA, Vienna, Vol. **3** (1997) 555.
[14] Fujita, T. et al., Phys. Rev. Lett. **678** (1997) 237.