Investigation of hydrogen recycling property and its control with hot wall in long duration discharges on QUEST

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Abstract. Fully non-inductive plasma maintenance was successfully achieved by a microwave of 8.2GHz, 40kW up to more than 1h55min with well-controlled plasma-facing wall (PFW) temperature of 373 K using a hot wall on the middle sized spherical tokamak, QUEST of which the PFW is composed of atmospheric plasma splay tungsten (APS-W) and stainless steel. Fuel hydrogen (H) behavior in PFW has been investigated with measuring injecting and evacuating hydrogen molecules (H_2) into the plasma-producing vessel. A fuel particle balance equation based on the H barrier is applied to the longest duration discharge, and it found the model could well-predict it. Higher wall temperature is likely to give rise to faster wall saturation and the capability of the hot wall to control fuel recycling and wall pumping properties is successfully demonstrated.

1. Introduction

Steady state operation (SSO) of magnetic fusion devices is one of the goals for fusion research. As for SSO of spherical tokamaks (STs), issues related to non-inductive plasma maintenance and plasma-wall interaction (PWI) are highly addressed. As for PWI, there are wide-range of issues, which are complicatedly linked each other in the material science matter as well as plasma. Especially, power and particle balances during plasma discharges are an essential subject to establish SSO. The world record of plasma duration on tokamaks for more than 5h16min was achieved in TRIAM-1M [1], where an accurate power balance of the discharge was investigated [2] and a particle balance was also studied [3]. The power balance of the discharge seems to be complete, because every monitor of temperature on plasma facing materials (PFMs) kept constant [4]. However, the longest plasma was spontaneously abruptly terminated and the reason is still unclear. One candidate is a tiny unbalance of particle, because in the middle of the discharge, wall pumping did not work and then unacceptable hydrogen (H) or hydrogen molecule (H_2) release from the wall was expected to happen. Density control by gas-puffing got difficult, and finally lead to plasma termination. No one know why the H behavior in the material was changed during the discharge. Therefore to investigate the capability of H behavior is essential to establish SSO.

Moreover long term tritium (T) retention in PFMs is one of the most important issues and application of metal PFMs is promising to avoid unacceptable T retention for future fusion power plants. The ITER-like wall (ILW) project has been promoted in JET for the prediction of T retention in coming ITER D-T operation and significant reduction of long term deuterium (D) retention in ILW has been achieved [5]. Alternatively, short term (dynamic) retention may play an essential role in fuel circulation of the ILW [6] and it sometimes leads to be out of density control through excess in fuel supply due to exorbitant fuel recycling. Moreover, it is well known that higher fuel recycling is likely to drive lower plasma confinement [7]. Thus as the fuel circulation has a significant impact on plasma performance, investigation of dynamic retention characteristics is still indispensable.

Recently, maintenance of “detachment of plasma” around a divertor plate is a crucial issue for preventing from reaching huge heat load to PFM. Tentative heat load accompanied with edge localized mode (ELM) frequently breaks the detachment condition, and the recovery to detachment is significantly delayed by wall pumping enhanced by newly-developed deposition layer due to ELM related heat and particle fluxes [8]. To estimate how many particles are able to be stored into the newly developed PFWs, the understanding wall pumping behavior should be investigated in the view of divertor action.

Fully non-inductive plasma start-up and its sustainment was successfully demonstrated on the spherical tokamak QUEST, using a well-controlled microwave source at 8.2 GHz RF up to a power of 100 kW [9-10] and power [11] and particle balances in long duration discharge has been studied. QUEST is a distinguishing tokamak-type devices to provide a capability of long duration discharges [12, 13] and, in fact, has already obtained good reproducibility of more than 10 min non-inductive RF driven plasmas [14]. A fuel particle balance has been investigated in the long duration discharges on QUEST and a plausible explanation has been proposed [15].

In this paper, we reports time evolutions of wall pumping in dynamic retention dominant wall in long duration discharges, plausible explanation of the progress of wall pumping rate, and the capability of the hot wall to control wall pumping. In the next section, experimental apparatuses of QUEST and historical progress to achieve long duration discharges are introduced, and experimental results are shown in the section 3, including the first experimental result of the hot wall. The contents are summarized in the section 4.

2. Experimental apparatus and Historical progress in SSO

The schematic cross-sectional view of QUEST [11-14] is shown in Fig. 1. Four pairs of poloidal field (PF) coils, three separated center solenoid (CS) ones and a pair of horizontal magnetic field ones are installed on QUEST to form various magnetic configurations. A pair of cancellation coils to form a field null for ohmic heating are also installed. Each coil can operate individually to form various configurations. Three types of microwaves of 2.45GHz [2]: < 50kW, 8.2GHz: < 400kW (one system consists of eight 25 kW klystrons) [12] and 28GHz, 300kW [16-18] are available to drive plasma current and heat plasmas, and they have the capability to operate in steady state except the 28 GHz system.

The vacuum vessel in the high field side (center-stack vessel) is completely covered by a center-stack vessel cover made of stainless steel of 3mm in thickness coated by atmospheric W plasma spray (APS-W) of 0.1mm in thickness. Four fixed water-cooled limiters made of W blocks are installed at the mid-plane in four, equally distributed, toroidal locations and these protrude out from the center-stack vessel cover by 15 mm. Two fixed water-cooled limiters made of a W block are also installed at the upper positions, 85 cm above the mid-plane, at two toroidal locations equally separated from each other. The vacuum vessel in the low field side has been modified to the hot wall made of stainless steel type 316L coated with APS-W of 0.1mm in thickness as shown in Fig. 2. The hot wall was installed on QUEST since 2014 autumn/winter (A/W) campaign and its operation began in the middle of 2014A/W. The hot wall has 24 x 2 heater-cooling panels on top and bottom conical areas as shown in Fig. 2, and thermal insulation to the vacuum vessel of which temperature should be lower than 423K to protect plasma-heating devises and diagnostics. In the mid-plane area, a thin 316L sutainless panel with arropriate hole to install something from ports and a radiation shield is used to aviod to deliver heat load to unexpected areas. The vacuum vessel is covered by lagging materials and its air-side surface temperature is regulated in lower than 323K to avoid burn injury for human.

The top flat-divertor is composed of 16 panels made of stainless steel coated with W of 0.1mm in thickness. These divertor plates also contain four fixed limiters made of W block as shown in Fig. 1. Four water-cooled divertor limiters made of W block tightly connected to copper (Cu) blocks are installed on the top divertor panels, and have been available since the 2011 S/S campaign. The W side faces the plasma and the Cu side connects to the inlet and outlet water cooling channels. The W block on each of them protrudes out by 5 cm from the top divertor plates. A pair of electrode made of stainless steel type 304L is installed for coaxial helicity injection (CHI) experiment and one electrode is electrically insulated by ceramic plates from the vacuum vessel.

Overall, approximately 20 m^2 faces the plasma, and out of this 5.6 m^2 of stainless steel surface faces the plasma and the other 14.1 m^2 is covered with W or APS-W. Two movable water-cooled limiters made of W block was install to effectively remove heat load from energetic electrons [11].

Historical progress for SSO on QUEST during the 2010-2016 campaigns is summarized in Fig. 3. The progress during 2010-2012 and typical magnetic configurations are referred in Ref 11. Since the 2012 S/S campaign, reasonable power balance could be achieved at the power level (100 kW) and the main issue is now shifting to particle balance [11]. Since 2014 A/W campaign, the hot wall has been installed and active heating of the hot wall is available, but active cooling is not working because of lack of connection of water-cooling channel at present. As the hot wall is always exposed on heat load from the plasma such as charge exchange neutrals and escaping plasma and radiation during plasma discharges, surface temperature of the hot wall was raised by approximately 10-20 degree in the 1h55min discharge. The PFWs in the mid-plane areas is composed of the thin stainless steel panel and its temperature is likely to be raised, although it does not have active heating. In the beginning of each plasma discharge, the temperature of the PFWs in the mid-plane area is lower than the hot wall itself and reaches frequently to the similar temperature during long duration discharges. It should be noted that this different time evolution of each PFW gives rise to complicate wall behavior and may lead to inaccuracy of understanding. Increment of the PFW temperature is independent on wall temperature at the beginning of the discharge and tendency of wall behavior depending on its surface temperature can be isolated. Complete control of the wall temperature with installing active cooling instrument is future work.

3. Experimental results

The first experiment with the hot wall was performed in 2014 autumn/winter campaign (shot no. 28707). Shot history of plasma current, H_α radiation, $I_{H\alpha}$, and OII radiation, I_{OII}, are plotted during the first four experimental days for the hot wall operation in Fig. 4. The hot wall temperature was adjust to 473K. Exorbitant $I_{H\alpha}$ was observed at the first day and no plasma current start-up was obtained. The peak of I_{OII} was retarded by almost ten discharges from the peak of $I_{H\alpha}$. It should be noted that the injected RF power, magnetic configuration and plasma duration (~30 s) are similar except the third day. In the last discharge of the first day, $I_{H\alpha}$ was still higher than that without the hot wall operation. In the next day, the level of $I_{H\alpha}$ was gradually reduced shot by shot. In the middle of the second day, small plasma current was observed and the plasma current was gradually increasing. Finally the plasma current reached to 6 kA on the second day. This clearly shows that the hot wall experiment was ready.

In 2015 Autumn/Winter campaign, several 1000 s discharge on the inboard (IB) null configuration [19] was obtained with the hot wall temperature of 473K, and an 1h55min discharge on a limiter configuration could be achieved in 2016S/S campaign with the hot wall temperature of 393K. The typical waveforms of the longest discharge are shown in Fig. 5. The plasma current was reconstructed with hall-generator signals [20]. Although the plasma density and current was extremely low, the limiter configuration with aspect ratio of 1.8 was formed according to magnetic analysis in similar discharges. Intensity of H_α, $I_{H\alpha}$ was controlled to be constant with a developed feedback system [20]. A collisional radiation (CR) model predicts a proportional relation between $I_{H\alpha}$, and ionization rate of hydrogen (H), Γ_{ion}. in the wide range of electron density (10^{17}-10^{19} m^{-3}) and temperature (10-50 eV). In steady state condition, Γ_{ion} should be balanced with loss fuel of H, Γ_{loss}. The lost H ions is reached to PFMs and play a partial role in H flux into PFMs. Normally charge exchange (CX) neutrals get higher energy in the interaction of ions and is likely to reach rapidly to PFMs. The CR model calculation indicates that the CX neutral flux is almost proportional to $I_{H\alpha}$ and is approximately one-third of Γ_{ion} in the present condition on QUEST. Therefore, $I_{H\alpha}$ is a good indicator to control the amount of in-coming H flux to PFMs [21]. It found that $I_{H\alpha}$ could not be controlled after approximately 4000s and the less- controllability of plasma density frequently induces a drastic plasma modification and a plasma termination as shown in Fig. 5 around 6900 s. In the discharge, the plasma is difficult to maintain a closed-flux surface and shifts to electron cyclotron resonance (ECR) plasma. In-vessel H_2 pressure was monitored with a quadrupole mass analyzer (QMS) which is directly installed on the vacuum vessel and is covered with magnetic material to avoid effect of QUEST-oriented magnetic field. Plasma density and temperature in the far-scrape-off layer (SOL) region was measured with a reciprocating probe [22] and the time evolution of density is similar with those of the core plasma.

Before installation of the hot wall, the whole surface of the QUEST PFW was intensively investigated with ellipsometry, transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), and self-developed colorimetry [23], and it is found that the top and bottom halves of the PFW are covered with thin (<10 nm) and thick (50-100 nm) deposition layers composed of carbon, W and SS materials, respectively. Especially deuterium (D) storing capability of QUEST plasma exposed specimens is measured with implantation of D_2^+ ions and consequent thermal desorption spectroscopy (TDS) [15] and with NRA during D plasma exposure, which provide a proof of a little permeation to substrate. D is hardly observed in the substrate. Consequently a barrier for hydrogen is formed around boundary between deposition layer and the substrate and a wall model with hydrogen barrier (HB) was proposed [15]. The HB model being different from conventional diffusion and recombination limiting models [24] takes the difference of chemical potential of H-isotope in between deposition layer and substrate into consideration and consequently assumes the HB at the boundary. The HB model prediction is applied to the study of particle balance in long duration plasmas with the hot wall on QUEST. The global H storing capability in the PFW measured with the difference between incoming and out-going H has a significant relation to H flux to the PFW and wall temperature experimentally, and the HB model can quantitatively fit its property as shown in Eq. (1). We can obtain an equation to express the time evolution of wall pumping at a certain hydrogen flux, Γ_{in} under the assumption that H diffusion in the deposition layer is significantly fast as the followings,

$$\begin{aligned} \frac{d(H_W + H_T)}{dt} &= \Gamma_{in} S - \frac{k}{S d_R^2} H_W^2 \\ \frac{dH_T}{dt} &= \alpha H_W \left(1 - \frac{H_T}{H_T^0}\right) - \gamma H_T \end{aligned} \qquad (1).$$

Here H_W, H_T, H_T^0, S, Γ_{in}, k, d_R, α, and γ are the number of H dissolved in wall material, the number of H trapped in defects, the upper-limit number of H trapped in defects, surface area, net influx per unit of area into wall material, surface recombination coefficient of H atoms, and thickness of deposition layer, H trapping rate, and de-trapping rate respectively. Normally thickness of deposition layer is less than 100 μm and H diffusion in the layer is sufficiently fast. The equation (1) indicates that dH_W/dt has a parabolic relation of H_W as long as H_T can be negligible.

The relation as described above was examined by the longest duration discharge on QUEST. The time evolutions of wall-pumping rate, dH_W/dt is always derived from the difference between injecting with evacuating H_2 flux. The wall stored H, H_W+H_T can be obtained by time-integration of $d(H_W+H_T)/dt$ setting default value at zero. On the QUEST wall, dynamic retention of H is dominant even when the wall drops into a room temperature (RT) as uncontrolled state. The wall controlled at higher temperature is rather active and most of wall-stored H is always released during shot interval. The absolute number of H_W is calibrated with a manometer installed in the H_2 gas fueling line. The volume of the fueling line was measured and the variation of its pressure is measured with the manometer. Thus, the absolute number of H_2 gas can be obtained. The gas fueling system has a flowmeter being regulating H_2 gas flux and H_2 gas is always injected with the flowmeter except an initial gas for plasma breakdown. When no plasma exist in the vessel which is always evacuating with a turbo molecular pump and four cryopumps. A quadrupole mass analyzer (QMS) has been placed on the bottom plate of the vessel that three cryopumps are also installed. Before plasma experiment, H_2 gas is injected with the flowmeter in ten levels of flux, and saturated partial pressures of H_2 in every level are measured with the QMS. Consequently, the QMS signal can indicate absolute H_2 flux evacuating from the vessel. The injecting H2 flux is always monitored with the manometer. Absolute $d(H_W+H_T)/dt$ can be derived from both the injecting and evacuating H_2 flux calibrated with the same manometer.

Time variations of wall pumping rate, $d(H_W+H_T)/dt$ in the longest discharge with the hot wall temperature, T_W of 393 K (#32737) and in the discharge with T_W of 473 K (#32700) are plotted as a function of wall stored H as shown in Fig. 6. The parabolic relation is clearly observed in low H_W and this suggests the proposed HB model expresses the fuel H balance in the longest discharge on QUEST. In the initial phase of the discharges (less than 1 x 10^{20} wall stored H), the measured data are scattered and it basically gives rise to uncontrollability of H_α signal in developed feedback system. Therefore it should be noted that the calculation results are able to compare with data larger than 10^{20} H on the horizontal axis. The value of $d(H_W+H_T)/dt$ at $H_W+H_T=0$ should be correspond to Γ_{in} S according to Eq. (1), and this can be also confirmed by the measured H flux into the wall with plasma-induced permeation probes (PDPs) [25]. In the region of H_W+H_T higher than 3x10^{20} H, the relation is not so well-adjustable to the predicted equation ignoring H_T. We try to calculate the Eq. (1) directly with the values of H_T^0, α, and γ

estimated by the microscopic analysis of plasma exposed specimen [15]. The given curve is well-fitted to the experimental observation. Here we can use the same value of recombination coefficient in Ref 15 and it suggests that the surface condition of PFMs is not so different from previous QUEST experiments without the hot wall. The microscopic investigation should be required to understand the wall condition.

4. Summary

Non-inductive plasma start-up and maintenance were successfully demonstrated with RF induced current drive on QUEST and the longest duration of plasma maintenance reached to 1h55min during which the well-predicted fuel particle balance was confirmed. The possibility of the wall temperature control to modify the wall pumping rate is successfully demonstrated using the hot wall capability.

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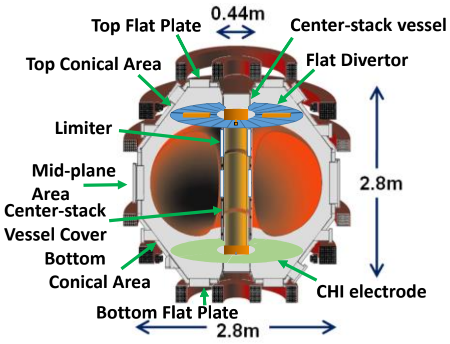

Fig. 1 Schematic view of QUEST is illustrated. Flat divertor panels coated by W plasma spray are installed in the upper side and a pair of electrode is installed for coaxial helicity injection (CHI) in the lower side of the vacuum vessel. In this figure, the hot wall installed in low field side is not

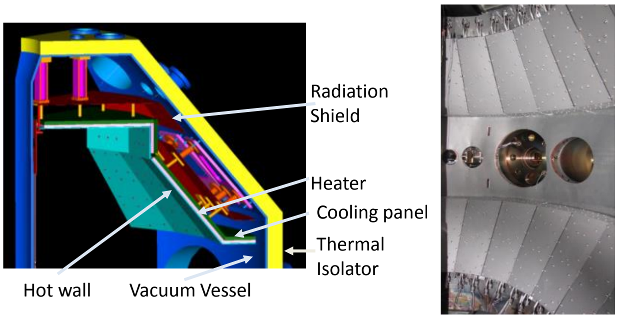

Fig. 2 Left: Cross-sectional view of the hot wall, which are composed of heater-cooling panels and a trifarious radiation shield, is shown. Right: Present status of the hot wall. There are some holes for plasma heating devices and diagnostics on the midplane. The surface of the hot wall is covered with APS-W of 100 μm in thickness.

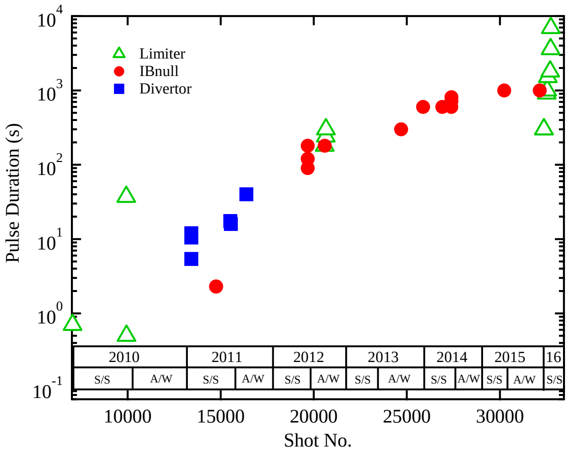

Fig. 3 Historical progress on SSO for the various types of magnetic configurations during 2010-2016 campaigns is summarized. Triangles, circles, and rectangles show the data set of limiter, inboard null, and divertor configurations, which can be shown in Ref. 11. Since shot no. 28707, the hot wall started to be operated at 473K. The hot wall temperature is normally set at 473K, and is sometimes changed in the range of 393-523K depending on the intended use. It should be noted that the longest discharge (shot no. 32737) was executed with the hot wall temperature of 393K.

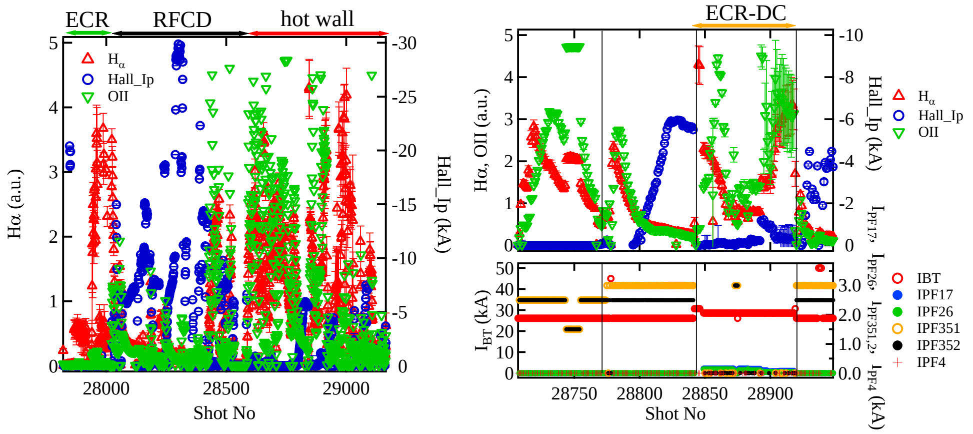

Fig. 4 A shot history of plasma current (blue circles), $I_{H\alpha}$ (red triangles), and I_{OII} (green triangles) during the 2014A/W campaign are plotted in the left figure. The right figure shows a shot history with each coil current during first four days from the beginning of hot wall operation. The position of each coil on the poloidal cross-section is referred in Ref 21 and 22.

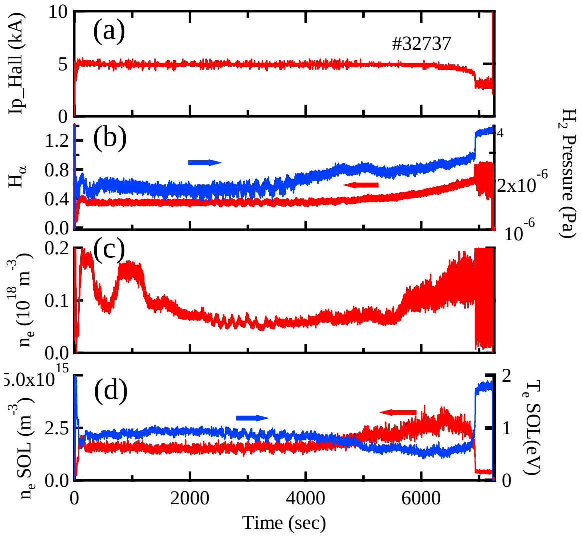

Fig. 5 Time evolutions of plasma current (a), intensity of Ha (red) and partial pressure of H_2 in the vessel (blue) (b), electron density (c), electron density in SOL (red) and temperature in SOL (blue) (d) in the longest duration discharge of 1h55min. After 4000s, no H_2 fueling was done.

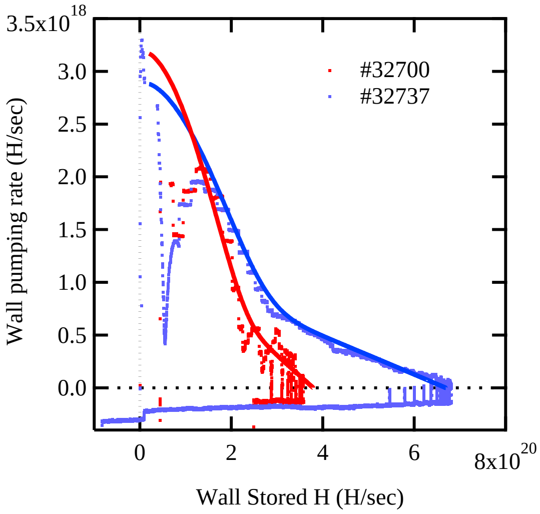

Fig. 6 The wall pumping rates for H, dH_W/dt of #32737 (hot wall temperature, 393 K: blue dots) and #32700 (473 K: red dots) are plotted as a function of each wall-stored H. The red and blue solid lines indicate calculation results based on the equation (1), respectively.