Particle balance investigation with the combination of rate equations of hydrogen state and hydrogen barrier model in long duration discharges on all-metal PFW QUEST

K. HANADA, N. YOSHIDA, M. HASEGAWA, H. IDEI, Y. NAGASHIMA, K. NAKAMURA, T. ONCHI, O. WATANABE, H. WATANABE, K. TOKUNAGA, A. HIGASHIJIMA, S. KAWASAKI, H. NAKASHIMA, T. NAGATA, S. SHIMABUKURO
Research Institute for Applied Mechanics, Kyusyu University
Kasuga 816-8580, Japan
Email contact of main author: hanada@riam.kyushu-u.ac.jp

A. HATAYAMA, K. OKAMOTO
Faculty of Science and Technology, Keio University
Yokohama 223-8522, Japan

I. TAKAGI, T. HIRATA, T. SHIKAMA, S. MURAKAMI
Graduate School of Engineering, Kyoto University,
Kyoto 615-8530, Japan

H. LONG, Z. X. WANG, Y. OYA, S. KOJIMA, K. GAKU
Interdisciplinary Graduate School of Engineering Science, Kyusyu University
Kasuga 816-8580, Japan

M. OYA
Faculty of Engineering Science, Kyushu University
Kasuga 816-8580, Japan

M. MIYAMOTO
Interdisciplinary Faculty of Science and Engineering, Shimane University
Matsue 277-8561, Japan

Y. OYA
Faculty of Science, Shizuoka University,
Shizuoka 422-8529, Japan

A. KUZUMIN
National Institute for Fusion Science
Toki 509-5292, Japan

T. TAKASE,
Graduate School of Frontier Science, University of Tokyo
Kashiwa 277-8561, Japan

X. GAO, H. LIU, J. QIAN
Institute of Plasma Physics, Chinese Academy of Science
Hefei 230031, China

R. RAMAN
University of Washington
Seattle, WA, USA

M. ONO
Princeton Plasma Physics Laboratory, Princeton University
Princeton, NJ, USA

Abstract

Fuel particle balance has been investigated using all-metal and temperature controllable plasma facing wall (PFW) on QUEST. Out-going flux of fuel particles from PFWs during long duration discharges is in agreement with a prediction of the hydrogen (H) barrier model which includes presence of transport barrier for H at the boundary between plasma-induced deposition layer and substrate. Temperature dependence of H out-going flux from the PFWs was clearly observed and agreed with the prediction of the H barrier model. This means that fuel particle balance in all-metal PFW devices can be controlled by wall temperature. A simple calculation based on the combination of rate equations of H states and the H barrier model predicts a significant impact in the response of plasma density. This result indicates that a proper wall model including the effect of deposition layer that creates H barrier should be developed even in all-metal PFW devices.

1. INTRODUCTION

Investigation of the fuel particle balance is an indispensable work to realize future fusion power plants. Simulations of 1.5-3 GW thermal output fusion power plant indicate that deuterium (D)- tritium (T) reactions occur under fuel burnup fraction of approximately 1-5% [1,2], meaning that the remaining 95-99% of D-T fuel must be either pumped out or it must be continuously circulating in the core plasma, scrape-off layer (SOL), vacuum regions, and plasma facing walls (PFWs) as molecules, atoms, and several types of ions. Much of the circulating fuel particles is likely to be stored in and be sometimes released from PFWs via adsorption, reflection, absorption, desorption, diffusion, and permeation. As the time constant of each elementary step has considerable variation in the range of a few μs to thousands seconds, all process aimed at studying fuel particle balance should be investigated in longer duration discharges that are many times longer than the longest step time scale. It is well-known that the quantity of wall-stored fuel particles also depends on the implanted particle energy and the PFWs surface condition. The wall-stored fuel particles therefore may play an important role in the performance of future fusion power plants through recycling, and T retention and permeation; however, their impact during steady state operation (SSO) is poorly understood due to a lack of information on wall property and supporting data from experimental discharges of sufficient discharge pulse duration.

Recently, discharges longer than 1 h were achieved in the Q-shu University Experiment with Steady State Spherical Tokamak (QUEST) [3] with all-metal PFWs with full non-inductive electron cyclotron current drive (ECCD) using a RF source of 8.2 GHz [4]. In addition, a 1 h 55 min discharge was obtained [5] with the assist of an all-metal hot wall which has the temperature control capability of the PFWs, T_W [6] and with proper fuelling control based on feedback [7] using a H_α radiation in the Balmer lines. Moreover, long duration discharges, lasting more than 1000 s have been reproducibly achieved. The time evolution of the wall-stored fuel particles during these long duration discharges closely matches the predictions of a previously proposed H barrier model [5,8]. This barrier has also been observed in T [9], and the described characteristics are common for hydrogen isotopes.

This study aims at experimentally assessing the importance of several parameters that are required to study fuel particle balance and to investigate combining the H state rate equations and the H barrier model, as well as the effects of the wall model on fuel particle balance. Section 2 describes the experimental apparatus. The experimental results are described in detail in section 3. In section 4, the calculation results based on the modelling are shown, and the study is summarized in section 5.

2. EXPERIMENTAL APPARATUS

QUEST is a medium sized spherical tokamak of major radius, R~0.64 m, minor radius, a~0.4 m, toroidal magnetic field, B_T<0.25 T at R= 0.6 m with a temperature controllable PFW called a "hot wall". [5] The main plasma heating sources are a gyrotron that can generate microwaves at 28GHz and 350kW [10] in output power [11], and eight klystrons at 8.2 GHz and in 25 kW each in output power [4,5]. QUEST is capable of performing steady state operations with all-metal PFWs [3-5]. Figure 1 shows a cross-sectional view of QUEST. The vacuum vessel of approximately 2.8m in diameter and 2.8 m in height was made of 316L-type stainless steel. The vessel in the high field side was covered by 3 mm-thick stainless steel coated with 0.1 mm-thick atmospheric plasma-sprayed tungsten (APS-W). The top flat-divertor is composed of 16 panels of 316L-type stainless steel coated with 0.1 mm-thick APS-W. There are four divertor limiters made of W block mounted on copper water cooling channels that are installed on the divertor panel. The lower divertor has sixteen electrodes evenly-distributed in the toroidal direction. There are fabricated from 304L-type stainless steel. There were installed for coaxial helicity injection (CHI) experiments [12, 13] . The hot walls cover the top and bottom conical portions of the vacuum vessel [14]. Each of the top and bottom hot wall assemblies consist of 24 panels of 316L-type stainless steel surface panel that is 5 mm thick and coated by 0.1 mm-thick APS-W. The hot wall system has a resistive heater and two types of water cooling channels for temperature control [6]. Overall, there is approximately 23.5 m^2 PFW: 9.3 m^2 of 316L-type stainless steel and 14.2 m^2 area covered with APS-W. All-PFWs on QUEST are made of several kinds of metal as noted above. Model calculation for particle balance was done using 26 m^2 of wall surface area including approximately 2.5 m^2 of port area surface that is composed of 316L-type stainless steel.

Fuel particles injected into the vessel are pumped by four cryopumps of 10 m^3/s each in pumping capability and a turbo-molecular pump (TMP) of 2 m^3/s. Every pump is connecting to the vessel through a short and large vacuum pipe and gate-valves. Measured effective pumping capability for hydrogen molecules (H_2) is approximately 4 m^3/s, which always varies during operation as the surface adsorption capability is changing, so the calibration is performed before and after the plasma experiment each day. A properly accounting of the evacuated fuel particle flux is important for a particle balance estimate. Every pump is calibrated with a flowmeter calibrated absolutely by a manometer. Ten different flow levels are applied by the flowmeter and H_2 pressures are measured with three quadrupole mass analyzer system (QMS) installed in the vessel behind top and bottom divertor plate, and in the plasma side. This has been available since 2018 spring/summer campaign. Their locations are shown in FIG 1. After allowing sufficient time to saturate the H_2 pressures, the pressure measured with each QMS represents evacuating flux of H_2. Before 2018 spring/summer campaign, the QMS located behind the bottom CHI electrodes was used to estimate evacuating flux from the vessel. The evacuating flux of three cryopumps installed in the bottom side can be estimated by the H_2 pressure measured with the QMS installed behind the bottom divertor plate. In a similar manner, the cryopump located on the top side and the TMP are also calibrated.

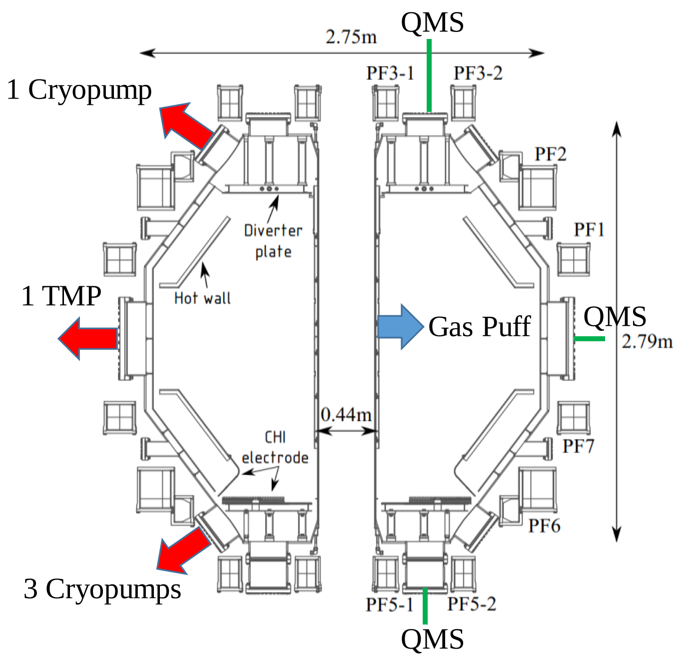

FIG 1 Conceptual cross-sectional view of QUEST. PF1-7 denote the position of poloidal field coils. A QMS located behind the CHI electrode was installed before 2018 spring/summer campaign. Three QMSs located on top, plasma chamber, and bottom are set up in 2018 spring/summer campaign. It should be noted that the coils located inside the center-stack are not drawn in the figure.

3. EXPERIMENTAL RESULTS

Typical waveforms during a long discharge on QUEST is shown in FIG 2. Plasma current, I_p, and injected microwave power, P_{RF}, are kept constant at 40kW. The plasma was maintained by fully non-inductive RF current drive with 8.2GHz. The intensity of H_α signal was controlled to keep a targeted value in a feedback control manner [7] as shown in FIG 2(b). Supply of H_2 gas into the vessel had stopped around 600 s in FIG 2(c) and this indicates no more fuelling was necessary to keep the H_α level at the targeted value, which indicates "wall saturation". The number of the wall-stored fuel particle was gradually increasing and saturated around 600 s as shown in FIG 2(d). Since the intensity of the H_α level was still increasing after stopping the supply of H_2 gas, we term this situation "density runaway". From here on it is difficult to control the density at the proper value and sudden plasma collapse is a possibility. Sufficient wall control to avoid this is a future important objective.

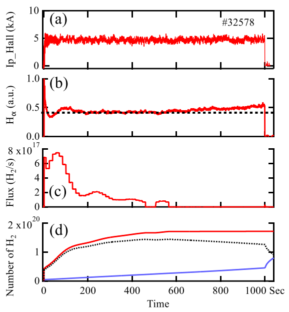

FIG 2 Typical waveforms of a long duration discharge at T_W=473K, (a) Plasma current, I_p, (b) Intensity of H_α line radiation (red line) and a targeted value (black dashed line), (c) injecting H_2 flux into the vessel using the flowmeter, (d) time-integrated supplied H_2 to the vessel (red line), time-integrated evacuated H_2 from the vessel (blue line), and calculated wall-stored H converted into H_2 (black dotted line) are plotted.

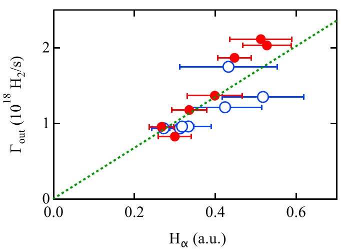

FIG 3 Evacuating H_2 flux just after plasma termination is plotted as a function of H_α intensity level targeted in feedback control. Red rectangles denote the shot with T_W=473K and blue circles indicate that with T_W=373K. Typical error bar of the data is shown in the figure. The error is caused by the calibration of evacuating flux. The dotted line denotes a fitting line for the data.

During wall saturation, in-coming fuel particle flux to PFWs must be balanced with out-going flux from PFWs, and apparently wall-pumping is no longer working. Taking advantage of this situation, in-coming fuel particle flux to the PFWs can be experimentally investigated by out-going flux just after the plasma termination. The measured out-going fuel particle fluxes in various plasmas that was in the wall saturation state is plotted as a function of the intensity of H_α radiation denoted in FIG 3. The out-going flux is approximately proportional to the H_α radiation and does not depend on the temperature of PFWs. It should be noted that data from more than 15 long duration discharges that reach to wall-saturation in various H_α signal levels is required to produce this figure. This means QUEST has a capability of good-reproducibility for these long duration discharges. This can be explained by the following consideration. In-going fuel particle flux to PFW is composed of escaping ion which must be balanced to the production rate of hydrogen ion in steady state condition and charge exchange neutral fluxes. It is well-known that the ionization rate of H atom is almost proportional to the H_α radiation. Previous study shows even production rate of charge exchange neutral is almost proportional to the H_α radiation in the considered electron temperature range [5]. In fact, the in-coming fuel particle flux measured with plasma induced permeation probes [15] in ECR plasmas was almost proportional to the H_α radiation in the previous study [16] in QUEST.

In QUEST, good reproducibility for approximately 1000 s discharges could be achieved, and it found that the out-going from the PFWs just after the long duration discharges up to 1000 s is almost proportional to square of the number of wall stored H, H_W at each T_W, as shown in FIG 4. The relation can be predicted by the H barrier model [4,5] as expressed by,

$$\frac{\mathrm{d(H}_W)}{\mathrm{dt}} = \Gamma_{in} S_W - \frac{2k}{S_W d^2}\mathrm{H}_W^2 \qquad (1).$$

Here, Γ_{in}, S_W, k, and d are respectively the net flux per unit area of H implanted into PFWs, the surface area of PFWs, the surface recombination coefficient of H, the thickness of deposition layer. As Γ_{in} equals to zero after the plasma termination, out-going flux must be proportional to square of H_W and the constant of proportion provides recombination coefficient of the real PFWs.

The PFWs was covered with a thin plasma-induced deposition layer [17] and fuel particles in the deposition layer is less likely to be transported into the SUS316L and tungsten substrates. The averaged thickness of the deposition layer on specimens exposed to long duration plasmas during one campaign (2016 spring/summer) was approximately 30 nm [17]. The presence of fuel particle barrier depends on the difference in the potential energy for fuel particles between the deposition layer and the substrate. Materials in deposition layer are accumulated during plasma operation and are unlikely to form a clear lattice structure where the potential energy is likely to get higher. Even in tungsten PFW experiments such as ASDEX-U [18] and JET [19,20], the tungsten surface is covered with a mixed material layer that includes many types of materials. The H barrier model can be also applied to those all metal PFW fusion machines.

The plotted data are almost linearly proportional to the square of H_W, which agree with the prediction of the hydrogen barrier model. The gradient of lines in FIG 4 is corresponding to surface recombination coefficient, k, as denoted in Equation 1. The observation shown in FIG 4 means the value of k depends on and increases with T_W. This tendency is in agreement with the analysis for time evolution of wall-stored H [4]. Using these observations, we could obtain the value of k averaged in the whole of PFWs experimentally. In fact, the achieved values are used in the calculation of particle balance for the QUEST experiment in the next section.

During a long duration discharge, it was seen that a large dust particulate introduced into the plasma caused a huge spike and then reduction of the H_α signal as shown in FIG 5, which suggests reduced out-going flux from the walls. The ablated dust particlate may modify surface condition and the value of k may be also changed. In fact, the data of out-going flux just after the discharge with the large dust event suggests the surface recombination is lowered as shown in FIG 4 (see the asterisks). This suggests that it is indeed alter the surface conditions by insertion of a large dust particle. This modification of out-going flux was lasting after the following several shots (dust shot #32568: recovery on the same line at #32573) as denoted by the arrows in FIG 4, and then the value of k recovered to that the level prior to the large dust appearance. The large dust event prevents the production of reproducible plasmas and conditioning using six subsequent shots including a long duration discharge was required to recover the original plasma. The dust may peel away from a part of the deposition layer that is microscopically observed [17] and is mainly composed of carbon and metal. The dust ablated into the plasma and its components must spread and deposit on the PFWs. This indicates that surface condition of PFWs plays an essential role in fuel particle balance in long duration discharges. To better understand the dust event, in-situ observation of surface condition is necessary which is a future work.

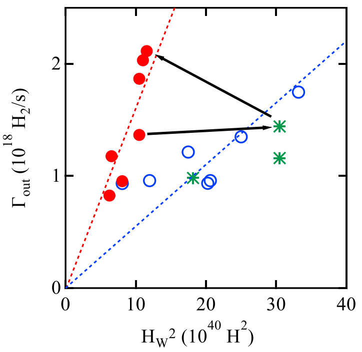

FIG. 4. Out-going flux from the PFWs just after the long duration discharges is plotted as a function of the square of the wall-stored H during each discharge at the wall temperature, T_W of 393 K (open circles) and 473 K (closed circles). The green asterisks denote the data just after the plasma with a big dust appearance. The arrow shows the shot sequence before and after dust appearance (red circle #32563; dust shot #32568 green asterisk #32572; red circle #32573).

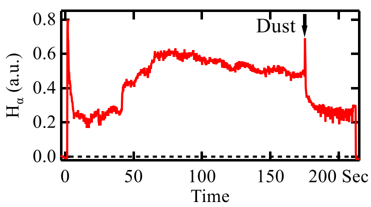

FIG 5 Time evolution of H_α signal in a long duration plasma (#32568) that a large dust dropped into. The arrow denotes the timing of the dust appearance.

4. PARTICLE BALANCE CALCULATION USING HYDROGEN BARRIER MODEL

Fuel particles are continuously circulating during the plasma discharge, and a particle balance calculation taking account of H state as molecules, atoms, and several types of ions [21] is useful for understanding.

Plasma, non-plasma region that surrounds the plasma, and PFWs are considered in the calculation [22], specifically the H barrier and a fully reflecting wall models were applied in the integrated calculations. Here, the reflecting model assumes that every reflecting fuel particle is in atom state. The calculation result is shown in FIG. 5. The values of k in each T_W are decided by the gradient of the fitting line against the out-going fluxes in FIG 4, and main parameters are taken from the 1 h 55 min discharge on QUEST. The electron density in the H barrier model is gradually increasing up to 1000 s at 393 K and this behaviour is not seen in the calculation that assumes the fully reflecting wall model. The saturated value of density is a little higher than that derived from the full reflecting model. This difference gives rise to increment of out-going flux due to fast-moving charge exchanged H that penetrates through non-plasma region and reaches the PFWs directly. This charge exchange neutral causes reduction of net ionization rate and the charge exchange rate of H atom is significantly larger than that of H molecule. In the case of the fully reflecting wall, most of H exists as H atom, but H_2 is dominant in the case of the H barrier model in the non-plasma region as shown in FIG 6(c). Consequently, net influx of fuel particle into the plasma is reduced in the full reflecting wall model based on the difference of the charge exchange rate of H^+-H, and H^+-H_2 and H_2^+-H_2 which makes the difference of electron density in steady state. The effect may be much larger in higher density plasmas. We find that the wall model involves a significant impact on the density response as shown in density after the change in the supplied H_2 at 1000 s. Slower density response is likely to give rise to difficulties in controlling the output power in fusion power plants and a proper wall model should be developed even in all-metal PFW devices. In present experiments this type of discharge has never been obtained because the density runaway prevents the plasma from being maintained in steady-state conditions. At present, we must be gradually decreasing supplied fuel H_2 with the duration of plasma. This calculation may eventually predict how much of H_2 should be supplied to obtain a target density.

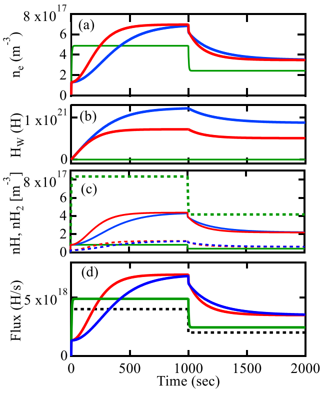

FIG 6 Time evolution of (a) electron density, n_e, (b) wall stored H, H_W, (c) density of H (dotted) and H_2 (solid) in non-plasma region, (d) net influxes to plasma region (influx as neutral subtracted charge exchange out-going flux) and, supplied flux into the vessel (black dashed). Red and blue lines are the case of H barrier model of wall temperature, T_W = 473 K and 393 K, respectively. Green lines denote the case of the full reflecting model. Electron temperature, T_e = 10 eV, recombination rate, k_r = 1.30 ×10^{-37} m^4/s (T_W = 393 K) and 3.81×10^{-37} m^4/s (T_W = 473 K), thickness of deposition layer, d = 30 nm, pumping speed 4 m^3/s.

5. SUMARRY

Fuel particle balance with all-metal plasma facing wall in steady state operation has been investigated in QUEST. We find that the plasma-induced deposition layer that is commonly observed on the surface of plasma facing wall plays an essential role in the fuel particle balance thorough forming a transport barrier of hydrogen atom. The H barrier model predicts that hydrogen out-going flux from the plasma facing wall is proportional to the square of the number of the wall-stored H and the prediction was confirmed by the measured out-going flux just after the plasma termination. The surface recombination coefficient was estimated by the gradient, and an integrated calculation is carried out using the measured recombination coefficient. The calculation indicates that the wall model plays an important role in response of plasma density as well as fuel particle balance.

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