Global gas balance and influence of atomic hydrogen irradiation on the wall inventory in steady-state operation of QUEST tokamak


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Abstract

Hydrogen wall pumping is studied in steady state tokamak operation (SSTO) of QUEST with all metal plasma facing materials PFMs at 100 °C. The duration of SSTO is up to 820 s in fully non-inductive plasma. Global gas balance analysis shows that wall pumping at the apparent (retention–release) rate of 1–6 × 10^15 H/s is dominant and 70–80% of injected H2 can be retained in PFMs. However, immediately after plasma termination the H2 release rate enhances to ~10^15 H/s. In order to understand a true retention process the direct measurement of retention flux has been carried out by permeation probes. The comparison between the evaluated wall retention and results from global analysis is discussed.

1. Introduction

Hydrogen (H) retention in the first walls must be controlled to achieve SSTO. H retention strongly depends on the materials (tungsten, graphites) and their irradiation parameters (wall temperature Twall, or energies of ion, neutral and electron fluxes) [1].

Recent retention studies in the ITER-like wall carried out in the JET tokamak [2,3] for different types of discharges shows significant (~10 times) reduction of the H retention fluxes for metal wall compared to the carbon one. Even without carbon materials long term codeposition in metal films is much lower, but still significant and further understanding of retention in long discharges is required. Usual technique to estimate retention in tokamaks is gas balance, which has been used in many tokamaks [2–6]. In AUG [6,7] with full tungsten wall this technique has shown clear saturation of the wall after it was loaded with 19 × 10^21 at., and then gas balance was controlled by fuelling and external pumping. In the end phase, however, although fuelling is stopped, the plasma density and neutral pressure drop not immediately, indicating H atoms release from the wall sustained them constant. In 5–10 s SSTO in AUG particle retention was analyzed. We use same particle balance equation for H:

\[ N(t) = -\int_0^t S_{pump}(t) dt - N_p(t) + Q_{gas}(t) + Q_{out}(t) + Q_{rel}(t) + Q_{ret}(t). \]  

where N(t) is the number of hydrogen atoms at the time t in the vessel, S_{pump} is the effective H2 pumping speed, P(t) – H2 pressure, Q_{gas}(t) is the number of H atoms injected until time t, and Q_{out}(t) (~N(0)) corresponds to the outgassing under vacuum conditions. N_p(t) is plasma inventory which is usually less than 10% of Q_{gas}. Since there are two unknown quantities, Q_{out}(t) (positive sign), H atoms released from the walls due to plasma interaction and Q_{ret}(t) (negative sign), H atoms retained in the walls, the sum of them is only obtained in this analysis. PdCu membrane probes were used to measure the H flux through a thin membrane caused by plasma driven penetration (PDP). PDP measurement allows to calculate the net retention flux in the wall, independently of the nature of the incident flux (H ions and atoms could be detected at our P_{H2}), and helps to distinguish retention and release processes in global gas balance calculation. This article aims at evaluating Q_{ret}(t) by the independent method and understanding retention behavior in the
long time scale. In the present study the following pressure $P$ differential equation for hydrogen is analyzed experimentally:

$$\frac{dP}{dt} = -\frac{P}{\tau_{\text{pump}}} + \frac{q_{\text{gas}}(t)}{q_{\text{rel}}(t)} + \frac{q_{\text{wall}}(t)}{T_{\text{wall}}} + \frac{q_{\text{ion}}(t)}{T_{\text{inc}}} + \frac{q_{\text{rel}}(t)}{T_{\text{inc}}} .$$

(2)

where $\tau_{\text{pump}}$ is the pumping time constant, and $q_i$ (H/S) corresponds to $dQ_i/dt$ in Eq. (1).

This paper is organized as follows: experimental set-up and measurement procedures for global gas balance and PDP are described in Section 2. The global gas balance will be presented in Section 3. Estimation of $Q_{\text{ret}}(t)$ using PDP will be shown in Section 4. Finally, summary will be given in Section 5.

2. Experimental apparatus and permeation probes

QUEST is a medium sized spherical tokamak [8] with the major and minor radii of 0.68 and 0.4 m, respectively. Typical parameters in the core and SOL/wall regions for SSTO driven by electron cyclotron waves ECWs are as follows: $T_e = 400-600$ eV, $n_e \sim 1-2 \times 10^{16}$ m$^{-3}$, $B_t$ is 10–20 eV. The magnetic field $B_t$ is 0.15 T and $I_p$ is 20 kA. In the SOL and on the top and bottom plates, $T_{\text{wall}} \sim 5 - 20$ eV, $n_{\text{wall}} \sim 2 - 6 \times 10^{15}$ m$^{-3}$, and $T_{\text{wall}} \sim 5 - 10$ eV, measured by Langmuir probe arrays. The RF power at 8.2 GHz is $<100$ kW. The cross sectional view of the vessel and diagnostic systems is shown schematically in Fig. 1. The vessel volume is 13.5 m$^3$ and the total surface area of the plasma facing components PFCs is $\sim 35$ m$^2$. The vessel is made of stainless steel (SS) SUS316 (~70% of PFCs) and about 30% of PFCs (center stack and top/bottom plates) are SS with atmospheric plasma sprayed W coating with thickness of 125 ± 25 μm and monoblock W limiters. Note that no carbon materials are used in QUEST. The vessel (“side” wall, shown with black line in Fig. 1a) $T_{\text{wall}}$ is controlled at 100 °C. W-limiters (except bottom plate) are water cooled and $T_{\text{lim}} \sim 30–40$ °C. Four limiters are located at top and bottom plates and eight limiters are on CS. W-coated SS walls (cyan lines in Fig. 1) are not actively cooled, during long pulses $T_{\text{wall}} < 180$ °C. Pumping systems consists of four cryogenic pumps located at different toroidal positions and one turbo molecular pump at the mid-plane. The effective $\tau_{\text{pump}}$ during plasma operation is 2 s. Total pressure $P_{\text{total}}$ in the vessel is measured by ASDEX gauges [9] located below the bottom plate (AG2), and the fast ionization gauge AG1 at the wall. Partial gas pressures ($H_2$ and He) are measured by a quadrupole mass-analyzer (QMA). All gauges are calibrated using standard ($H_2$ and He) leaks. Using pressure build-up method and differential pressure gauges in the puff line both $q_{\text{gas}}$ and $Q_{\text{gas}}$ are calibrated. The wall retention rate $q_{\text{wall}}$ is deduced by the permeated flux $\Gamma_{\text{pdp}} = (\frac{dQ_t}{dt} + \frac{q_{\text{gas}}}{q_{\text{wall}}}) / A_{\text{pdp}}$. The membrane thickness and temperature are 20 μm and 300 °C, respectively. The detection area $A_{\text{pdp}}$ is $\sim 7.5 \times 10^{-2}$ m$^2$. Probes are located at four different positions, at the top/bottom plates and at the “side” wall. QMA are absolutely calibrated by a standard $H_2$ leak and relative sensitivity for probes is also checked in $H_2$ gas ($P_{\text{H}_2} \sim 2.6$ Pa), showing that a change of recombination ($k_0$ (upstream), $k_d$ (downstream)) and diffusion (D) coefficients is less than 10% after experimental campaign. Probes are sensitive to both neutral and ion fluxes, but significant permeation of the hydrogen gas starts at pressures ($P \sim 0.1$ Pa) much higher than our operating pressures ($\sim 10^{-2} - 10^{-3}$ Pa). With the help of TMAP7 [10] and fitting procedure [11] $D$, $k_0$, and $k_d$ are decided as follows: $D = (2.9 \pm 0.2) \times 10^{-9}$ m$^2$s$^{-1}$, $k_0 = (1.3 \pm 0.6) \times 10^{-33}$ m$^2$s$^{-1}$, $k_d = (7.0 \pm 0.4) \times 10^{-34}$ m$^2$s$^{-1}$. These coefficients are applied to evaluate the incident flux $\Gamma_{\text{pdp}}(t)$, which relates closely to $q_{\text{gas}}$ in SSTO and deduce $Q_{\text{gas}}$ by multiplying the typical surface areas (top/bottom, “side” wall).

3. Global gas balance

The ratio $R(t) = 1 - Q_{\text{pump}} / Q_{\text{gas}}$ is introduced to understand the retention ($R > 0$) and release ($R < 0$) performance of the wall in the long pulse, where $Q_{\text{pump}} = \int_{t_f}^{t} S_{\text{pump}}(t) \, dt$. It has been checked that $R(t)$ for puff in vacuum with out plasma is $\sim 0$, which indicates that all injected particles could be pumped out by the pumping system and nor release or retention without plasma irradiation is observed. For ECRC with irradiation of all areas of the PFCs except the “side” walls by swept $B_t$, $R$ was usually kept constant at $\sim 0.2–0.3$ for one hour, which indicates that the recycling is in equilibrium and H atoms should be mainly stored in the irradiated surface areas whose thickness is comparable with ion stopping range. In order to check wall conditioning $Q_{\text{out}}$ was measured before every experimental day (Fig. 2). Since $q_{\text{out}} (~10^{15} – 10^{16}$ atoms/s) was $\sim 0.1$% of $Q_{\text{rel}} (1 - 6 \times 10^{18}$ H/S) during H-discharges, the walls could be well conditioned for whole campaign. This fact shows that all H, stored in the wall during the experimental day, was released within a long interval of $\sim 10$ h. In long discharges (LD) $R(t = T)$, where $T$ is the discharge duration, is plotted as function of $Q_{\text{out}}$ in Fig. 3a. One can see that H retention is scattered, due to the particle irradiation history; 40–80% of $Q_{\text{out}}$ was retained by
the wall during the discharge. The R traces for shot #25874 and #25305 are also denoted by thin and thick lines, showing time evolution of the wall retention during LD. In Fig. 3b Qgas (symbols) and Qsump (solid curves) for all discharges (many short pulses and a few long pulses) during 2 days are shown as a function of time. During short discharges (<15 s) R ~ 0.5 and H, retained in the wall was released in the interval duration (~6 min) and were completely pumped out until the next shot. Just after plasma termination there is no gas injection nor particle implantation, and from the sharp pressure rise using Eq. (2) R(t) was estimated, it is ~10^{19} \text{H/S}. In the SSTO discharges of 600 s, however, it is noted that the large amount of particles are released from the PFCs. If the large amount of particles are released from the PFCs, the gas fueling rate on the constancy of R decreases from 0.5 to 0.8 and wall pumping becomes significant. R(t) for three sequential shots #25305-7 corresponding to solid, dashed and dotted lines, respectively. The end of each curve indicates the discharge duration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In order to achieve SSTO the interval between H injections is feedback controlled to keep ~Q_{\text{inj}} and the H2 intensity at CS constant. H injection duration was usually ~5–10 ms. H2 feedback controlled SSTO is demonstrated for 820 s in Fig. 4. R immediately rises to ~0.9 and then gradually decays to ~0.75. This reflects the gradual extension of the fuelling interval and hence decrease of q_{\text{gas}}, this fact can be seen on the slow reduction in P_{\text{He}},). Non-stationary evolutions were seen on P_{\text{He}} and T_{\text{wall}} at the small area on the bottom plate. The former was linearly rising, though P_{\text{total}} was constant. T_{\text{wall}} on the most of the PFCs were kept at 180 °C. So their variations may not affect the evolution of global gas balance. Note an off-normal event at ~300 s where the bursts in n_{e}, P_{\text{He}},) and ion saturation current I_s at the sideboard of the upper plate occur, as a consequence of enhanced PWI. Although I_p drops, it recovers to the previous level. For particle fluxes to the walls monitored by I_s and PDPs it is noted that they behave differently. I_s was well kept constant except this off-normal event, but it was observed that PDP7 located on the upper side wall dropped suddenly synchronizing to this event and small changes in other PDPs occurred at several times. Fig. 4g shows the T_{\text{wall}} calculated from measured T_{\text{pdp}} (Fig. 4f), which suggests that the redistribution of the retention flux occurs at several times during SSTO. Finally, all parameters changed at 800 s and their variations caused the plasma current termination. In this event particle fluxes to the walls monitored by I_s and PDPs behaved differently from PDP7. Noticeable drop in T_{\text{pdp}} also indicates fast change of the local equilibrium of release and retention. Although the probe material is different from the PPFMs, Q_{\text{rel}} = \int_0^t \dot{Q}_{\text{rel}} dt \cdot A_s is calculated, where A_s = 2.1 m\(^2\) (bottom PDP) and A_s = 8.7 m\(^2\) (PDPs at the "side" wall), and uniform \Gamma_{\text{rel}} on each surface is assumed. The results are compared with the net value of "Q_{\text{wall}} = Q_{\text{rel}} − Q_{\text{ex}}" obtained in the global gas balance, as shown in Fig. 5. It is seen that Q_{\text{rel}} is ~4 times higher than Q_{\text{wall}}. As P_{\text{He}}, P_{\text{total}}, and P_{\text{He}} are abruptly enhanced at plasma termination (t = 900 s), it can be understood that the large amount of particles are released from the PFCs. If we assume that Q_{\text{rel}} during SSTO is roughly the same as that
calculated from \( q_{\text{rel}} \approx 10^{10} \text{H/s} \) at \( t \approx 900 \text{s} \), \( q_{\text{rel}} \) is of the same order as \( q_{\text{ret}} \). One should notice that \( q_{\text{rel}} \) from the “side” wall is fifteen times higher than that from the bottom plate. “Side” wall is outside of the main PWI area (see Fig. 1). Langmuir probe array measurements at the top plate shows that \( I_s, T_e \) drops to zero at the top plate with \( R > 0.7 \text{m} \). No significant ion or electron flux is expected to the “side” walls. Most likely atomic H gives main contribution to the retention fluxes measured by PDP 6 and 7.

5. Summary

The standard gas balance was carried out in non-inductively driven plasma and it was observed that wall pumping is much more efficient than fuelling, \( q_{\text{ret}} - q_{\text{rel}} > 0 \), in QUEST with fully metal walls. Long duration for the wall to be depleted was required when \( q_{\text{gas}} \) exceeds \( 10^{21} - 10^{22} \text{H} \), below which the gas balance could be controlled with \( R < 0.6 \) during the short pulse discharges and the interval time of 6 min. The feedback procedure is developed to remain \( R \) constant by adjusting the time average \( q_{\text{gas}} \) to keep particle recycling constant. Thus SSTO of plasma has been achieved for 820 s. In order to distinguish the release and retention processes, which cannot be separated by the gas balance analysis, direct measurement of the H permeation flux has been carried out at several positions. It was seen that the main retention area is the outboard side wall, whose \( q_{\text{ret}} \) is eight times larger than that on the bottom plate. Although there is a large discrepancy between \( q_{\text{ret}} \) from PDPs and the net value “\( q_{\text{ret}} - q_{\text{rel}} \)” from the gas balance, and \( q_{\text{rel}} \) just after plasma termination is also extremely higher than the net value of “\( q_{\text{ret}} - q_{\text{rel}} \)” during SSTO, these can be understood that actual \( q_{\text{ret}} \) and \( q_{\text{rel}} \) are order of magnitude higher that the net value.

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