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Hydrogenic retention studies in DIII-D H-mode discharges

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Recent experiments on DIII-D address the retention of deuterium in an all carbon PFC device. Although there is already an extensive database of retention studies in carbon PFC tokamaks [1-4], this study adds further information to that database in the following ways: 1) two independent global particle balance methods are directly compared; and 2) experiments are performed with a careful accounting of the number of retained particles left in the vessel and two types of vessel bakes are performed to remove a large fraction of those particles. This understanding is particularly timely in that it aids in the understanding of particle control for long pulse devices (e.g. KSTAR, EAST, JT-60SA) and tritium wall retention for burning plasma devices (e.g., ITER).

For the particle balance comparison, one method, called the "dynamic" particle balance, gives information on wall retention within the different phases of the discharge (i.e., ohmic, L-mode, and/or H-mode) and is useful in discerning when in the discharge wall retention is dominant. The other method provides highly accurate information on the total number of particles left in the vessel, which are assumed to be retained in the PFC. This method is termed a "static" particle balance because it is a shot-integrated measurement and thus provides no information on when the retention occurs within a discharge. For the release of retained particles, the first type of vessel bake performed was an ordinary vacuum vessel bake to ~600 K at ~0.1 mPa. This bake was designed to remove the particles loosely bound to the surface of the PFC by short-term retention processes. This retention process also saturates at some particle inventory dependent on PFC surface temperature and particle incident energy. The second bake was a thermo-oxidation bake of the DIII-D vessel at 623 K and 270 Pa partial pressure of O_2 [5]. This bake was designed to remove the fuel trapped in the co-deposition layers accumulated on the eroded carbon PFC surfaces. This is considered a long-term retention process, meaning the particles stay in the PFC until some invasive method to remove them is applied. This process does not saturate at any particle inventory. Due to each of these two facts, the co-deposition trapping of fuel in carbon PFCs is a concern for particle control in any future machine, but is especially troublesome in a burning plasma

device because of the safety and operational concerns of tritium retention. On DIII-D, the thermo-oxidation bake was followed soon after by high performance discharges.

The dynamic balance is calculated using the following equation;

$$\Gamma_{WALL}(t) = \Gamma_{IN}(t) - \left[Q_{PUMP}(t) + \frac{dN_P(t)}{dt} + \frac{dN_0(t)}{dt} \right] \quad . \tag{1}$$

The left-hand side of the equation, $\Gamma_{WALL}(t)$ is the remainder of the measured quanities on the right hand side (RHS) and is considered the wall flux. Positive values imply wall retention while negative values imply wall release or outgassing. In steady-state preiods of the discharge, the RHS of the equation simplifies to only two terms as dN_P/dt and dN_0/dt are essentially zero during these phases. Therefore, the main balance is just the difference between the injected particles, $\Gamma_{IN}(t)$, which can be from gas puffing or the NBI, and the particle exhaust, $Q_{pump}(t)$, due to the cryosystem. Recently, a careful calibration of the diagnostics used for these measurements was completed, and the measurement and systemic error was found to be ~20%. This error is dominated by systematic errors in the NBI cold particle injection rate and cryopumping speed calculations [6]. Figure 1 shows a typical example of a DIII-D dynamic particle balance. The steady-state phases of the discharge, which are the ohmic/L-mode, "ramp-up" phase, and the ELMy H-mode phase of the discharge are shaded in the figure. In Fig. 1(a), the time history of the sources is shown. It can be seen that in the ramp-up phase there is a very large injection rate ~40 Torr-L/s, and that in the H-mode phase this rate reduces to <10 Torr-L/s. The cryopump exhaust rate is shown in Fig. 1(b) while remaining fairly constant in the H-mode phase. Figures 1(c) and 1(d) show the wall flux and wall inventory respectively, where the wall inventory is the integral of the wall flux. Figure 1(c) shows a very large wall retention rate during the ramp-up phase and essentially zero wall retention

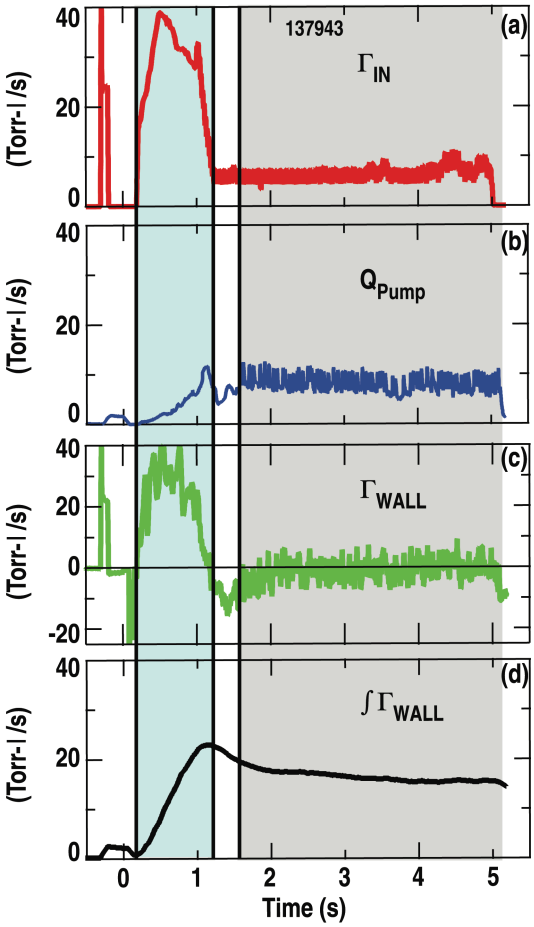

Fig. 1. The dynamic particle balance of a typical H-mode discharge in DIII-D. The shaded regions highlight the phases of the discharge that dominate the wall inventory. (a) is the injected particle flux; (b) is the exhaust flux; (c) is the resultant wall flux; and (d) is the time integral of the wall flux or the total wall inventory.

during the H-mode phase. This leads to a large increase in the wall inventory [Fig. 1(d)] during the ramp-up phase and a fixed or slightly falling wall inventory in the H-mode phase. Experiments to compare the dynamic and static particle balances were also completed. Here, electron cyclotron heating (ECH) was used instead of neutral beam injection (NBI) heating as this removed the systematic error from the NBI particle source and only left the $Q_{\text{pump}}(t)$ uncertainy in Eq. (1). The pumping speed was cross-calibrated with a measured value of exhausted particles by de-frosting the cryopumps into the vessel and measuring the pressure rise. The results of these tests are shown in the bar graph of Fig. 2. Each color block (green, yellow, red, and voilet, respectively) is the calculated exhausted particles from the dynamic particle balance and the solid blue bar is the measured exhaust from the static balance method. A series of 3-4 shots per comparison was done to increase the accuracy of the static method. This was repeated (5) times for statistics. As can be seen, there was excellent agreement between the two methods, with an average difference of ~5%. This same procedure was then used, in combination with a vessel bake after the experiment, to determine the amount of loosely bound particles in the PFC. In this particular experiment, a total of ~2400 Torr-L of deuterium was injected. The amount exhausted was determined to be between 1010–1140 Torr-L by the static or dynamic method, respectively. Finally, the vessel bake released ~1090 Torr-L. Therefore the retained particle inventory is calculated at ~170–300 Torr-L, which is ~7%–12% of the total injected particles for this experiment. When normalized to the divertor target ion flux, this retention amount is <0.2%. It should be noted that this estimate of the retention is relatively high as the vessel bake was not optimized for complete removal of the short-term inventory (i.e., the vessel pressure during the bake did not "turn over").

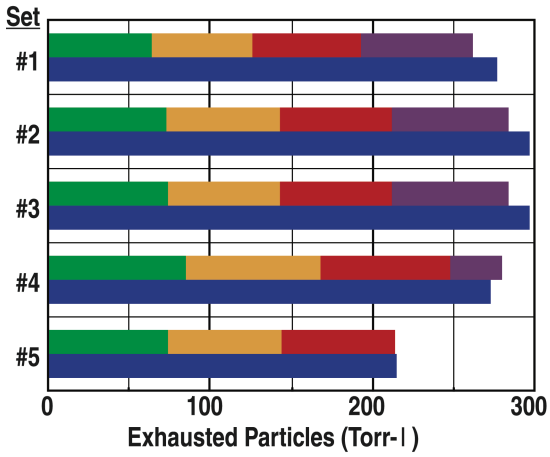

Fig. 2. Comparison of the exhausted particles for a series of discharges (y-axis). Each colored sub-block is the exhaust from a single discharge as calculated by the dynamic particle balance. The blue bar is the measurement particle released from the cryosystem by regenerating after each series of discharges.

Finally, in an effort to remove the fuel retained in the co-deposition layers a thermo-oxidation bake was performed. This procedure was carefully planned to avoid any oxidation of components critical to operating DIII-D [7]. Through a series of side laboratory experiments it was determined that the optimal parameters for a significant co-deposition removal while minimizing the potential damage to components was a two hour bake at 623 K and 270 Pa partial pressure of O_2. These bake parameters were successfully used to complete

the bake, and no damage to any component was detected. *Ex-situ* analysis of a number of the carbon tiles is currently underway to determine the exact amount of deuterium removed by this method. Beyond any damage to components in the vessel, another major issue with this method is start-up and conditioning after the introduction of these large amounts of O_2 into the vessel. Therefore, a dedicated campaign to recover high performance operations was conducted. This is summarized in Fig. 3. Here, a series of three discharges is shown; with a pre-bake reference discharge in black (126485); a discharge soon after the bake (16 discharges after the bake or ~½ run-day on DIII-D); and finally a discharge at the end of the campaign (60 discharges after the bake or ~2 run-days on DIII-D). It can be seen that the ~15%–20% reduction in confinement properties immediately after the bake is fully recovered after 2 days of operation (~360 discharge-seconds).

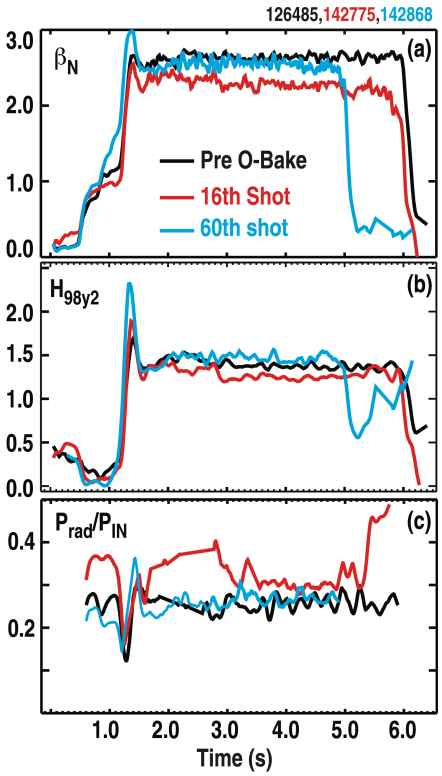

Fig. 3. Time history of confinement properties (a) and (b), impurity concentration, (c), for a series of discharges; one produced before the O_2 bake (126485); one 16 shots after the bake (142775) showing a slight degradation in confinement; and one with full recovery (142868) 60 sjpts pr ~2 rundays after the O_2 bake.

The results presented have two major conclusions. The first is that a majority of wall retention occurs during the ramp-up phase of the discharge. This result is significant for long pulse devices where a majority of the discharge will be in a steady-state condition and extrapolation of our results implies minimal retention in these devices. The second finding is that not only is a mild O_2 bake of the vessel to remove co-deposits benign to the vessel components, but high performance recovery is very quick. Both results are encouraging for the use of carbon in future devices.

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