Active Particle Control Experiments and Critical Particle Flux Discriminating between the Wall Pumping and Fueling in the Compact Plasma wall interaction Device CPD Spherical Tokamak

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Abstract Two approaches associated with wall recycling have been performed in a small spherical tokamak device CPD (Compact Plasma wall interaction experimental Device), that is, 1) demonstration of active particle recycling control, namely, “active wall pumping” using a rotating poloidal limiter whose surface is continuously gettering by lithium, and 2) basic study of the key parameters which discriminates between “wall pumping and fueling”. For the former, active control of “wall pumping” has been demonstrated during 50 kW RF-current drive discharges whose pulse length is typically ~300 ms with a flat-top of ~250 ms. The rotating limiter is in the shape of cylinder with the diameter and axial length of 150 mm and 120 mm, respectively. Although the rotating limiter is located at the outer board, as soon as the rotating drum is gettered with lithium, hydrogen recycling measured with Hα spectroscopy decreases by about a factor of 3 not only near the limiter but also in the center stack region. A clear reduction in hydrogen recycling by factor of ~3 is found both near the limiter and center stack region. Also, the oxygen impurity level measured with O-II spectroscopy is reduced by about a factor of 3. As a consequence of the reduced recycling, rf driven current has nearly doubled at the same vertical magnetic field. The surface analysis has been conducted to investigate hydrogen and lithium distributions over the rotating drum after plasma exposure, showing that both H and LiH are uniformly distributed. For the latter, global plasma wall interaction with plasma facing components in the vessel is studied in a simple torus produced by electron cyclotron waves. A static gas balance (pressure measurement) without external pumping systems has been performed to investigate the role of particle flux on a transition of “wall fueling” to “wall pumping”. It is found that a critical particle flux exists to discriminate between them. Beyond the critical value, a large fraction (~80%) of pressure drop (“wall pumping”) is found, suggesting that almost all injected particles are retained in the wall. Below it, a significant pressure rise (“wall fueling”) is found, which indicates that particles are fuelled from the wall during/just after the discharge.

1. Introduction

Steady state plasma operation is one of the crucial requirements for the future fusion reactors. It has been pointed out that the global particle (gas) balance in the main chamber and its control are critical in achieving steady state plasma density operation. It has been observed in Tore Supra (TS) and TRIAM-1M with sufficiently long (~6 min for TS and ~5 h for TRIAM-1M) discharge duration that "wall pumping" (particle retention into the wall) dominates during the initial phase of the discharge, but "wall fuelling" (particle release from the wall) starts increasing with the progress of the discharge and finally the wall becomes a particle source [1-3]. In the last IAEA conference "wall pumping/fuelling" was widely recognized as one of the crucial problems to control tritium inventory as well as fusion power [4, 5]. Namely, recycling of fuelled particle is nearly unavoidable in magnetic fusion devices, irrespective of plasma facing components (PFCs) surface properties, such as metal or carbon, and magnetic configurations (limiter or divertor).

Two approaches have been performed in CPD, that is, 1) "active control" of the particle recycling using a moving plasma facing component continuously gettered by lithium [6-9] and 2) study to understand the particle flux effects on "wall retention and release" without external pumping [10]. For the former, several techniques to control particle recycling have been developed in a number of magnetic fusion devices. For example, liquid lithium as a PFM (for plasma-facing material) or lithium coatings to cover PFCs have been tested as one of the candidate of surface coating methods in TdeV[11], FTU[12], CDX-U[13], and NSTX[14]. It is understood that lithium absorbs hydrogen until it is fully saturated to form LiH, during which period reduced recycling, i.e. "passive" wall pumping, is maintained. One of the disadvantages of this kind of method is a finite lifetime due to the surface saturation with absorbed and/or implanted particles after a certain number of discharges. The concept of "active" wall pumping have been proposed by Hirooka et al. [6] and a series of PoP (for proof-of-principle) experiments have been succeeded in a linear device [7-9]. Experiments with a rotating drum limiter (RL) as a poloidal limiter have been conducted in CPD[15]. In this report local active wall pumping effects on global particle recycling, impurity control, and core plasma properties will be presented.

For the latter, it is considered to be several key physics which dominate "wall pumping/fuelling". The surface temperature of the PFCs has been found to play a key role in affecting the reemission and retention depending on the temperature range [3, 16-20]. It has been also reported in ref. [4] that "wall pumping/fuelling" is varied as a function of the density (amount of the fueled particle). In order to avoid ambiguity of gas balance technique during the discharge, a static gas pressure balance method (the measurement of fuel gas pressure before and after the discharge without external pumping) was adopted to evaluate the wall behavior and the particle flux dependence on a transition from "wall pumping" to "wall fueling" or vice versa, was investigated in electron cyclotron resonance ECR plasma. A certain amount of particle flux is found to discriminate between "wall pumping" and "wall fueling". The global wall behavior on the plasma performance is studied as a function of shot history.

This paper is organized as follows. In section 2, description of CPD device, major PFCs and technical details of RL arrangement are given and experimental conditions as well as diagnostic tools are described. In section 3, the results of "active wall pumping" experiments using RL are shown and discussed. In section 4, particle flux effects on global wall behavior are described. Finally a summary is given in section 5.

2. CPD Device and Experimental Set up

2.1. Description of Experimental Device

CPD is a compact spherical tokamak device whose chamber height is $\pm$0.5 m and diameter 1.2 m. The machine has one ohmic solenoid (OH), four toroidal field (TF) coils and three pairs of poloidal field (PF) coils. The vacuum vessel is made of stainless steel and can be baked up to a temperature of 150 $^{\circ}$C. Hydrogen is used as the fuel gas and is fed into the vessel in pulsed mode prior to discharge. The gas pressure ($\sim 1.0\times10^{-5}$ – 3 $\times10^{-4}$ torr) is controlled with the help of a piezo electric valve. A set of 8.2 GHz klystrons (8 $\times$ 25 kW, CW) is used to initiate and sustain the plasma through ECR breakdown. Linearly polarized microwaves (ordinary and extraordinary modes) are injected through the rectangular horn antenna below the equatorial plane with an injection angle of ~ 15° from the normal direction to the toroidal field lines. The pumping system for CPD vessel consists of three turbo-molecular pumps, giving an overall pumping speed of ~1100 lit/s and one cryo-pump with a pumping speed of ~10,000 lit/s.

2.2. Major PFCs and Description of Lithium Coating on Rotating Limiter

The vacuum vessel is made of stainless steel whose surface area is ~6 m^2. Two major plasma facing components are the cover of center stack (CS) and RL, whose surfaces areas are 0.22 m^2 and ~ 0.01 m^2, respectively. The CS cover at R ~ 0.13 m acts as the inboard limiter. It consists of four similar curved plates and extends up to ±150 mm from the mid plane in the vertical direction. It is made of stainless steel (~ 3.0 mm thick) with a ~0.5 mm thick coating of inert gas plasma sprayed tungsten (IPS-W) on the top surface. The RL setup is mounted horizontally from outboard on the torus equator plane, and is moveable linearly for the distance of 50 mm, employing a motorized gear-belt drive mechanism. After the first experimental campaign [10], the material of the rotating drum has been changed from copper to stainless steel in order to avoid copper contamination, though no such evidence was observed after the first experimental campaign. This is made of water-cooled double-wall stainless steel in the shape of cylinder, the diameter and the axial length of which are about 150 mm and 120 mm, respectively. The plasma interactive surface is covered with about 0.5 mm thick IPS-W coatings. Positioned about 10 mm off the rotating drum surface are three lithium evaporators with built-in resistive heaters, the temperatures (350-450 ºC) of which are monitored individually by thermocouples during gettering operation. The deposition rate of lithium on the RL surface is controlled by the rotating speed (4-10 r.p.m.) and the evaporator temperature. If redeposition or sputtering of lithium atoms can be neglected, the normal deposition rate is ~ 30 nm/s on RL. Lithium deposition on the drum is suppressed by a pneumatically operated shutter made of molybdenum between the drum surface and these evaporators. All these components are inserted into a protection structure, which is made of water-cooled copper, but is also coated with IPS-W.

2.3. Experimental conditions and diagnostic tools

Experiments are carried out in two kinds of ECR plasmas, which are produced with typically 40-80 kW of RF power using either fundamental (R_{res} ~ 0.16 m and 0.18 m, resonant toroidal magnetic field B_{TF} ~ 0.3T) or second harmonic (R_{res}~ 0.21 m and 0.24 m, B_{TF} ~ 0.15T) ECR breakdown condition. In one configuration both TF and PF fields are used to ramp up the plasma current [22]. A study on the "active wall pumping" using the lithium coating RL has been performed. Under this condition plasma wall interaction PWI areas are expected to be CS and RL. On the other hand, in a simple torus plasma configuration without PF field and plasma current, a study on the global effects of the particle flux on "wall pumping/fuelling" has been performed. Since this plasma expands both vertically and horizontally, under experimental conditions the plasma interacts with all PFCs. Spectroscopic measurements, focused on H_α (656.1 nm) light intensity, have been carried out looking tangentially at the rotating drum surface from both vertical and horizontal ports. The measurements are done using one H_α monitor (from horizontal port) which consists of an optical filter and photo multiplier tube and one multi-channel optical spectrometer (MOS, 200-900 nm). A quadruple mass analyzer QMS and a pressure gauge equipped in the main chamber are used to analyze a static gas balance without external pumping. Other diagnostic tools include one IR spectrometer (Hamamatsu PMA–11) which is used to monitor the temperature rise, if any, on the RL surface and a CCD (framing rate of 1 kHz) camera which is used to monitor the interactions of plasma with both CS and RL. In addition, magnetic measurements using 40 channel flux loops and Rogowski coil, 140 GHz interferometer, 6 ~ 20 GHz reflectometry, Langmuir probes, lithium sheet beam imaging system [23,24] and high-speed visible camera system are equipped.

3. Active Recycling Control by lithium coated RL

3.1. Rf current drive plasma

Figure 1 shows variations in several plasma signals in typical discharges with (solid) and without (dotted) active lithium gettering. The flat-top current ranges from 0.3kA to 1kA, which are characterized by the open and closed flux surfaces, respectively. Although the change in the line density along the vertical line at R=0.3 m is insiginificant, according to the magnetic analysis the plasma length is varied half when the configuration changes from open one to closed one. The local 2D density measurement clearly supports the drastic change in the plasma boundary [22, 25]. The electron temperature T_e in the shadow of the RL changes from 7eV to 20eV measured by a Langmuir probe. Ion temperatures are considered to be much lower than T_e.

3.2. Active control of local and global recycling

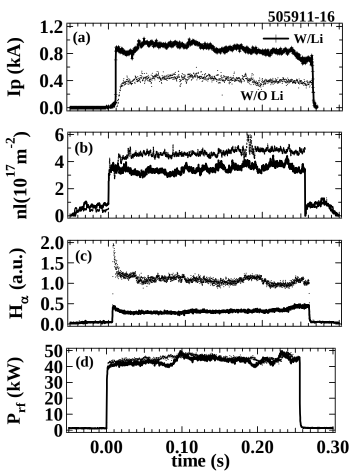

Fig.1 Waveform of plasma parameters (Ip,nl,H_α and P_{rf}) with and without Li getering.

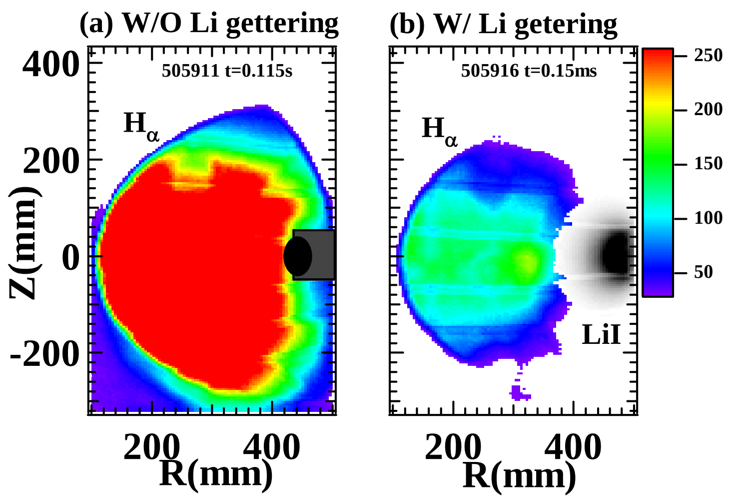

Fig.2 Filtered H_α images(505911 (a) and 505916(b)).RL position is shown in (a) and Li filtered image(BW) is also shown in (b).

In series of experiments (#505911-16) two H_α filtered images ((a) without and (b) with Li gettering) show how PWI at CS and RL are changed by reducing recycling. Image of LiI, taken at R=0.48m of RL in different shot, is also shown in (b). The LiI image is localized near RL suggesting that the gettered Li is ionized near RL. H_α viewing RL at early (■: 5ms after break down) and late times (▲:120 ms after) are plotted as a function of thickness of Li (Δ_{Li}) in Fig. 3(a). Here, the redeposition and sputtering effects are not taken into account. Constant H_α intensity viewing at CS taken during the preheating phase(○:-5 ms before) at 1 kW power, indicates good reproducibility of initial condition in series. Both H_α at two times decay gradually and finally reduce less than 1/3 as Δ_{Li} increases. Particle flux Γ_p at 100 mm behind RL is measured with a Langmuir probe, and it is found that the Δ_{Li} dependence is similar to that of H_α, as shown in Fig. 3(b). OII viewing at the CS from the outboard side is somewhat complicated(Fig. 3(c)). At t=5ms it increases with discharge, and finally it reduces. This reflects a change in the rise time of OII, namely, the fast T_e evolution due to reduced recycling during the breakdown phase. At t= 120ms OII shows a similar tendncy of both H_α and Γ_p. Thus, as soon as lithium gettering starts for active wall pumping, H_α, Γ_p and O-II are reduced by about a factor of 3~4 not only in the rotating limiter region but also near CS, indicating a global effect. These active wall pumping effects are similar to the observations in CDX-U [13] where ohmically heated plasmas are limited by a liquid lithium toroidal ring limiter.

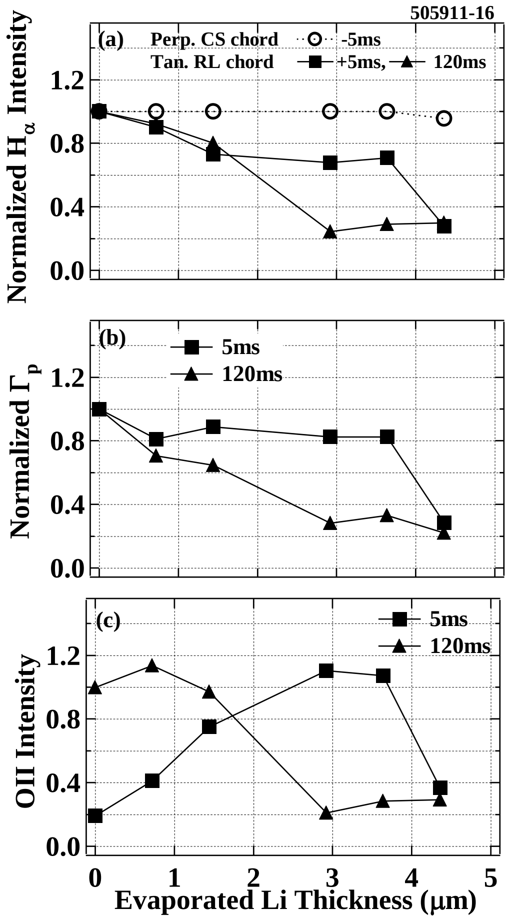

Fig.3 H_α, Γ_p and OII as a function of evaporated Li thickness.

As a consequence of the reduced recycling, the rf driven current is found to be increased by factors of 2-3, especially higher current ramp-up rate in the early time is caused by the initial reduced recycling, as shown in Fig.1. From the toroidal current decay curves after RF off, the decay time, assumed L/τ, is found to be increased by a factor of 2-3 indicating enhanced global T_e with active wall pumping.The global effects of the "active wall pumping" are summarized in the Ip and nl/H_α plane, as shown in Fig. 4. Two groups are

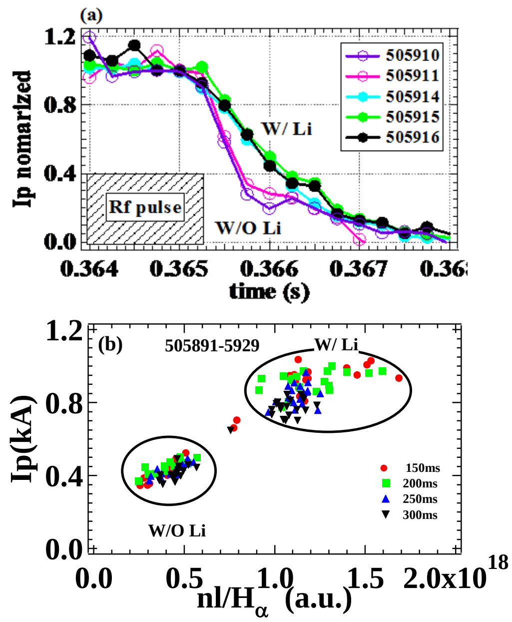

Fig.4 (a) Ip decay after rf off, and (b) Ip v.s. nl/H_α ; a measure of global particle confinemnet time.

clearly divided depending on the reduction of recycling. At the oven temperature of 400-420 ºC the evaporation flux Γ_{Li} is 10^{20} -10^{21}Li/m^{2}s, which is much larger than atomic H fluence (10^{17}-10^{18} H/m^2) and comparable of ion fluence (Γ_p at two times are ~ 10^{20} -10^{21} ions/m^2). Since two order of higher Li flux is possible at 600 ºC, more effective control of recycling will be expected.

3.3. Surface analysis of the rotating drum

In order to understand how the hydrogen atoms are retained in the continuoesly getterring Li layer, secondary ion mass spectrometry, SIMS, analysis have been done for the middle part of the RL surface. A 3keV oxygen ion (O^{2+}) beam is used as the probe at the current density about 1.1 kA/m^2. Under these conditions, the silicon - equivalent etching rate is approximately 8 nm/s by which the horizontal axis is converted depth from elapsed time. Relatively high intensity secondary ions detected are: Li^+, Fe^+, H^+, W^+, C^+ and LiH^+ with m/e=7, 6, 56, 1, 184, 183, 12, and 8, respectively, where m/e is the mass-to-charge ratio. In Fig. 5, depth profiles of H^+, LiH^+ and C^+ normalized by $^7Li^+$ with m/e=7 are shown. It is noteworthy that both H^+ and LiH^+ exhibit the same trend as $^7Li^+$ in depth distribution. This implies that lithium was hydrogenated as soon as it was deposited for gettering. Also, judging from their depth distributions, C^+ and Fe^+(not shown) are considered to be plasma impurities gettered in lithium deposits.

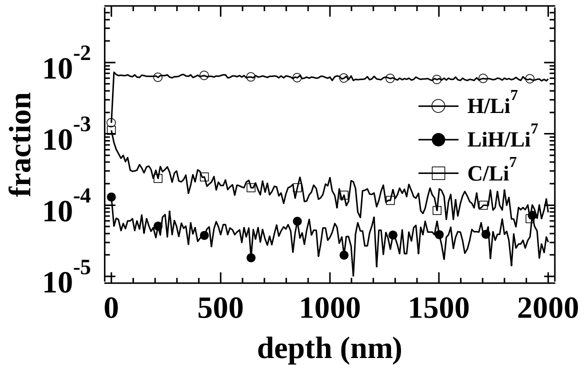

Fig.5 SIMS results; relative depth profiles of H,LiH and C normarized by ^{7}Li.

4. Critical particle flux on retention and release

4.1. Simple torus plasma

In simple torus plasma produced by rf, a vertical plasma column was first initiated at the 2nd harmonic resonance position, as observed through fast CCD camera, and then it expanded very quickly and filled the vessel volume as the rf power was increased. Hence it is expected that PWI will take place all over the vessel surface. This is one motivation for performing the study of wall recycling behavior in simple torus rf plasma. Furthermore, since the edge plasma density (~10^{17} m^{-3}) and T_e (< 10 eV) are sufficiently low, the role of very low energy (~ 30 eV) ions accelerated in a sheath or Franck - Condon energetic atomic hydrogen (~3eV) can be studied on “wall pumping/fuelling”. Gas pressure inside the vessel is recorded after the termination of plasma discharge, but with closed condition of all the gate valves. Two examples of H_α, particle influx into the PFCs, at two different gas pressures (2- 3×10^{-5}, 3-4×10^{-4} torr) are shown in Fig. 5. The base pressure and wall temperature in case (a) were ~8.5×10^{-8} torr and 150 °C (5.6 ×10^{-8} torr and 60 °C in case (b)), respectively. At the very beginning of the experimental campaign which was started after a long air vented period of two months, case (a), the relative fluctuation of H_α increases with increasing filling pressure, and the averaged intensity of H_α at lower filling pressure is somewhat higher than that at higher filling pressure. At the middle of the experimental campaign, case (b), although the higher fluctuation amplitude is observed, the averaged intensity of H_α is much reduced compared than that at the higher pressure.

4.2. The global behavior of wall recycling

The pressure ratio $PR=p_{after}/p_{before}$ is studied as a measure of "wall pumping and fuelling" in and from all PFCs. PR>1 (<1) means "fuelling" ("pumping"). All data during the experimental campaign are plotted as function of the filling pressure. In the high pressure range no "wall fuelling" is observed even in initial experiment at T_{wall} =150 °C (exp2). On the contrary data (exp1) taken at the first experimental day show "wall pumping" at high pressure range, although the wall seems to be dirty. It can be seen from Fig. 7 that there exists a critical pressure p_{crit} (particle flux), defined as PR=1. Shot history effects (wall conditioning including plasma discharge, Li-RL, Ti gettering etc.) are seen to reduce PR.

4.3. Global effects of wall pumping on plasma performance

Although the pressure dependence of PR remains similar, the PR value for the whole experimental range of filling pressure as well as the critical pressure is found to be reduced progressively. After two months of regular machine operation, "wall pumping" dominates almost in the whole experimental range of pressure. As a result plasma performance of current drive experiments operated at low pressure region at ~ 1-2×10^{-5} torr becomes progressively improved. The expansion of "wall pumping" range ($\Delta p= p_{after}-p_{before} < 0$) results in increasing I_p, as shown in Fig.8. These experiments suggest that charge exchange neutrals (a few eV) might play a role in "wall pumping".

5. Conclusion

From the viewpoint of active or passive PWI, and local as well as global PWI experiments have been performed in the small spherical tokamak CPD to study the "wall pumping/

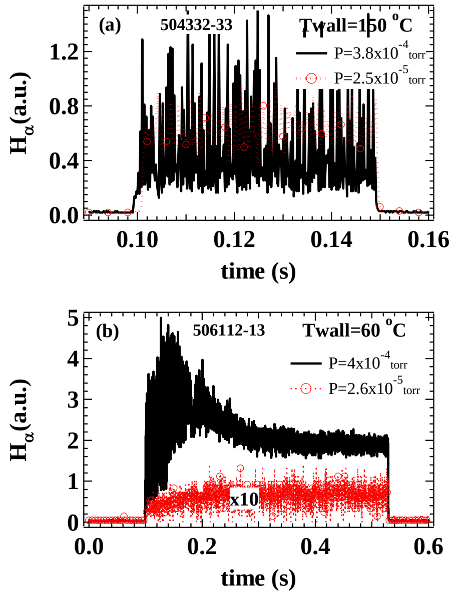

Fig.6 The waveform of H_α intensities taken at initial phase (a) and middle phase (b) in the experimental campaign. Data are compared at two pressures of 2.5× 10^{-5}-4×10^{-4} torr.

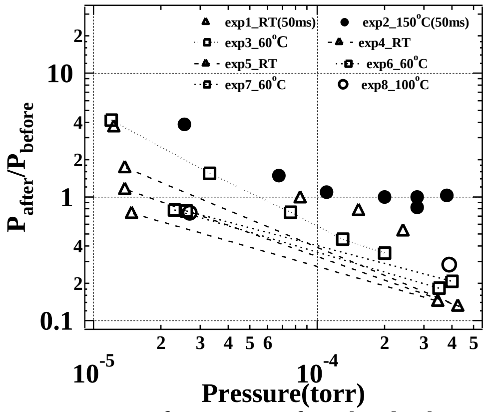

Fig. 7 Ratio of pressure after the discharge and that injected is plotted as a function of filling pressure for a number of experiments. In legend, those indicate different experiments. The wall temperature is mentioned in the legend. RT means room temperature.

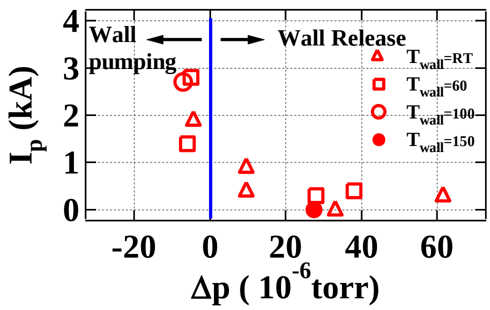

Fig. 8 Ip vs. characteristics of the wall behavor during the experimental campaign.

wall fuelling”. For active particle control, results indicate that hydrogen recycling is reduced by a factor of 3, which is studied by H_α intensities both from the local rotating limiter as well as the center stack. In addition to this global change in particle recycling controlled by the local “self-replenishing surface component”, Γp in the shadow of the RL and also oxygen impurity radiation has shown a notable decrease. Combined particle and impurity control effects have led to a significant increase in toroidal current as well. The key plasma parameter which dominates the global wall behavior is found in the static gas balance study in the ECR plasma discharge in the absence of any external pumping. It is found that wall behavior changes from “wall fuelling” dominated mode to “wall pumping” dominated mode beyond a critical fuelling pressure. Data taken during the whole experimental campaign show this critical pressure reduces as a function of shot history. As a consequence of reduced recycling condition, higher plasma performance is achieved. The low temperature ion and Frank-Condon neutral (~ 3 eV) H-atoms seem to play a role in the observed wall recycling behavior.

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