

Investigation of Recycling and Impurities Influxes in ADITYA-U Tokamak Plasmas^{*)}

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Fuel particle and impurity influxes have been investigated for ADITYA-U tokamak plasma operated with toroidal belt limiter using PMT based spectroscopic diagnostic system installed on machine. The influxes of hydrogen and impurity ions are estimated using various lines of sight (LoS) terminating on the graphite limiter and stainless steel wall to understand their contributions in recycled particle and impurities into the main plasma. It is found that the influxes of neutral hydrogen and oxygen are around 4 times higher in case of LoS terminating on the limiter than the wall while carbon influxes from the both LoSs are comparable. The comparable integrated particle influxes from both LoSs indicate the important role of the wall in the recycling and presence of the impurities in the plasma. The particle confinement time (τ_p) and recycling coefficient (R) are also estimated to quantify those from the estimated particle influxes. The τ_p values vary between 8 to 25 ms when plasma electron density is in the range of $2.0 - 3.2 \times 10^{19} \text{ m}^{-3}$. Analysis of recycling coefficient, R suggests that the Plasma Facing Component (PFC) acts as the particle sink at the beginning of the plasma operational campaign. The R values tend to become more than one as the campaign progresses suggesting that the PFC acting as the particle source.

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1. Introduction

In magnetically confined fusion plasma, fuel particles entering into the plasma plays an active role in understanding of global particle balance in fusion device, towards achieving active plasma density control and also in the modification of the edge plasma dynamic through their collision with the plasma particle via various atomic and molecular processes. It also plays an important role in achieving better plasma confinement as it has been found that lower recycling led to higher plasma confinement [1, 2]. Similarly, in H-mode type plasma operation, recycled neutral actively participates in the pedestal formation at the plasma edge [3]. The fuel particle enters into the plasma not only through various gas introduction methods, such as gas puff, molecular beam injection and pellet injection, but also through the recycling. This is

the process in which the particles leave from the plasma and re-enter into the plasma multiple times during single plasma discharge. The outgoing fuel particles also interact with various plasma facing components and wall of the vacuum vessel and introduces various impurities into the plasma. These impurities play an important role in the plasma through the radiation loss and by diluting plasma fuel particle [1, 4]. The impurity influxes and recycling from plasma facing components (PFC) depend not only on the wall conditioning but also on the particle outflux from the plasma [1]. Hence, the understanding of the sources of particle and their control become the important areas of research in fusion plasma.

Since the beginning of the high temperature plasma research, lot of work has been carried out on these issues [5–11]. Wagner *et al.* carried out experiment on ASDEX tokamak operated in limiter configuration and studied how the different material surfaces (Stainless steel, graphite, SiC) release the particle during recycling and also found

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out that the recycling coefficient at limiter is one [5], during steady state phase of discharge. In ISX-B tokamak, Isler *et al.* carried out an intensive measurement of impurity influxes and their concentrations from beryllium rail limiter [6]. In TRIAM-1 M tokamak, Sakamoto *et al.* compared low and high densities long duration plasma discharges to study the recycling and wall pumping [7]. It shows that the wall acts as sink and source of the particle depending on the wall conditioning and plasma duration. The wall keeps repeating the process of being saturated and refreshed, while the wall saturation is dominated during high power and high-density discharges. Similarly, in long duration discharge of HT-7 tokamak, it was found that the recycling coefficient in each plasma discharge increased with time and the electron density was increased in uncontrolled fashion accompanied by hydrogen and impurities originating from the limiter and part of inner surfaces [8]. Lot of work has been done in TEXTOR-94 tokamak to study the influence of limiters made of low and high Z material on the plasma [9]. In NSTX spherical tokamak, asymmetry in divertor impurity influx along the toroidal direction has been also observed indicating the inaccuracy in total integrated influx evaluation based on the measurement from single toroidal location [10]. In recent experiments on QUEST spherical tokamak, Hanada *et al.* made particle balance investigation with the combination of the hydrogen barrier model and rate equations of hydrogen state in long duration discharges on an all-metal plasma facing wall in QUEST [11]. In general, it is believed through these studies that the plasma facing components, like the limiter and divertor surfaces are mainly responsible for the particle recycling and for introducing the impurities into the plasma as these surfaces interact with the edge plasma [1, 2, 10]. Also, it has been noticed that although particle influxes from the plasma facing limiter and divertor surfaces are higher (around ten times) than those are coming into the plasma from the main vessel wall, the total particle introduced by the vessel wall is almost comparable or even higher than the first wall due to their larger surface area [2, 12]. The particle influxes from surfaces other than limiter and divertor also plays an important role. There has been an increased recognition that more attention needs to be paid to this area for the upcoming large fusion devices, like ITER, and other, where the main plasma recycling and influxes might be important factor along with those from divertor. Here, particle control is an important issue to achieve the continuous operation [13]. For this purpose, various sources of the particle and their relative importance needs to be investigated. In this context, the small and medium sized tokamaks are most suitable to carry out such study due to the relatively easy to access the machine and to diagnose its plasma. Therefore, the fuel recycling and impurity influxes have been investigated in the ADITYA-U tokamak through estimation of particle and impurity influxes from various surfaces.

ADITYA-U tokamak [14] is the upgraded version of

ADITYA tokamak [15]. The main objective of ADITYA-U tokamak is producing plasma in divertor configuration along with carrying out dedicated experiments relevant for large size fusion machines, such as runaway electron generation and its dynamics, disruption mitigation etc. It is also proposed to study the confinement improvement of plasma in shaped condition through the alteration of plasma edge dynamic via various methods of wall conditioning and coating [16], and gas injection [17, 18]. In this paper, we present the investigation of fuel particle and impurity influxes carried out in the circular plasmas of the ADITYA-U tokamak with graphite toroidal-belt limiter. The investigation includes the estimation of influxes from various surfaces. The recycling coefficient, R , has also been measured by estimating the particle in and out fluxes to quantify particle recycling. The particle confinement times have been derived from quantified particle influxes. In section 2 of the paper, the details of ADITYA-U tokamak and relevant diagnostic have been described. Technique to measure influx from different surface has been presented in the section 3, which is then followed by section 4 in which the results on the influxes and recycling have been detailed and discussed. In section 5 paper has been summarized.

2. ADITYA-U Tokamak and Relevant Diagnostics

ADITYA-U tokamak has major (R) and minor (a) radiuses of 0.75 m and 0.25 m, respectively. Since last three years, the machine is routinely producing circular plasma in toroidal-belt limiter configuration operated with toroidal magnetic field, B_t 0.8 - 1.4 T, with plasma current, I_p of ~ 70 - 200 kA with maximum duration 100 to 350 ms, chord-averaged electron density $\sim 1 - 5 \times 10^{19} \text{ m}^{-3}$ and temperature ~ 250 - 500 eV depending upon the experimental requirement. It has at toroidal belt limiter on the inboard side of wall and two poloidal limiters at the out-board side. All limiters are made up of graphite and the carbon is one of the major impurities. The plasma is produced with hydrogen gas injected into the machine from the bottom port using gas fuelling system consisting of piezo-electric valve, programmable pulse generator and corresponding electronics control system. The operation of plasma with divertor configuration has been just initiated by charging the bottom divertor coil [19]. In the divertor configuration, the machine is designed to obtain shaped plasmas with I_p of 100 - 150 kA, elongation (k) ~ 1.1 - 1.2, and triangularity ~ 0.45 .

The major diagnostics used in this investigation are the microwave interferometer for chord averaged density measurement, Langmuir probes to measure the particle outflux, electron temperature and density at plasma edge, and optical fiber, interference filter and photomultiplier tube (PMT) based spectroscopic system to detect the visible spectral line emissions from hydrogen and carbon and

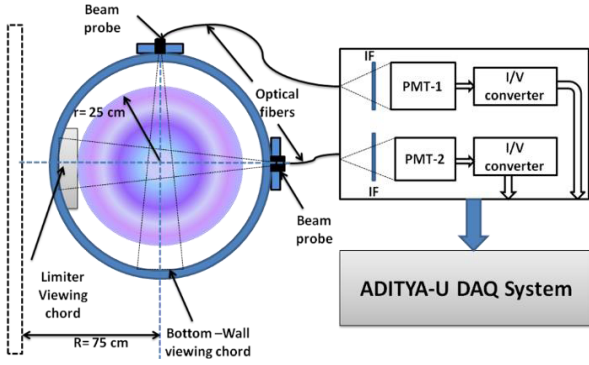


Fig. 1 PMT based experimental setup consists of two sets of PMT, each has three separate PMTs with interference filter for wavelength 656.3 nm, 464.7 nm, and 441.6 nm (total six PMT). One set collect emissions along the LoS terminating on bottom wall and another set terminating on inboard toroidal belt limiter.

oxygen impurities. The central chord averaged electron density is measured using a 7-channel microwave interferometer diagnostic [20]. The total 15 numbers of Langmuir probes have been installed into the machine on different radial, poloidal and toroidal locations. These are made of molybdenum material and having mushroom shape with tip diameter of ~ 5 mm. The probes are placed at radial location starting from 24.4 cm at the outboard side for the measurement of particle outfluxes. The spectroscopic diagnostic setup is shown in Fig. 1. One set of LoS used in this investigation is terminated on the bottom stainless steel wall and viewing from top port of the machine, while another set of LoS is viewing the plasma from the mid-plane radial port of the machine and terminated on the toroidal belt limiter placed on inboard side of the wall. The estimation of influxes has been done from both LoSs for the fuel particle (hydrogen), carbon and oxygen impurities. The light is collected using the collimating beam probe having focal length of 19 mm and diameter of 11 mm. The light is then transported to PMT through 1 mm core diameter and 13 m long optical fibers. Interference Filters (IF) for the wavelength selection are placed at the input of PMT. The current output of the PMT has been converted to voltage signal using I/V converter having gain of 10^5 and then the signal has been acquired, digitized and stored in the main ADITYA-U data acquisition system. In the schematic diagram given in Fig. 1, two PMTs based systems are shown to visualize the data collection from two LoS, but total six set-ups have been used during this experiment for the influx estimation using the LoS terminating on the limiter and bottom wall. The spectral lines are monitored for this purpose are H_{α} at 656.3 nm (3-2 transition), 441.6 nm ($3p^2D - 3s^2P$ transition) from O^{1+} and 464.7 nm ($2s3p^3P - 2s3s^3S$ transition) from C^{2+} impurity ions. All the spectroscopic systems are absolutely calibrated to get the absolute photon flux emanating from the plasma.

3. Measurement Technique

The particle influx can be estimated by detecting spectral line emissions from an atomic or ionic emitter, which is mostly residing near the tokamak plasma edge. The ions inside the tokamak plasma are located inside the thin shell in the plasma depending upon the ionization equilibrium if one neglects the effect of transport in the plasma. When the plasma is in ionization stage, as it happens during the steady state phase of the tokamak plasma, the influx of the particle can be estimated by the absolute brightness of the emitting species from a LoS measurement by taking into account the ionization equilibrium where the number of ionization event and emitted photons are related [21]. The influx is given by the following relation [1, 21]:

$$\Gamma_{particle} = 4\pi(S/XB) I_{abs}, \quad (1)$$

where, S and X are effective ionization and excitation rate coefficients and B is the branching ratio of observed spectral line from an atom or ion. I_{abs} is absolute intensity in units of $\text{photon} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$. The values of S/XB of neutral hydrogen, O^{1+} and C^{2+} ions for different densities and temperatures are given in Figs. 2 (a), (b) and (c), respectively. Here S/XB are taken from open ADAS database [22]. With negligible recombination, it is also required that the atomic rate coefficient be approximately constant in the range of temperature. Ionization potential of neutral hydrogen, O^{1+} , C^{2+} are 13.6, 35.1 and 47.8 eV, respectively. The atom and ions having such lower ionization energies ionize rapidly enough to remain well localized radially in a thin shell in the plasma edge. Then even if the S/XB has weak temperature dependency as in the case of O^{1+} shown in Fig. 2 (b), it can be used for the influx estimation. For the estimation purpose of influxes, the values of S/XB are considered at $1 \times 10^{18} \text{ m}^{-3}$ electron density and at 10 eV temperature for neutral hydrogen and oxygen ion while 20 eV for carbon ion. The influxes from the LoSs terminating on limiter and wall are measured separately using the optical set up as discussed in previous section, and the total integrated influx per sec was found by multiplying the influxes with the effective surface area, 2 m^2 for limiter and 5.4 m^2 for effective area exposed to plasma other than limiter.

The particle confinement time of the plasma can be obtained through the ratio of total particle content inside the plasma and outflux of the ions and is defined by [1, 23].

$$\tau_p = (N/\Phi). \quad (2)$$

Where N is the total fuel particle content of the plasma and Φ is the total outflux of the fuel ions. In the steady state phase of the discharge, the outflux can be considered similar to the neutral influx. The particle confinement has been estimated in the present work from the available single chord measurements of n_e and by taking into account of both particle influxes obtained along the LoSs terminating on both limiter and bottom wall. The above equation of particle confinement time was re-written in terms of working relationship by assuming parabolic profile of n_e and

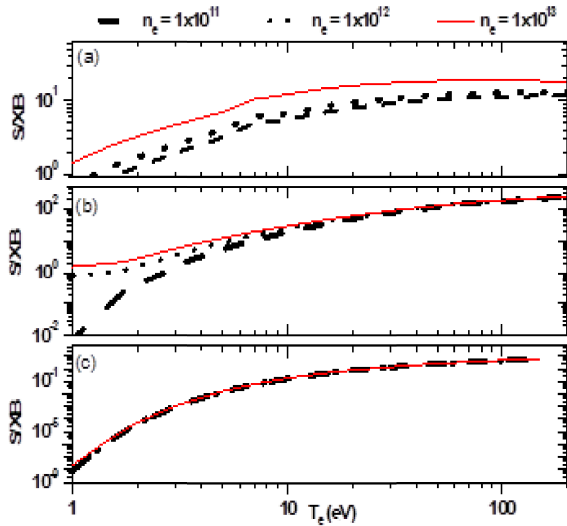


Fig. 2 The S/XB values for (a) neutral hydrogen neutral, (b) O^{1+} and (c) C^{2+} ions when corresponding line emission measured at 656.3, 441.6 and 464.7 nm, respectively.

experimentally measured central chord averaged and edge n_e for the estimation purpose.

From the estimated particle influx, the recycling coefficient R has also been measured. Here, influxes are estimated as discussed in last paragraph. The outflux has been estimated from the probe measurement. As the radial transport in the plasma edge dominated by fluctuation driven transport, then the radial drift of the particle can be obtained from the low frequency fluctuation in poloidal electric field. When the radial drift velocity is correlated with electron density fluctuation, the radial particle flux [23] can be written as:

$$\Gamma_{out} = \langle n_e v_r \rangle, \quad (3)$$

where, n_e and v_r are the DC components of electron density and the radial drift velocity. In ADITYA-U tokamak, the density measurement through Langmuir probe is available, but the radial velocity measurement is currently not available. With the similar plasma parameters in ADITYA tokamak, Jha *et al.* (24) carried out experiments to measure the radial velocity and its maximum value is found to be 2 km/s. This value of v_r is taken here for the estimation of particle outflux.

4. Result and Discussion

The spectral line emissions measured during a typical plasma discharge (shot no #33821) from different LoSs are shown in Fig. 3 along with the temporal evolution of the plasma current, I_p . It has maximum I_p of 87 kA and duration of 102 ms. Figures 3 (b), (c) and (d) illustrate the temporal evolution of H_α , and line emissions at 441.6 nm from O^{1+} and at 464.7 nm from C^{2+} ions, respectively. The signal described by black dotted line is from the LoS terminating the limiter while the red solid line is signal collected

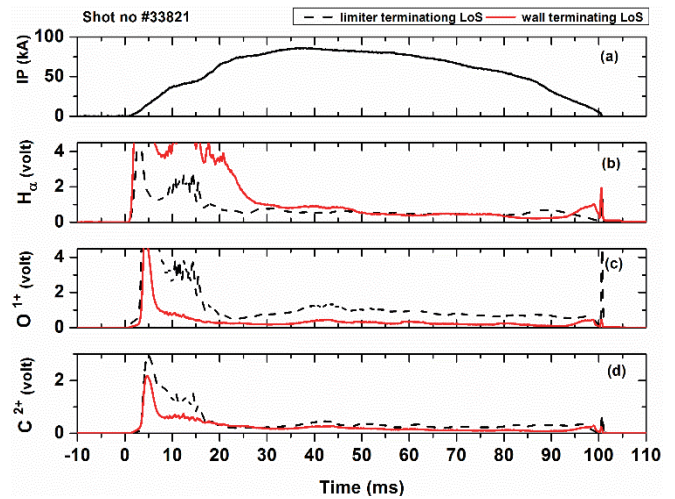


Fig. 3 Temporal evolution of (a) plasma current I_p , (b) H_α at 656.28 nm, (c) spectral line at 441.6 nm (mentioned as OII) from O^{1+} and (d) line at 464.7 nm (mentioned as CIII) from C^{2+} ions. The dashed black and red solid line represent the signals recorded from two different LoS terminating on limiter and bottom wall, respectively.

through the LoS terminating the bottom wall. The intensities of H_α and impurities signals signifies the behavior of neutral hydrogen and impurities during various phases of the discharge, such as initiation phase having the ionization of bulk hydrogen and impurities, current rise phase having significant interaction of the plasma with wall and limiter, steady state phase dominated by almost stable recycling of hydrogen and impurities influxes, disruption and termination phase of the plasma with the sharp spike in signals.

To carry out the statistical analysis of the particle influxes many discharges operated with B_t of 1.1 T at machine center have been analyzed where plasma duration was more than 100 ms and $I_p \sim 78 - 84$ kA. Plasma electron density was varied in between 2 to $3.5 \times 10^{19} \text{ m}^{-3}$. The particle influx is measured using equation (1) mentioned in the section 3. The measured particle influxes of the hydrogen, oxygen and carbon are given in Fig. 4. The error bars at some four to seven data points are also included in the figure. There are many sources of error, such as the photon, dark and electronic noises and error due to calibration and atomic data. Among them, the error associated with photon noise is most dominant. Hence the errors due to the photon noise, calibration and S/XB are included for the error estimation. This influx measurement on the ADITYA-U tokamak is also summarised in the Table 1. As shown in Fig. 4 (a) the neutral particle influx measured along the LoS terminating on the limiter surface is $\sim 6 \times 10^{16}$ to 1.2×10^{17} particle $\cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$, while the values of those measured along the LoS terminating on the bottom wall is ~ 1.4 to 4×10^{16} particle $\cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$. This shows that limiter contributes around 3 to 4 times higher hydrogen neutral influx than the wall. When the total in-

Table 1 Summary of measured influxes and integrated influxes from different LoSs.

| Species | Particle influx when LoS terminating on limiter ($\text{particle}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$) | Particle influx when LoS terminating on bottom wall ($\text{particle}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$) | Integrated influx when LoS terminating on limiter ($\text{particle}\cdot\text{sec}^{-1}$) | Integrated influx when LoS terminating on bottom wall ($\text{particle}\cdot\text{sec}^{-1}$) |
|-----------------|--|--|---|---|
| H | 9.0×10^{16} | 2.6×10^{16} | 1.8×10^{21} | 1.4×10^{21} |
| O ¹⁺ | 2.5×10^{15} | 6.0×10^{14} | 5.0×10^{19} | 3.2×10^{19} |
| C ²⁺ | 1.9×10^{15} | 1.7×10^{15} | 3.8×10^{19} | 9.2×10^{19} |

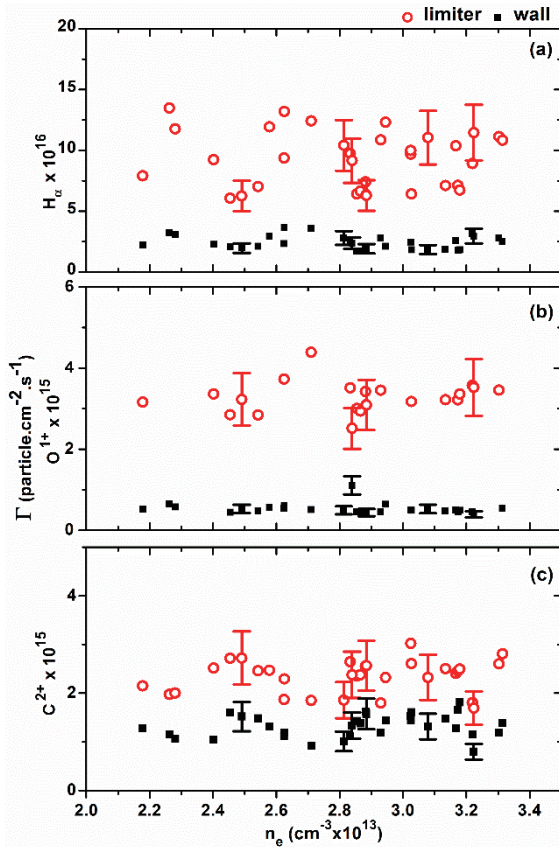


Fig. 4 Particle influxes of (a) neutral hydrogen, (b) oxygen impurity ion and (c) carbon impurity ion. Red circle and black square represent the influxes measured along the LoS terminating on limiter and bottom wall, respectively.

egrated influx obtained by multiplying respective surface areas, as shown in the Table 1, the contribution to the average integrated influx from the limiter and wall have now become $\sim 1.8 \times 10^{21} \text{ sec}^{-1}$ and $\sim 1.4 \times 10^{21} \text{ sec}^{-1}$, respectively. This integrated influx indicates that the wall plays a significant role in introducing the neutral particles in the ADITYA-U tokamak plasma. Similar observations indicating the importance of wall towards the integrated influx have been observed in many tokamaks [1, 6, 8, 25]. As for example, in ISX-B tokamak having deuterium plasma operated with Be rail limiter, the integrated influx from wall was found to be three times more than those from the limiter [6]. Similarly, higher particle influxes from lim-

iter have been observed in TEXTOR tokamak having deuterium plasma operated with toroidal belt limiter [26].

Figure 4 (b) shows the particle flux measurement for O¹⁺ impurity ion. Limiter terminating LoS is contributing ~ 1 to $4 \times 10^{15} \text{ particle}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$ flux into the plasma, while wall surface contributes ~ 4 to $8 \times 10^{14} \text{ particle}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$. It can be seen from Fig. 4 (b) that oxygen influx from limiter is around five times higher than the influx estimated using LoS terminating on the bottom wall. Then, it can be said that the limiter is the bigger source of oxygen impurities for ADITYA-U tokamak. Similar observation has been seen in other tokamaks also. In ISX-B tokamak operated with Be rail limiter [6], it has been observed that oxygen emission is higher in the limiter viewing LoS than that terminating on the wall. Whereas in ADITYA-U In term of integrated influx per sec, limiter and wall contribute around $\sim 5.0 \times 10^{19}$ and $\sim 3.2 \times 10^{19} \text{ particle}\cdot\text{sec}^{-1}$, respectively. However, the observation on the integrated influxes of both hydrogen and oxygen differs among tokamaks as the ratio of limiter to wall surface areas are different, which influences the particle transport in the edge and scrape of layer (SoL) plasmas. In case of ADITYA-U tokamak, integrated hydrogen and oxygen influxes from the limiter are approximately 1.5 times higher than those from wall whereas in ISX-B tokamak having rail limiter to wall ratio of ~ 0.1 , hydrogen and oxygen integrated influxes from wall are 3.3 and 19 times higher than the limiter [6]. Again, in the case of TEXTOR tokamak operated with toroidal belt limiter, ratio of the total ion fluxes to the limiter and to the wall is around 2:1 for a typical discharge [26] which is almost similar to the ADITYA-U tokamak.

In case of carbon impurity, as estimated in terms of the particle influx of C²⁺ ion, the limiter influx is ~ 1.7 to $2.2 \times 10^{15} \text{ particle}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$ while influx estimated from LoS terminating on bottom wall is ~ 1.4 to $1.9 \times 10^{15} \text{ particle}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$ as shown in Fig. 4 (c). This tells that the particle influxes along both LoSs are almost similar. The limiter contributes $\sim 3.8 \times 10^{19} \text{ particle}\cdot\text{sec}^{-1}$, which is somewhat lower than the contribution $\sim 9.2 \times 10^{19} \text{ particle}\cdot\text{sec}^{-1}$ from wall surface. However, the C²⁺ influxes are almost similar from both the LoSs. The C²⁺ ion is having higher ionization energy and then it resides relatively higher temperature region of the edge plasma and influenced by the plasma transport causing similar influxes

from both the LoSs terminating on the bottom wall and limiter.

In tokamak the stainless steel wall is considered to be major source of oxygen. However, it has been seen in our observation that the limiter influx of oxygen is higher than the wall. The possible reason behind higher influxes (in terms of $\text{particle} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$) of both hydrogen and oxygen from LoS terminating on the graphite limiter than on the wall may be due to the higher outflux of plasma particles on the graphite limiter as compared to the stainless steel (SS) wall of the vessel. In the steady state phase of the tokamak plasma, the particle influx is directly linked with the outflux from the plasma. In ADITYA-U tokamak, the toroidal limiter is in direct contact with the plasma, then plasma particle interacts with the limiter via both perpendicular and parallel transport along the field line. Whereas, the particle coming out due to the perpendicular transport in the SoL region of the plasma mainly strike on the wall. As a result, both hydrogen and oxygen influxes from limiter are higher than the wall. It is to be also noted that the data presented here having relatively higher scattering. This arises due to the shot to shot variation in the plasma parameters such as plasma size, T_e and I_p , which should be constant in principle for the statistical analysis of the influxes with respect to n_e . Among these parameters, plasma positions were almost identical for the analyzed discharges and plasma currents were kept between 78 to 84 kA. But the measurement of the core T_e were not available for the all the analyzed discharges. Then, all these factors might be contributing in the spread of the data.

Subsequently the ratio of impurities influxes from different surfaces with respect to hydrogen influxes of those surfaces are determined and presented in Fig. 5 along with error bar. The ratio of oxygen influx to the hydrogen from limiter is $\Gamma_{O,L}/\Gamma_{H,L} \sim 4\%$ (as shown in Fig. 5 (a) with red circles) while the same ratio from wall surface $\Gamma_{O,W}/\Gamma_{H,W}$ is $\sim 2\%$ (as shown in Fig. 5 (b) with red circles). In the same way, the ratio of carbon influx to the hydrogen from limiter, $\Gamma_{C,L}/\Gamma_{H,L}$ is $\sim 2\%$ as shown in Fig. 5 (a) with black squares while the same ratio from wall surface $\Gamma_{C,W}/\Gamma_{H,W}$ is $\sim 4-6\%$ as shown in Fig. 5 (b) with black squares. The errors associated with measurement is $\sim 28\%$ which is marked in the figure. This ratio of influxes can be considered as the indicative values of impurity concentration at the plasma edge. Then it can be stated that the concentration of carbon and oxygen impurities in ADITYA-U tokamak is almost similar to those found out in ADITYA tokamak through both spectroscopic estimation [27, 28] and modelling ADITYA tokamak plasma by TSC code [29].

The particle confinement time has been also measured by taking the ratio of total particle content in the main plasma with number of particles coming out of the plasma. Here, the weighted average of particle influxes from both LoSs terminating on the limiter and bottom wall have been included to get the total particle influxes and analysis has been done during current flat top phase and considering the

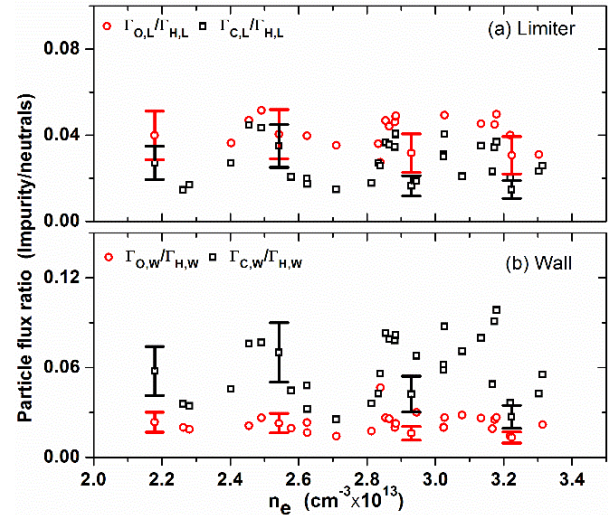


Fig. 5 Ratio of impurities influxes to neutral hydrogen influxes for the LoSs terminating on (a) limiter (b) bottom wall.

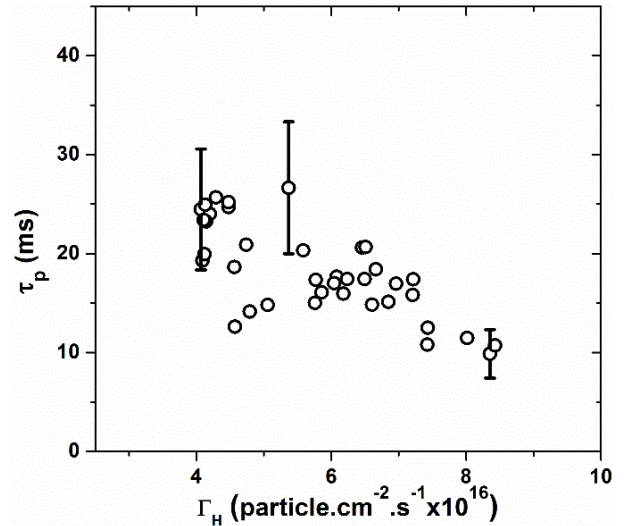


Fig. 6 Change in particle confinement time, τ_p with hydrogen influx (Γ_H).

particle outflux is same of the influx. The particle confinement time (τ_p) lies in the range of 8 ± 2.5 to 25 ± 5 ms for the discharges having plasma densities 2 to $3.5 \times 10^{19} \text{ m}^{-3}$. However, the τ_p with respect to the hydrogen influxes (Γ_H) has been plotted in Fig. 6 to understand the effect of recycling on the particle confinement time. It can be seen that particle confinement times is higher with lower hydrogen influxes. This indicates that the plasma confinement becomes higher with lower recycling as observed in many tokamaks [1, 12, 24]. Here the error bars have been estimated by taking the lower and upper limit of n_e and hydrogen influx and the obtained errors (maximum value 25%) are also marked in the figure.

The hydrogen neutral particle influxes have been also used for the approximate estimation of the recycling coefficient and the outflux has been measured using the Lang-

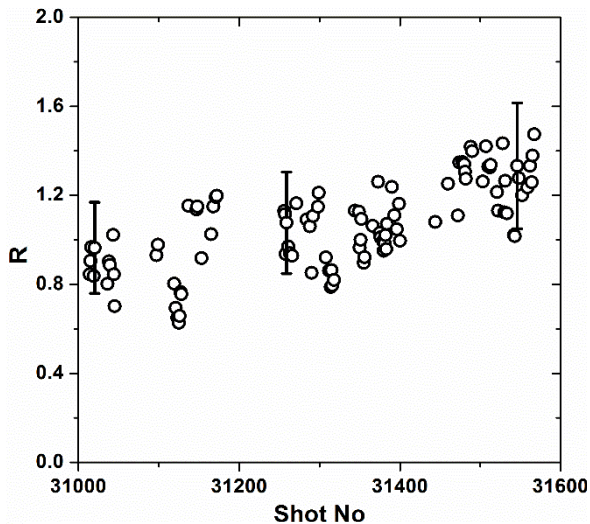


Fig. 7 The recycling coefficient, R with respect to plasma shots number.

muir probe as per technique discussed in section 3. As the measurement from the array of Langmuir array placed at various radial location of plasma edge was not available during this experiment, a constant value of radial velocity, 2 km/s has been taken for the estimation of particle outflux as mentioned in section 3. Of course, the variation of n_e and v_r on shot to shot basis will influence the outflux estimation. However, this has not been incorporated in the analysis. Figure 7 shows the estimated recycling coefficient for the shots having number from 31000 to 31600 along with error bar at three data points. The values of recycling coefficient vary in between 0.6 to 1.4. Although, the data is quite scattered in nature still a definite trend is visible that it is gradually increasing with the shot numbers. The scattering and large variation might be related to use of constant values of radial velocity in the estimation of particle outfluxes. It is seen at the beginning of campaign when the machine was clean, the recycling coefficients have values less than 1 indicating plasma facing components (PFC) acting as sink. With the progress of the plasma operation in time, PFC gets contaminated due to the absorption of plasma particle and recycling coefficient value increases and reaches to its maximum value of ~ 1.4 and one can say that now PFC is acting as source. Similar observation has been made in many tokamaks [4, 5] and even in single discharge during the long pulse operation of TRIAM-1 M [7] and HT-7 [8] tokamaks, where wall acting as both source and sink has been observed.

5. Summary

In this paper a detailed investigation of influx measurement has been carried out on ADITYA-U tokamak during its operation with limiter. Two set of spectroscopic diagnostics, each having three channels, based on the optical fiber, interference filter and PMTs, have been used

to measure the visible spectral lines of neutral hydrogen, carbon and oxygen ions along the lines of sight (LoS) terminating on both the limiter and bottom wall. The particle influxes and integrated influxes have been estimated from the measurement of H_α emission at 656.3 nm. The oxygen influx has been estimated through the monitoring of spectral line at 441.6 nm from O^{1+} ions. Based upon the result presented here, it is found that the limiter surface contributes higher hydrogen and oxygen impurity influxes than that from the wall. The average values are 9×10^{16} and 2.6×10^{16} particles \cdot sec $^{-1}$ for the hydrogen and 2.5×10^{15} and 6.0×10^{14} particles \cdot sec $^{-1}$ for the oxygen from the both LoSs terminating on the limiter and wall, respectively. Higher influx from the limiter than the wall is likely to be related to the higher particle outflux on the limiter than wall during the steady state phase of plasma. The integrated particle influxes for hydrogen both oxygen are around 1.5 times from limiter than wall indicating the important role the wall play toward the recycling and the presence of impurity in the plasma. The influx of carbon as estimated through the monitoring of spectral line at 464.7 nm of C^{2+} ions is almost similar from the both LoSs terminating on wall and limiter. This is mostly due to the fact that the C^{2+} ions with higher ionization energy resides relatively at higher temperature region of the edge plasma and is then influenced by the plasma transport causing similar influxes. It can be stated that the obtained results provide important information for comprehensive understanding of particle controls toward further improved operation of the ADITYA-U tokamak.

The particle confinement time is also measured using central line averaged electron density and by taking into account of both hydrogen influxes obtained from the LoSs terminating on both the limiter and bottom wall. The values come in the range of 8 to 25 ms. The decrease of particle confinement time with increasing hydrogen influxes suggests better plasma confinement with lower particle recycling. Initial measurement of the recycling coefficient suggests that the machine acts as sink in the beginning of the experimental campaign while it starts to act as source later days of campaign. In future, this study will be further extended during the operation of the ADITYA-U plasma in divertor configuration.

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