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Improvement of Plasma Performance with Lithium Wall Conditioning in Aditya Tokamak

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Abstract Lithiumization of the vacuum vessel wall of the Aditya tokamak using a lithium rod exposed to glow discharge cleaning plasma has been done to understand its effect on plasma performance. After the Li-coating, an increment of ∼100 eV in plasma electron temperature has been observed in most of the discharges compared to discharges without Li coating, and the shot reproducibility is considerably improved. Detailed studies of impurity behaviour and hydrogen recycling are made in the Li coated discharges by observing spectral lines of hydrogen, carbon, and oxygen in the visible region using optical fiber, an interference filter, and PMT based systems. A large reduction in O I signal (up to ∼40% to 50%) and a 20% to 30% decrease of H_α signal indicate significant reduction of wall recycling. Furthermore, VUV emissions from O V and Fe XV monitored by a grazing incidence monochromator also show the reduction. Lower Fe XV emission indicates the declined impurity penetration to the core plasma in the Li coated discharges. Significant increase of the particle and energy confinement times and the reduction of $Z_{\rm eff}$ of the plasma certainly indicate the improved plasma parameters in the Aditya tokamak after lithium wall conditioning.

Keywords: lithiumization, wall conditioning, impurity, Aditya tokamak

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1 Introduction

The confinement properties of tokamak plasmas are strongly influenced by plasma wall interactions. Hence, the choice of plasma facing materials and the techniques of wall conditioning play a crucial role in achieving fusion grade plasma performance in tokamaks. In addition to various conventional discharge cleaning methods, wall conditioning through using wall coatings using low Z materials has shown improved plasma characteristics through the control of recycling processes of the hydrogen, deuterium, and tritium as well as of the impurity atoms/ions in the plasma [1,2]. Impurity contamination strongly restricts the plasma performance through the enhancement of the bremsstrahlung emission in high density operation, the dilution of fuel ions, and the energy loss by radiation. Lithium coating, commonly known as 'lithiumization', is one such coating technique compared to other low Z coating elements, such as Be, B and C, which affects the plasma characteristics due to the low radiation power of lithium and its strong reactivity and wall getter capabilities for low Z species, especially for hydrogen and oxygen [3∼5]. In the TFTR tokamak, improved confinement for supershot discharges is obtained with the use of lithium pellet injection as a routine wall conditioning [6]. A similar technique is also applied in the DIII-D tokamak and reduction of central and edge oxygen concentration and better shot reproducibility and improved plasma performance are realized [7]. Wall conditioning with lithium evaporation in vacuum employed in the JIPP T-IIU tokamak leads to a 20% ∼ 50% reduction in oxygen and carbon impurity with less hydrogen recycling [8]. In the NSTX tokamak, an injected lithium pellet and lithium evaporation using an oven lead to an increase in electron and ion temperatures and also in energy confinement [9,10]. Extension of the effective density limit in NBI plasma, higher ion temperature, and a reduced H-mode threshold are observed in TJ-II stellarator after lithiumization [11]. Recent experiments in EAST and the HT-7 tokamak with lithium coating show improved plasma performances, including lower radiation losses, higher electron temperature, and reproducible plasma discharges [12,13].

Moreover, liquid lithium has shown potential of becoming an alternative plasma facing component as compared to the conventional solid material, which faces technical difficulties in handling high power density and large neutron fluxes for long periods of time. Flowing liquid Li can dissipate a high heat load resulting from the bombardment of high energy particles. Furthermore, it can also replenish the eroded surface occurring during normal operation or disruption of the plasma [14]. However, liquid metal splashing into the plasma is a major concern. Recent experiments with a liquid lithium limiter by means of a capillary-pore system configuration in FTU [15], T-11 M [16], and the HT-7 [13] tokamak have been successfully carried out without splashing liquid lithium into the plasma. Considering the potential application of lithium as the plasma facing material for fusion grade plasma devices, lithium coating experiments are carried out in Aditya tokamak [17] to develop the relevant technique and to improve the understanding of its effect on plasma performance.

In this paper, plasma performance with lithium wall conditioning in the Aditya tokamak is reported. Section 2 briefly deals with the lithium coating experiment and relevant diagnostics. The effect of lithiumization on the major plasma parameter and behaviour of plasma impurities has been studied in detail in section 3. In this section, improvement of plasma performance has also been reported through the study of plasma confinement and effective charge of plasma, $Z_{\rm eff}$. The conclusion is drawn in section 4.

2 Experimental set-up

The present experiment has been carried out in the Aditya tokamak [17,18], which is a medium-sized air-core tokamak having major (R) and minor (a) radius of 75 cm and 25 cm, respectively. It has a circular graphite limiter and a stainless steel vacuum vessel with a rectangular cross-section. The maximum and minimum gaps between the vessel wall and the limiter are 6 cm and 4 cm, respectively. The working gas is hydrogen. Typical plasma parameters for the discharges reported in this paper are: toroidal magnetic field, $B_{\rm t}=0.75$ T, plasma current, $I_{\rm p}$=65 ∼ 72 kA, line average electron density, $n_{\rm e}$=1.2 ∼ 1.8×10^{13} cm^{-3}, and central electron temperature, $T_{\rm e}(0)=280\sim400$ eV, plasma duration 70 ∼ 90 ms. Fig. 1 shows the locations of different diagnostics on the Aditya tokamak used in this study. The chord averaged electron density is measured by a 7-channel microwave interferometer [19]. The estimation of electron temperature, which mainly reflects the core plasma temperature, is made by the ratio method using soft X-ray emission. Estimation of radiated power is done using single-chord Bolometer measurement through the center of the plasma. The impurity line emissions at 777.1 nm from O I and 569.6 nm from C III and H_α (656.3 nm) emissions are routinely monitored by the diagnostics based on the combination of interference filter and photo multiplier tube (PMT) detectors. Light has been collected using optical fibres viewing the plasma midplane and terminating on the inner wall. Bremsstrahlung emission at 523.4 nm is also regularly monitored from the top port of the machine to estimate $Z_{\rm eff}$ of the Aditya tokamak plasma. Spatial profiles of visible spectral lines are routinely collected using a 9-channel multi-track high resolution spectrometer viewing the plasma along the vertical chords from the top port [20]. This spectrometer is also used to measure the impurity ion temperature. Vacuum ultra violet (VUV) spectral lines from O V at 63.0 nm and Fe XV at 41.7 nm are recorded using an electron multiplier tube (EMT) detector coupled to a grazing incidence VUV monochromator (Acton research Corp.: Model no - GIM X 551.5) along a chord passing through the centre of plasma. The plasma current in the Aditya tokamak is measured using a Rogowski coil placed inside the vacuum vessel. Four flux loops, each consisting of a single turn loop of copper wire, are placed on the vacuum vessel to measure the loop voltage.

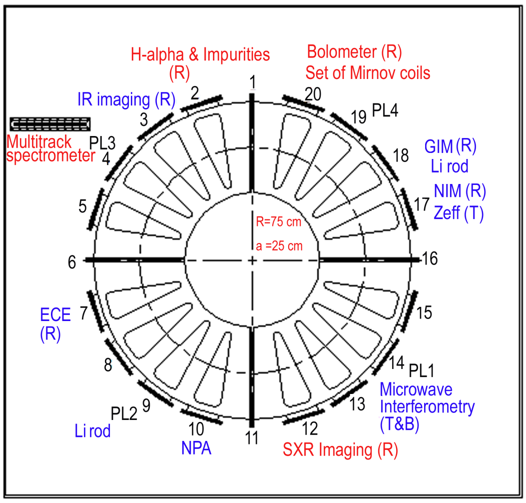

Fig.1 Schematic diagram of the Aditya tokamak, indicating all major and relevant diagnostics. PL1, 2, 3 and 4 – pumping line 1, 2, 3 and 4, NPA – neutral particle analyser, R– radial, T– top, T&B – top and bottom, GIM – grazing incidence monocromator, NIM – normal incidence monochromator, IR – infra red, SXR – soft X-ray and ECE – electron cyclotron emission (color online)

Lithium coating of the vacuum vessel has been done by exposing a tiny lithium rod into the glow discharge cleaning plasma [21]. The lithium rod is mounted on a holder and inserted into the machine through an ultra-high vacuum compatible vacuum feed-through. Lithiumization of the Aditya tokamak vacuum vessel has been done by introducing two Li rods of diameter ∼ 12 mm and length ∼ 25 mm, into the glow discharge plasma of hydrogen from two locations separated toroidally by 168 degrees. The hydrogen glow discharge was operated with voltage 350 Volt and discharge current ∼ 3.5 A. The filling pressure of hydrogen in these cleaning discharges is usually kept at 8×10^{-4} Torr. The rods are inserted from the bottom ports and the tip of the rods is placed at 150 mm away from the center of the machine.

The achieved thickness of the Li film is 10 ∼ 20 nm with 12 hours of glow discharge operation with Li rods. This has been verified by inserting a stainless steel plate inside the vacuum vessel near to the bottom wall of the machine and analyzing the Li coating on it using XRD and ESCA. The estimated number of Li sputtered from the rod during each coating is $\sim 10^{21}$ by referring to the glow discharge parameters mentioned above. Regular plasma operation has been carried out after retracting back the lithium rod into the shadow of the limiter.

The status and uniformity of the coating is ascertained by monitoring the lithium spectral line emissions regularly from at least three different toroidal locations of the vessel, of which two locations are ∼90 degrees away from each Li rod. Almost similar intensities of Li I and Li II spectral lines observed from these locations, which substantiates that the Li is coated everywhere on the vacuum vessel wall fairly uniformly. However, exact quantification of uniformity requires additional measurements at other toroidal and poloidal locations using more Li I monitoring spectroscopic channels. The effect of lithium coating resulting from the above-mentioned method sustains for 12 to 15 discharges in the Aditya tokamak. In our case we observed that the intensity of Li I decreases pretty sharply, and diminishes to a very small constant value after 12 to 15 discharges.

3 Results and discussion

3.1 Description on main plasma parameters

Fig. 2 shows the time evolution of plasma current, loop voltage, chord average electron density, electron temperature, H_α emission, and radiated power for discharges before and after lithiumization of the Aditya tokamak vacuum vessel wall. It can be clearly seen from Fig. 2 that the line averaged electron density, n_e, and the plasma electron temperature, T_e, attains substantially higher values in the discharge with lithium coating compared to without lithium coating discharge in the plasma current flat top region. The H_α emission is noticeably reduced after the Li coating, which clearly indicates the reduction of hydrogen recycling from the wall. Higher n_e values along with lower H_α signals suggest the improvement of the particle confinement. It can also be inferred from Fig. 2 that the energy confinement is also improved by referring to the increased n_e and T_e after lithiumization while having almost similar input powers in both discharges (quantified in detail in Section 3.3). The above-mentioned improvement in the discharge characteristics has been observed in many discharges with lithiumization. The results of the values of loop voltage, radiated power, T_e and H_α emission at the plasma current flat-top region for different discharges with and without lithiumization have been plotted against n_e in Fig. 3. Here, open and solid circles stand for the discharges before and after the Li coating, respectively. The data corresponding to that shown in Fig. 2 are duplicated in Fig. 3 with a cross mark on the symbol. We have observed a substantial increase in plasma temperature (up to 30%) and up to 20%∼30% reduction in H_α emission in most of the discharges with lithiumization. This reduced recycling principally gives better handling regarding the control of electron density. As a result, higher density has been achieved with lithiumization in the Aditya tokamak. Moreover, better shot reproducibility has been obtained after the coating.

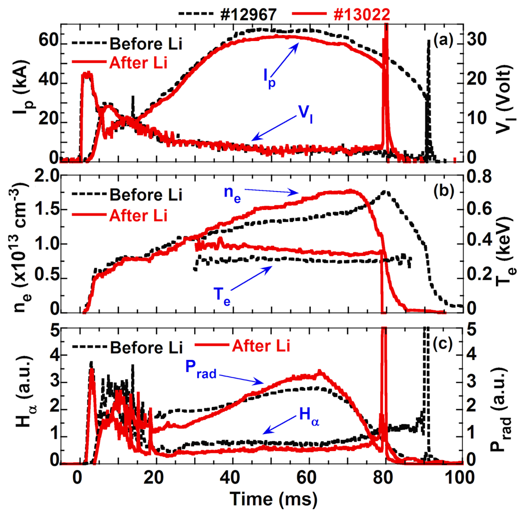

Fig.2 Time evolution of (a) plasma current I_p and loop voltage V_l, (b) chord average electron density n_e and electron temperature T_e, and (c) H_α signal and radiated power P_{rad}, for discharges before (− − −) and after (———) lithiumization (color online)

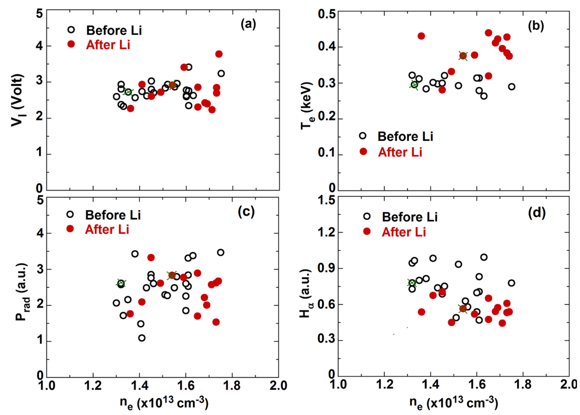

Fig.3 (a) Loop voltage V_l, (b) electron temperature T_e, (c) radiated power P_{rad} and (d) H_α signal plotted versus chord average electron density n_e, for discharges before (open circle) and after (solid circle) lithiumization. Cross marks on the circles indicate data correspond to Fig. 2 (color online)

3.2 Analysis on impurity behaviour

Impurity behaviour in the Aditya tokamak changes drastically after lithiumization. In this section we present a detailed study of impurity behaviour during the Li coating experiment. Fig. 4 illustrates the temporal evolution of O I, C III, and bremsstruhlang continuum for the same set of discharges as that presented in

Fig. 2. Oxygen and visible continuum emissions show a signification reduction after lithiumization, with visible continuum emission reduced by up to 40% and O I emission reduced by more than 50%. This larger reduction of O I emission is understandable considering the strong oxygen gettering capabilities of lithium. It is also been observed that the reduction in oxygen and visible continuum emissions not only happened during the steady-state phases of the discharge, but also occurred during the breakdown phase. This indicates that the impurity generation during breakdown has also been reduced significantly after the Li coating, which is also supported by the observation of reduced C III emission during the start-up phase. However, the C III emission did not show any reduction during the steady-state phase of the discharges before and after the Li coating, which may be due to the fact that the carbon impurity is mainly coming from the graphite limiter and not from the wall. Again, the statistics of emission from different impurity species from several discharges with and without lithiumization in the plasma current flat-top region has been plotted against chord averaged electron density, n_e, in Fig. 5. Here too, the data correspond to that shown in Fig. 4 are duplicated in Fig. 5 with a cross mark on the symbol. The figure clearly shows the major decline in the O I signal and appreciable reduction in the visible continuum signal after lithiumization. This reduction of O I signal mainly reflects the decrease of influx of oxygen impurity coming from the vessel wall, and the fall of visible continuum signal indicates the reduction of $Z_{\rm eff}$ of the plasma. However, C III signal does not show any reduction after lithiumization, and as mentioned earlier, the carbon mainly originates from the graphite limiter of the Aditya tokamak, upon which the lithium coating degrades much faster as compared to the walls of the vacuum vessel.

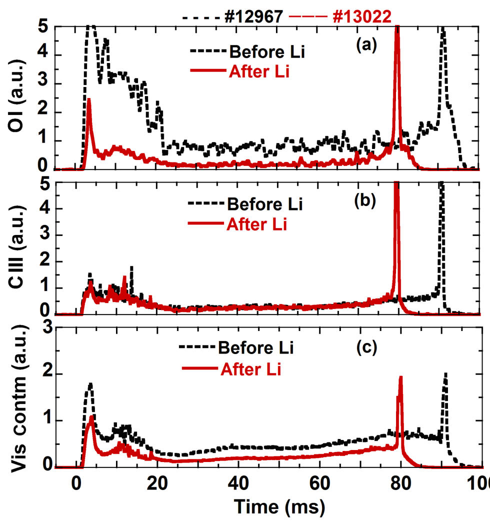

Fig.4 Time evolution of signals from (a) O I at 777.1 nm, (b) C III at 569.6 nm, and (c) bremsstrahlung continuum (Vis contm) at 523.4 nm for discharges before (– – –) and after (——) lithiumization (color online)

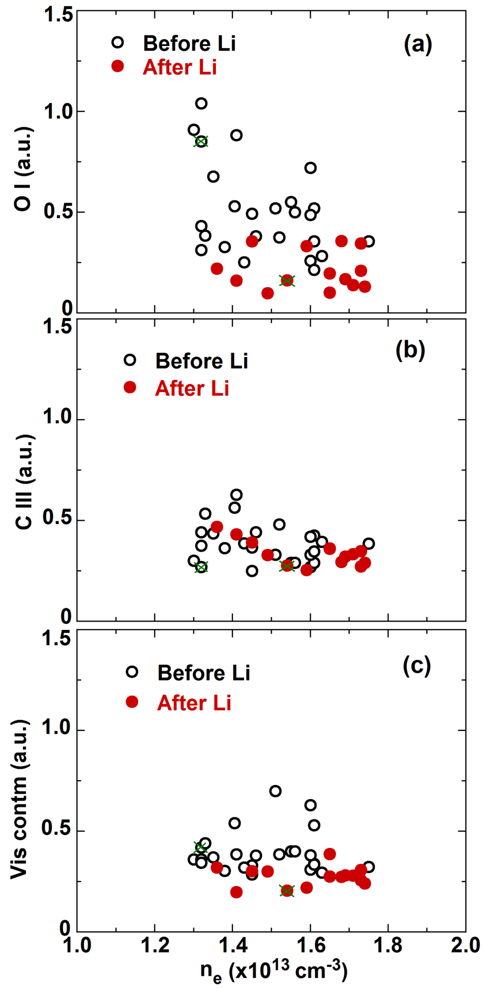

Fig.5 Signals from (a) O I at 777.1 nm, (b) C III at 569.6 nm and (c) bremsstrahlung continuum (Vis contm) at 523.4 nm plotted versus chord average electron density, n_e, for discharges before (open circle) and after (solid circle) lithiumization. Cross marks on the circles indicate that the data correspond to Fig. 4 (color online)

Visible spectra around 545 nm, which include Li II spectral line at 548.4 nm having transition of 1s2s ^{3}S-1s2p ^{3}P, has also been monitored using the high resolution multitrack spectrometer. Fig. 6 illustrate the presence of a strong Li II spectral line after the Li coating. This wavelength range also includes several spectral lines, whose intensity significantly reduces after lithiumization. Many of these lines are identified as the spectral lines from neutral iron (iron spectral lines in the VUV region have been observed) using the NIST tables [22]. Small intensity Li II lines are recorded in the discharge experiment before Li coating. This might be related to lithium present on the surfaces following the past experiment or the lithium beam used for diagnostics purpose. Impurity behaviour inside the main plasma has also been studied through the monitoring of O V emission at 63.0 nm having transition of 2s^2 ^{1}S$_0$-2s2p ^{1}P$_1$ and Fe XV emission at 41.7 nm having transition of 3s^2 ^{1}S$_0$-3s3p ^{3}P$_1$. Fig. 7 illustrates the signal from O V and Fe XV before and after the coating. These emissions are markedly reduced after lithiumization. In the Aditya tokamak, the experimentally measured spatial profile of O V emission peaks at $\sim 17\,\mathrm{cm}$ [20] and hence is not coming from the plasma core. However, as the fractional abundance of Fe ions shows the presence of Fe^{14+} in the temperature range of 100 eV to 400 eV with its maximum lying in the range of 180 eV to 200 eV [23], the Fe^{14+} is certainly coming from the core plasma in the Aditya tokamak. The reduction in Fe XV emission justifies the observation of reduction in $Z_{\rm eff}$ and also indicates reduced impurity penetration into the core of the plasma. However, this lower radiation from O V and Fe XV is not exactly reflected in the total radiated power measured by bolometer diagnostics, which did not show any change before and after the coating. The contribution coming from Fe in total radiation might not be significant enough to influence it since the Aditya plasma is dominated by low Z impurities, like C and O.

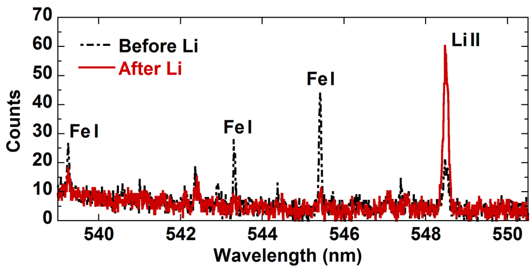

Fig.6 Visible spectra around 545 nm for discharges before (– · –·) and after (——) the lithiumization (color online)

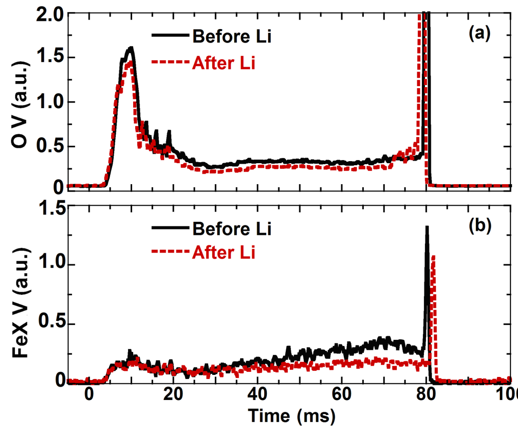

Fig.7 Time evolution of VUV signals from (a) O V at 63.0 nm, and (b) Fe XV at 41.7 nm for discharges before (——) and after (– – –) lithiumization (color online)

3.3 Study on confinement and $Z_{\rm eff}$

Plasma confinement improvement with lithiumization has been studied through the estimation of particle and energy confinement time. This has been done in the large number of plasma discharges before and after lithiumization. Since only single chord measurements were available for most of the relevant diagnostics during this campaign, the temperature and density profiles have been assumed to be parabolic and their experimentally measured central and edge values were used for estimating the confinement times. The particle confinement time is defined by [24]

$$\tau_{\rm p} = \frac{N}{\Phi}, \tag{1}$$

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 to be similar to the neutral influx. The neutral influx measurement is based on absolute intensity of H_α photons released from wall, limiters etc. However, it should be noted that influx from the wall is only taken into account here for the estimation. Similarly, the energy confinement time is defined by [24]

$$\tau_{\rm e} = \frac{3/2 < n_{\rm i}T_{\rm i} + n_{\rm e}T_{\rm e} > V}{I_{\rm p}V_{\rm l} - P_{\rm rad}}, \tag{2}$$

where $I_{\rm p}$ is the plasma current, $V_{\rm l}$ is the loop voltage, V is the plasma volume, and $P_{\rm rad}$ is the total radiated power. Estimated particle and energy confine times are plotted versus chord averaged electron density, $n_{\rm e}$, as shown in Fig. 8. The cross marks on the circles indicate

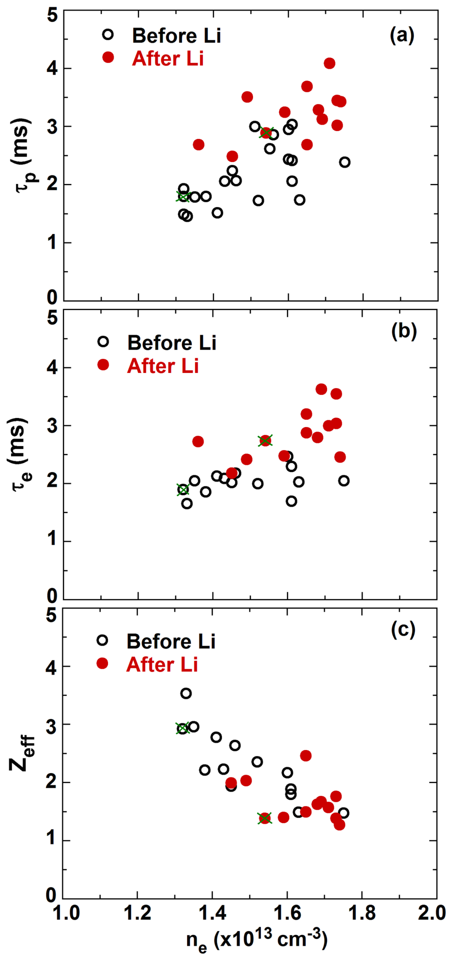

Fig.8 (a) particle ($\tau_{\rm p}$) and (b) energy ($\tau_{\rm e}$) confinement times and (c) $Z_{\rm eff}$ plotted versus chord average electron density, $n_{\rm e}$, for discharges before (open circle) and after (solid circle) lithiumization. Cross marks on the circles indicate data correspond to the discharges shown in Fig. 2 (color online)

that the data correspond to the discharges shown in Fig. 2. Particle confinement times have increased 35% to 60% after the Li coating and energy confinement times increased up to 50%. The $Z_{\rm eff}$, which qualitatively indicates purity of the plasma, is also estimated from the visible continuum measurement [25]. Parabolic profiles of temperature and density are assumed, and their experimentally measured central and edge values were used for $Z_{\rm eff}$ estimation. It also shows a significant reduction. The values were scattered around 2.0 to 3.0 before the Li coating, and were reduced to around 1.5 to 2.0 after the Li coating. These studies definitely indicate the improvement of plasma performance in the Aditya tokamak with lithiumization.

4 Conclusion

In the Aditya tokamak, Li coating experiments were carried out by means of exposing a tiny lithium rod under glow discharge cleaning plasma. Significant reductions were found in O I and O V signals. This clearly indicates the reduction of oxygen impurity inside the Aditya plasma. However, C III signal does not show any change. It was also found that the signal from VUV emission of Fe XV has also been decreased. Similarly the 20% ∼ 30% decrease of hydrogen wall recycling and higher $T_{\rm e}$ have been achieved after the Li coating, along with better shot reproducibility. Analysis of the particle and energy confinement times and $Z_{\rm eff}$ certainly indicate the improved plasma performance in the Aditya tokamak after lithiumization.

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