

Transport of Li and W impurities and their influence on discharge parameters of the T-10 tokamak

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In this paper the study of influx and transport of Li and W and their influence on the parameters of OH and ECRH discharges is presented. The movable Li-limiter [1] and the main W-limiters are installed in the same poloidal cross-section of the T-10 tokamak (major radius $R = 1.5$ m, minor radius $a = 0.3$ m). This Li-limiter together with thin Li-films deposited on the chamber wall are the sources of lithium in T-10. Wide range of diagnostics was used in this study: visible spectroscopy, Z_{eff} diagnostics from bremsstrahlung, active CXRS diagnostics, bolometers, AXUV and SXR diagnostics. The modeling of transport of impurities atoms and ions in the plasma column is performed with this data.

Experiments have shown that the operation of the Li-limiter as a source of Li strongly depends on its location in relation to circular and rail W-limiters. Two main regimes can be distinguished:

- Passive ("Pas", $r_{Li} = 33 \dots 40$ cm) – the source of Li is located in the "shadow" of a circular W-limiter;
- Active ("Act", $r_{Li} < 30$ cm) – the source of Li is located in the plasma and operates as a current limiter.

The construction of the Li-limiter made it possible to vary influx of lithium into the plasma both by means of sputtering and evaporation of Li via a built-in heater. In the Pas-regime the main Li fluxes to the discharge are created by heating Li-limiter and sputtering of lithium films by deuterons in SOL. In the Act-regime, when source of Li is located in the main plasma, a much more intense source of lithium is created due to the physical sputtering of the Li-limiter itself by deuterons and lithium ions.

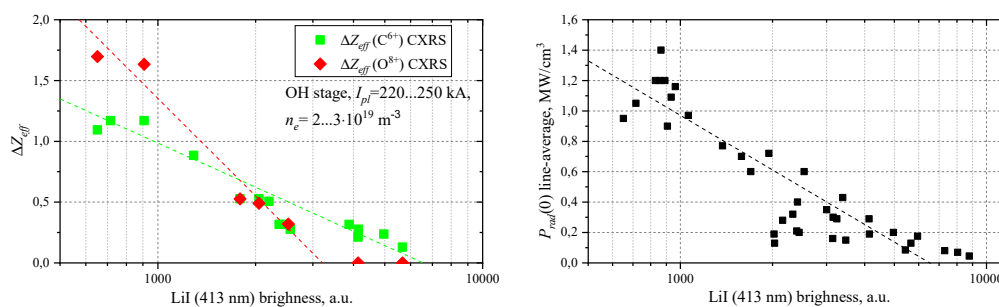


Figure 1: Efficiency of light impurities removal and reduction of the $P_{rad}(0)$ due to W removal as a function of the level of lithiation

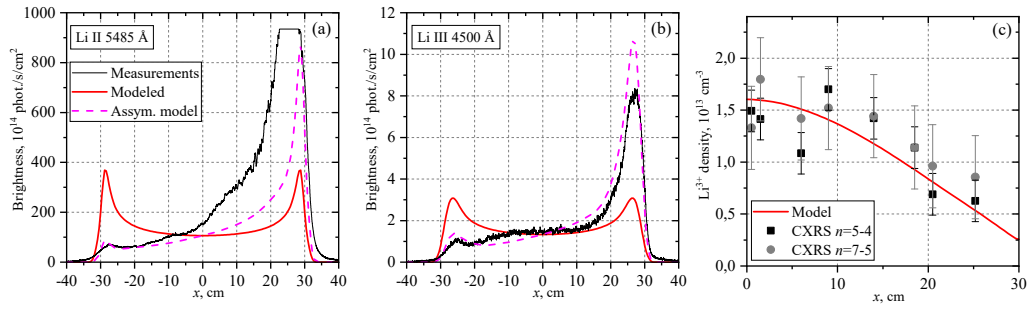


Figure 2: The results of modeling the emission of Li III lines 450 nm (a) and 516.7 nm (b), and the density of Li nuclei (c) in the Act-regime.

In the Pas-regime the Li^{1+} have a short life time in SOL ($\tau_{\text{life}} \leq 0.5 \mu\text{s}$ due to zero Li recycling on the W-limiters) and is not able to diffuse neither to the chamber wall nor to the main plasma. This is confirmed by the following facts:

- Li is absent on the chamber surfaces far from the Li-limiter, even after years of lithiation
- the intake of Li^{1+} into the discharge is extremely low ($\sim 10^{13} \text{ cm}^{-2} \cdot \text{s}^{-1}$) and, according to the simulation, is unable to create the value of the Li^{3+} density in the column measurable by T-10 CXRS diagnostics ($\geq 0.3\%$ of n_e).

The lithiation of the chamber near the W-limiters, where the densities of C and O atoms and molecules is 30...50 times higher than average along the torus greatly enhances the effect from gettering of C and O by lithium. Due to this, the decrease in the C and O densities (n_C, n_O) by 10...30 times leads to a proportional decrease in the edge radiative losses $P_{\text{rad}}^{\text{edge}}$ emitted by C and O ions. This decrease is not compensated by an increase in the radiation of Li ions. This is confirmed by the growth of the edge temperature of the plasma T_e^{edge} in $\sim 1.3 \dots 1.5$ times in the experiment. Such a weakening of $P_{\text{rad}}^{\text{edge}}$ makes it possible to raise the plasma density up to the Greenwald level limited by the MHD-mode $m = 2$ and the development of the MARFE [2].

Despite the T_e^{edge} growth a sharp decrease in the n_C and n_O leads to a reduction in the sputtering of tungsten by C and O ions and nuclei [1] resulting in a decrease in the flux of W atoms into the plasma. The lithiation reduces Z_{eff} from 4...5 to ≈ 1 resulting in the decrease of the plasma collisionality and the neoclassical accumulation of impurities near the column axis and simultaneously enhances the anomalous transport of particles [3], preventing the penetration of impurities into the plasma center. Thus, lithium influencing two processes (reduction of the impurities intake into the plasma and their accumulation into the center) controls the level of light impurities, changing the Z_{eff} . Lithiation in the Pas-regime makes it possible to change the level of light and heavy impurities in the center of the column: C nuclei – 10...20 times, O nuclei – 20...40 times, and W ions – 40...60 times (Fig. 1).

In the Pas-regime the main result of the ECR-heating is an increase in the intensity of the Li^{1+} lines ($\lambda = 548.6 \text{ nm}$) and the radiative losses on lithium ions in $\sim 2 \dots 3$ times with $P_{\text{ECRH}} \sim 1 \text{ MW}$. This indicates a proportional increase in the Li flow into the discharge with the increasing of the charged particles fluxes to the edge of the column during ECRH. However, this increase in the radiation intensity of Li ions is insufficient neither to re-emit heat fluxes going to W-

limiters, nor to measure the absolute values and profiles of lithium nuclei $n_{\text{Li}^{3+}}(r)$ and Li^{2+} ion lines.

The transition to the Act-regime allows increasing the flux of lithium into the discharge by up to ~ 100 times and getting the Li^{2+} CX-lines 450.0 nm and particularly weak 516.7 nm to measurable intensities. This allowed us to determine the $n_{\text{Li}^{3+}}(r)$ profile using the CXRS from these spectral lines (Fig. 2). Both measurements give similar profiles and absolute values of $n_{\text{Li}^{3+}}(r)$ within the limits of errors. CXRS measurements show that in the Act-regime the content of lithium nuclei $C_{\text{Li}} = n_{\text{Li}}/n_e$ in the column grows from $C_{\text{Li}} \leq 0.3\%$ to $\approx 30\%$, while the deuteron content in the center of the column decreases from $C_{\text{D}} \sim 100\%$ to $\leq 10\%$. This leads to an increase in Z_{eff} from $Z_{\text{eff}} \approx 1.2$ to ≈ 2.7 , and in the radiation loss power by Li ions and atoms $P_{\text{Li}}^{\text{edge}}$ from ≈ 0.4 kW to ≈ 40 kW. It can be noted that even with the maximum possible C_{Li} in the plasma, the $P_{\text{rad}}^{\text{edge}}$ does not exceed 10...15% of the OH power in the discharge, which indicates the low efficiency of Li in converting heat fluxes to radiation losses.

Due to the accumulation of impurities in the Li films, lithiation of the chamber had to be performed regularly to maintain a low value of Z_{eff} during working with Li-limiter in the Pas-regime. This determines special working requirements allowing only non-frequent use of the Li-limiter in the Act-mode and only in OH discharges. However, in the close-to-Act-regime ($C_{\text{Li}} \approx 8\%$) with central ECRH it is seen that the content of Li nuclei in the plasma center does not decrease, but grows because of the predominant increase in the Li intake in the discharge comparing to the increase in the electrons intake. The same behaviour is expected for the Act-mode.

The transport model, which describes the density profiles of the nuclei and ions (and their sources) of He, C, O, Ar, K, W impurities in OH discharges, also describes the $n_{\text{Li}^{3+}}(r)$ and Li^{2+} line intensities profiles for $\lambda = 450.0$ nm and 516.7 nm with good accuracy. This proves that the transport of Li in a tokamak does not have any deviations from other impurities and follows the same dependencies.

Experiments to investigate the influx, transport of tungsten and its effect on the discharge parameters were carried out in a plasma with W-limiters and $Z_{\text{eff}} = 1 \dots 5$. The simulation of the W transport was carried out with the previously developed and verified for the T-10 transport model in STRAHL + ASTRA codes [3, 4].

The following regular sequence (W-cycle) is found. Its distinctive features can be seen on the SXR signal (Fig. 3): following the $Z_{\text{eff}}(r)$ peaking, tungsten accumulation occurs at the center of the column with peaking of the radiation losses profile $P_{\text{W}}(r)$. Due to its high emissivity, W

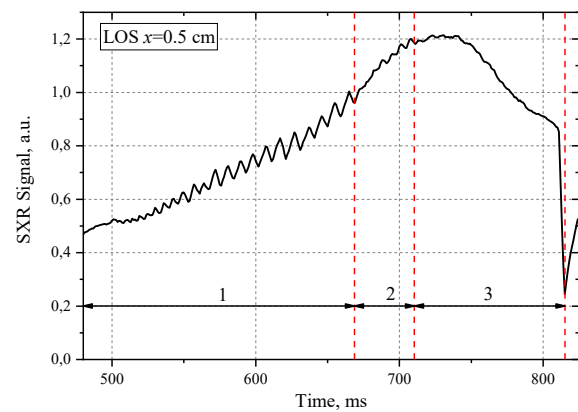


Figure 3: The W-cycle seen on SXR

1 – peaking $Z_{\text{eff}}(r)$, 2 – accumulation of W in the center of the column, SO suppression due to $P_{\text{W}}(r)$ peaking, 3 – further $P_{\text{W}}(r)$ peaking causes flattening $T_e(r)$, development of the mode $m = 2$, small disruption with an ejection of 30...50% of the reserved energy. Then cycle repeats.

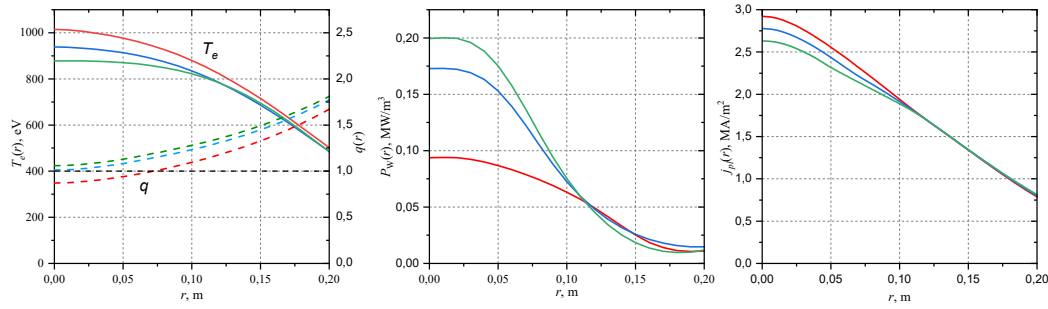


Figure 4: Dynamics of changes in discharge parameters during the development of the W-cycle

Red - stage 1, blue - stage 2, green - stage 3 on Fig. 3

provides a high power of $P_W(r)$ (0.16 MW/m^3) in the center and flattens out the T_e profile. This flattens the current density profile $j_{pl}(r) \propto T_e(r)^{1.5}/Z_{eff}(r)^{0.8}$, leading to an increase in $q(0)$ to ≥ 1 , resulting in suppression of sawtooth oscillations (SO) (Fig. 4). The development of the MHD-mode $m = 2$ following listed rearrangements of the discharge parameters correlates with the calculated broadening of the $j_{pl}(r)$, presumably because of the further peaking of the $P_W(r)$. The development of $m = 2$ mode leads to a "small" disruption with the ejection of the main gas, impurities and a decrease in the central values of T_i , T_e , j_{pl} , and γ parameter which we define as $\gamma = \bar{n}_e \cdot Z_{eff}/I_{pl}^{1.5}$. This process is cycling and can repeat many times to the end of the discharge usually ending by current disruption.

The conditions for development of the W-cycle in the T-10 plasma are determined in this work. Firstly, it is a certain level of light impurities that establish Z_{eff} value in the range $1.5 \dots 4$. That way two following processes occur in discharge: the intense influx of W into the column and its effective accumulation into the plasma center creating a sufficiently peaked $P_W(r)$ profile. The latter is determined by the peaking of the W ions near the column axis: $f_W(r) \approx f_e(r)^{Z_W/Z_{eff}}$, where $f_{W,e}$ are the density profiles of W and e. Secondly, a high value of γ in the discharge. This provides dominance of the neoclassical transport over the anomalous transport of tungsten [3]. Thirdly, low values of B_t , at which a flattened j_{pl} profile occurs naturally and it is easier to be affected by W emission, since $P_W(r)$ weakly depends on B_t .

The non-central ECRH enhances accumulation and peaking of W and facilitates suppression of SO due to the flattening of the $j_{pl}(r)$ profile, resulting in accelerated development of the W cycle. At the same time, as was shown for T-10 in [4], the use of central ECRH leads to the removal of tungsten accumulated in OH stage from the plasma, which prevents the development of the W cycle during the entire gyrotron impulse.

Acknowledgments

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