Study of tungsten transport in OH & ECRH plasmas on the T-10 tokamak

I.A. Zemtsov[1], V.A. Krupin[1], M.R. Nurgaliev[1], L.A. Klyuchnikov[1], A.R. Nemets[1], A.Yu. Dnestrovskij[1], D.V. Sarychev[1], V.S. Lisitsa[1], V.A. Shurygin[1], A.A. Borschegovskij [1], S.A Grashin[1], D.S. Sergeev[1], A.V. Sushkov[1], V.M. Trukhin[1], N.A. Solovev[1], S.N. Tugarinov[1], N.N. Naumenko[2]

[1] *National Research Centre "Kurchatov Institute", Moscow, Russia*

[2] *B.I. Stepanov Institute of physics NASB, Minsk, Republic of Belarus*

During the experimental campaign of 2015-2016 on the T-10 tokamak (round cross-section, major radius $R = 1.5$ m, minor radius $a = 0.3$ m) a tungsten limiters were installed. Tungsten is one of the most widely used materials for plasma facing components (PFC) in operating fusion facilities and other plasma installations. Applicability of tungsten is determined by its high melting point (3422 °C) and low sputtering by ions and deuterium atoms (about $\sim 10^{-4}$). However, because of its high emissivity, W ions can significantly affect discharge parameters by removing energy from the center of the plasma via line radiation.

This paper is a continuation of the study of tungsten transport in the T-10 plasma presented in [1]. In [2] it is shown that in the tokamak plasma the radial profiles of fractional abundances of tungsten ionization stages ($f_z = n_z/n_W$, where n_z is the density of an ion with a charge Z and $n_W = \Sigma n_z$ is the total density of tungsten), are determined by coronal equilibrium. In [1] it is verified and confirmed for the T-10 conditions. This fact makes it possible to use integral measurements of radiation losses $P_{rad} = \Sigma I_i$ to determine the total tungsten density in the plasma Σn_i by the formula $\Sigma n_i = P_{rad}/(n_e \cdot L_W^{eff})$, where n_e is the electron concentration and L_W^{eff} is the effective cooling factor for tungsten ions in a coronal equilibrium.

In OH-discharges on T-10 the behavior of W, as well as of other impurities, is determined by the ratio between its anomalous and neoclassical transport. Experimental data shows strong dependence of the tungsten accumulation in the plasma center on the content of light impurities in the plasma. This dependence might be corresponded with the change in the ratio mentioned above. In a lithized plasma with a low density of light impurities and $Z_{eff} = 1\dots1.5$, densities of tungsten in the plasma center are obtained to be dozens of times lower than in a plasma with $Z_{eff} = 3\dots4$. This can be explained by two effects:

1. Sputtering of tungsten by C and O ions increases with Z_{eff} due to high amount of impurity in such plasmas.

2. The increase of neoclassical transport of W ions and the decrease of anomalous plasma transport with the Z_{eff} growth [3]:

$$D_{an}(r) = 9 \cdot 10^{-4} \frac{I_{pl}^{1.5}(r)}{n_e(r) \cdot Z_{eff}(r)}, \quad V_{an}(r) = \frac{D_{an}(r)}{n_e(r)} \frac{\partial n_e}{\partial r}, \tag{1}$$

where D_{an}, V_{an} are the anomalous diffusion in m^2/s and convective velocity in m/s respectively; I_{pl} is the total plasma current in kA; n_e is the electron concentration in 10^{19} m^{-3}. As a result, in discharges with high Z_{eff}, tungsten penetrates into the center of the bulk more efficiently than in a plasma with low Z_{eff}. At the same time, in a "clean" plasma, the peaking of the tungsten density profile $n_W(r)$ (within the sawtooth oscillations invers radius r_S) is substantially higher than in the plasma contaminated with light impurities. These results are confirmed by modeling of impurity transport that was carried out using the STRAHL code [4]. As shown in Figure 1 the half-widths of the profiles $n_W(r)$ are well described by a set of anomalous and neoclassical transport coefficients (1). In discharges, where sawtooth oscillations (ST) are present in the plasma, the modeled $n_W(r)$ profiles diverse form experimental data inside r_S. An additional diffusion coefficient D_{ST} was introduced into the model as a simplified way to take into account the effect of ST on the n_W profile shape. D_{ST} is uniform inside the radius r_S: $D_{ST} \sim r_S^2/\tau_{ST}$, where τ_{ST} is the period of sawteeth.

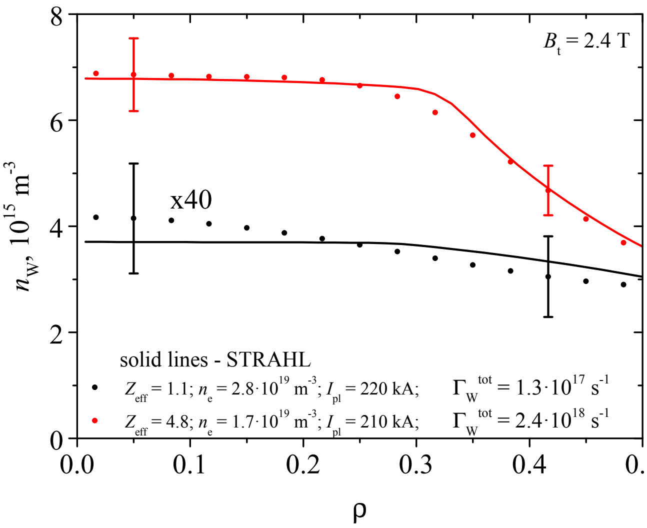

Figure 1: *Comparison of n_W profiles obtained in the experiment (points) with modeling results (solid line)*

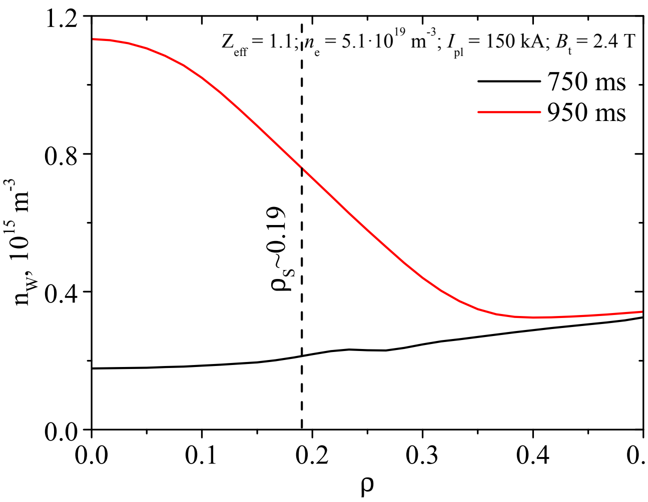

Figure 2: *The n_W profiles in the ohmic discharge 67993 at the initial stage of W accumulation (750 ms) and after the ST suppression (950 ms)*

The influence of the level of light impurities in the plasma on the quantity of tungsten densities in the center of the bulk is demonstrated in Fig. 1. To describe experimental n_W profile in absolute values the total flux of tungsten through the edge of the plasma bulk Γ_W is fitted. For the plasma with $Z_{eff} = 1.1$ total flux $\Gamma_W = 1.3 \cdot 10^{17}$ s^{-1}, and for a plasma with $Z_{eff} = 4.8$ – $\Gamma_W = 2.4 \cdot 10^{18}$ s^{-1}. Thus, an incensement in the Γ_W in a "dirty" plasma by a factor of ~ 15 leads to an incensement in the n_W in the plasma center up to 60 times of that in "pure" plasma. As it follows from the simulation for a selected pair of discharges, the contribution of the transport to creation of a central density of W in a "clean" plasma is ~ 4 times less than for a plasma with a high content of light impurities.

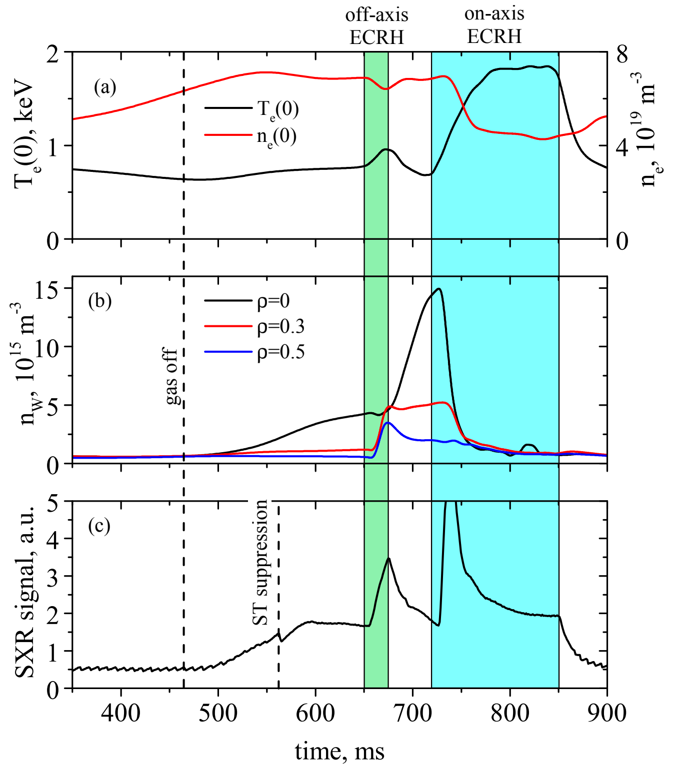

Figure 3: *W removal with ECRH in discharge 70540 ($I_{pl} = 190$ kA, $n_e = 3.7 \cdot 10^{19}$ m^{-3}, $B_t = 2.4$ T, off-axis ECRH power 0.5 MW, on-axis ECRH power 1 MW)*

As it was shown earlier in [1], in T-10 plasma tungsten has a neoclassical tendency to accumulate in the center of the plasma. However, since significant part of tungsten is localized in the bulk within the r_S the shape of the $n_W(r)$ profile is mostly determined by the presence or absence of ST in the discharge. In the absence of sawtooth oscillations, the profile of $n_W(r)$ gets much sharper than in the presence of ST (Figures 1-2). It is possible that under certain conditions W itself is capable of suppressing sawtooth oscillations and thereby increases its own accumulation (Fig. 2).

Tungsten accumulation is disrupted in the presence of continuous deuterium pumping into the plasma. The central ECR heating gives the same effect. The strongest removal of tungsten is observed in discharges with high values of τ_E, β_p i.e. with high tungsten accumulation in ohmic stage of the discharge. The removal of W occurs due to the following three processes:

- the increase of ST intensity;

- amplification of modes m = 1, 2;
- the increase of anomalous transport with simultaneous decrease of neoclassical pinching of W ions.

High ST activity with the on-axis ECR heating makes it difficult to study the contribution of anomalous transport to the removal of tungsten. Therefore, a special discharge regime was set up (Figure 3) in which the gas pumping was disabled and a short off-axis ECRH performed before central ECR heating (counter-ECCD). As was shown in [1], the end of the gas pumping leads to conditions for increasing the tungsten accumulation on T-10. The off-axis ECRH contributes to a tungsten inflow increase into the discharge. It results in a significant radiation losses from the center of the bulk due to grow of the W densities in this region. It makes removal effect from counter-ECCD central ECR heating more pronounced. As it is shown in Figure 3, central ECR heating removes tungsten under conditions of weak mode $m = 1$ and completely suppressed ST. Therefore, the W removal in this discharge is caused mainly due to an increase in the anomalous and decrease of the neoclassical W transport.

The experimental data demonstrates a direct relationship between the tungsten accumulation and improved heat and particles confinement in the plasma. This makes it possible to use tungsten as an indicator of the change in the heat and particles transport. Concerning this, it may be interesting to look for correlations between tungsten behavior and the evolution of geodesic acoustic waves in the T-10 plasma [5], which might explain the mechanism of turbulent transport in the tokamak plasma [6].

Acknowledgments

The authors are grateful to Dr. R. Dux for providing STRAHL codeand advices on its usage. Experiments were carried out with the financial support of the State Corporation ROSATOM (contract No. Н.4х.241.9Б.17.1011 of 20.02.2017). The transport modelling was performed within the Russian Science Foundation project No. 14-22-00193.

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