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# Study of the ECR-heating influence on the anomalous transport of tungsten ions in T-10 plasma

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An increasing number of installations for magnetic plasma confinement implement tungsten as a material for the plasma-facing components. For example, tungsten plates are used in the ITER divertor. Tungsten is the heaviest plasma impurity and despite the fact that its content in plasma $I_{pl} = 220$ is relatively low ($P_{EC} = 0.75$), due to its high emissivity W ions can radiate from the plasma a significant amount of electron energy and thereby greatly affect the plasma parameters. Besides that, most installations conduct experiments with additional heating, which introduces the energy of fast atoms and high-frequency waves into the plasma. This dramatically affects the transport processes in the plasma. The neoclassical transport of impurities is defined theoretically, but their anomalous transport is not. The study of anomalous transport characteristics in regimes with additional heating is a highly relevant task.

The T-10 tokamak is an installation with a circle cross section and a limiter configuration (major radius $c_\mathrm{W} = \sum n_\mathrm{W}/n_e$ m, minor radius $c_\mathrm{W} \approx 10^{-4}$–$10^{-5}$ m) where the carbon (poloidal) limiter was replaced by a tungsten one in 2015. T-10 is equipped with a gyrotron complex with a total capacity of up to 2.5 MW for heating electrons at the second harmonic of electron cyclotron frequency (ECR-heating). Three gyrotrons are used: "A"(1 MW, 140 GHz, co-injection, capable of rotation along the poloidal angle), "B"(0.5 MW, 129 GHz, with injection perpendicular to the plasma current) and "C"(1 MW, 140 GHz, capable of rotation along the toroidal angle, with co-/counter-injection). The electron temperature $R = 1.5$ is measured using ECE-diagnostics and the slope of the spectrum in the SXR-region. CXRS-diagnostics [1, 2] is used to measure the ion temperature $a = 0.3$ and the density of light impurity nuclei $T_e(r)$. The electron density $T_i(r)$ is measured with a 16-channel interferometer.

The tungsten inflow into the discharge is estimated from the brightness of the WI atom line $n_Z(r)$ nm at the W-limiter region. The density of tungsten ions is determined from the integrated radiation losses power recorded by AXUV-diagnostics. In [3], it is shown that the AXUV signal in the central region of the column (within $n_e(r)$) is almost exclusively generated by tungsten radiation. In [4] the preservation of coronal equilibrium is determined on ASDEX Upgrade. It is confirmed for T-10 conditions (in ohmic and ECR regimes) [5]. This makes it possible to determine the profile of the total tungsten ions density $\lambda = 400.1$ from the expression: a/2$\sum n_i(r)$P$_\mathrm{W}^{rad}$P$_\mathrm{W}^{rad}(r) = n_e(r)L_\mathrm{W}^{eff}(r)\sum_i n_i(r)$,L$_\mathrm{W}^{eff}$ where $a/2$ is power of radiation losses in the central region, registered by AXUV detectors, is tungsten cooling factor [6] calculated in the coronal equilibrium approximation.

In T-10 experiments with ECR-heating, tungsten is removed from the center of the plasma column [7, 8]. In discharges where the removal is exponential, the description of the AXUV-signal experimental dynamics in the region from 0 to in the transport model allows to estimate the transport coefficients of W ions. For this purpose, a system of two continuity equations (dynamic and stationary) is solved:

$$n_\mathrm{W}\begin{cases}\frac{\partial n_\mathrm{W}(r,t)}{\partial t} + \mathrm{div}\left[-D(r)\cdot\nabla n_\mathrm{W}(r,t) + V(r)\cdot n_\mathrm{W}(r,t)\right] = Q_\mathrm{W}(r,t),\\ \mathrm{div}\left[-D(r)\cdot\nabla n_\mathrm{W}(r) + V(r)\cdot n_\mathrm{W}(r)\right] = Q_\mathrm{W}(r),\end{cases} \qquad (1)\mathrm{D}$$

where $V$ is the full density of tungsten ions, $Q_\mathrm{W}$ and $Q_{\mathrm{W}\approx 0}$ are the desired diffusion coefficient and pinching velocity, $D(r)$ is the sum of sources and sinks ($V(r)$ for the central region of the plasma). The solution is carried out by choosing $\tau_{exp}$ and $D = D_{neo} + D_{an}$ that allow us to describe the temporal behavior of the tungsten radiation profile recorded by the AXUV detector in the best way. The scenario of such a discharge is shown in Fig. 1: at the ECRH stage, there is a quasistationary part (600 –640 ms) where the electron density and temperature are nearly constant, but the decay of the AXUV-signal in the central region is pronounced. It indicates the removal of tungsten from the center of the plasma. The red line on last plot is an exponential approximation of the AXUV signal to find the experimental decay time $V = V_{neo} + V_{an}$.

The system (1) is solved using the STRAHL code integrated in the ASTRA code. Transport coefficients are considered as the sum of neoclassical and anomalous components: $m = 2$ and $n_e$. Neoclassic is calculated using the NEOART code.

To conduct the complete study, the selection of discharges with different ECR heating parameters (on-axis / off-axis heating, presence/ absence of sawtooth oscillations, active / suppressed MHD mode $T_e$) suitable for processing is carried out. The dynamics of tungsten removal from the central region of the cord is simulated for time intervals in which the exponential decay of AXUV-signals occurs without changes in $P_{EC} = 0.75$ and $D$.

An example of an AXUV decay description in a discharge with central heating with a power $V$ MW is shown in Fig. 1 (red line). The calculation is made with the coefficients $\tau_{exp} \approx 14$ and $^2$ shown in Fig. 2. The characteristic decay time is $a/2$. Thus, the introduction of on-axis ECR-heating leads to the tungsten removal from the plasma center mainly due to an increase in its anomalous diffusion.

**References**

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## Country or International Organization

Russia

## Affiliation

NRC “Kurchatov Institute”

**Authors:** Mr ZEMTSOV, Ivan (National Research Centre ”Kurchatov Institute”); Mr KRUPIN, Vadim (NRC ”Kurchatov Institute”); Mr NURGALIEV, Maxim (National Research Centre ”Kurchatov Institute”); Mr KLYUCHNIKOV, Leonid (NRC ”Kurchatov Institute”); Mr NEMETS, Anton (NRC ”Kurchatov Institute”); DNESTROVSKIY, Alexey (NRC Kurchatov Institute)

**Co-authors:** Mrs MYALTON, Tatiana (NRC ”Kurchatov Institute”); Mr SARYCHEV, Dmitrii (NRC ”Kurchatov Institute”); SUBBOTIN, Georgy (MIPT); Mr SERGEEV, Dmitrii (NRC ”Kurchatov Institute”); Mr SOLOVEV, Nikita (NRC ”Kurchatov Institute”); Mr BORSCHEGOVSKIY, Alexander (NRC ”Kurchatov Institute”)

**Presenter:** Mr ZEMTSOV, Ivan (National Research Centre ”Kurchatov Institute”)

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