Effects of OH accumulation and ECRH removal of impurities on the T-10 tokamak

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The effect of impurities removal during ECR heating has been previously shown on several tokamaks (see for example [1-3]). Relevance of this type researches is caused by a necessity to control impurities concertation in plasma. Impurities significantly affect fusion reaction efficiency by means of the thermonuclear fuel dilution by light impurities and the temperature decrease in the reaction zone due to radiation losses on heavy impurities. An investigation of steady state transport processes of intrinsic impurities C, O and Fe in ohmic and ECR heated plasmas of the T-10 tokamak is presented in this work.

The T-10 tokamak is a circle shape facility with following parameters: $R = 1.5$ m, $a = 0.3$ m, $B_t \leq 2.5$ T, $I_{pl} \leq 300$ kA. The CXRS diagnostics [4] based on a diagnostic neutral beam is used to measure densities of C and O nuclei. Heavy impurities on T-10 were presented only by iron in campaigns with a graphite limiter. Now the graphite limiter is replaced by a tungsten one, but all the results presented here are obtained with graphite. In order to estimate Fe behavior grid of 16 absolute extreme ultraviolet (AXUV) and 32 SXR detectors are used. AXUV detectors register total radiation in wide spectral range. Herewith, radiation from the plasma center is determined mainly by highly intensive transitions Δn=0 of Fe^{+16} to Fe^{+23} ions. SXR signals present total emission of light and heavy impurities.

The effect of impurities removal from the plasma center during the central ECRH is more drastic in discharges with low plasma current $I_{pl} \leq 200$ kA, relatively high density $\overline{n}_e \geq 3\cdot 10^{19}$ m^{-3}, and $Z_{eff} \geq 3$ as it was shown in [1]. An enhanced impurity accumulation in the plasma center is observed in the same discharges. It is a reason of carried out detailed studies of the ohmic discharge stage preceded auxiliary heating input.

Time histories of plasma parameters at the OH and ECRH stages are presented in FIG.1. Dynamics of central electron density $n_e(0)$, electron temperature $T_e(0)$, and source of carbon Λ_C estimated via spectral line 4647 Å of C^{2+} ions are shown in FIG.1a. Electron density and temperature change slowly in temporal interval from 400 to 600 ms. However, density of carbon nuclei $n_{C^{6+}}$ (FIG.1b) increases faster than $n_e(r)$ without observable profile changes up to ~500 ms. Then abrupt peaking of C^{6+} density profile occurs (from 500 ms to 600 ms). Total light impurities density obtained by means of bremsstrahlung diagnostics of effective ionic charge Z_{eff} in visible spectral range replicates detailed behavior of carbon nuclei density measured by CXRS. The same statement can be concluded about Fe behavior. AXUV (FIG.1c) and SXR (FIG.1d) diagnostics show significant increase of radiation in the plasma center during the process of impurities accumulation.

In order to unify experimental data the empirical parameter of impurity accumulation level in plasma center $A_C(0)$ is introduced here. The parameter $A_C(0)$ for carbon is

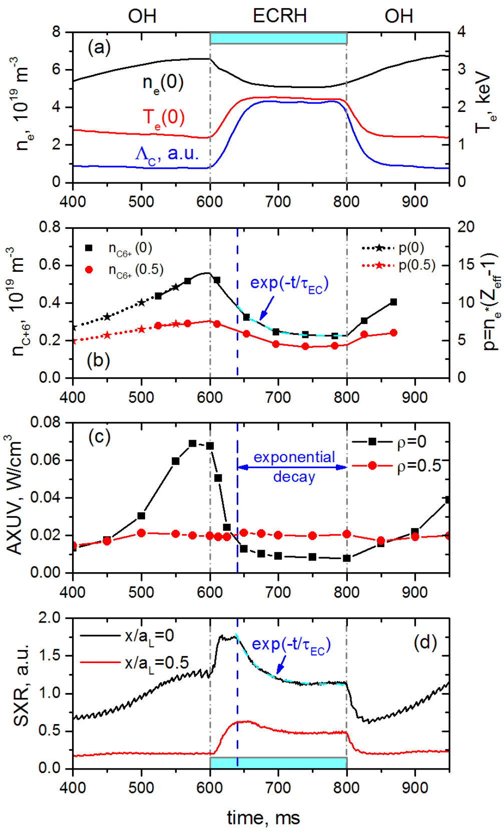

FIG. 1. Dynamics of plasma parameters during ohmic accumulation and ECRH removal in discharge 65485: γ=3.7·10^16 m^-3/kA^1.5 $\bar{n}_e$≈4·10^19 m^-3, I_{pl}=220 kA, P_{EC}=1 MW,

$$A_C(0) = \frac{n_{C^{6+}}(0)}{\Lambda_C} = P_{C^{6+}} \cdot \frac{\bar{n}_{C^{6+}}}{\Lambda_C}, \tag{1}$$

where $n_{C^{6+}}(0)$ is the carbon nuclei density at ρ=0; $\bar{n}_{C^{6+}}$ is the line averaged carbon nuclei density; $P_{C^{6+}} = n_{C^{6+}}(0)/\bar{n}_{C^{6+}}$ is the density peaking factor; Λ_C is the carbon ionization source. It is necessary to note that $A_C(0)$ is some kind of analog of the balance particle confinement time [5] but in the plasma center. Above-mentioned the dependence of impurity accumulation on plasma parameters can be presented as a dependence of $A_C(0)$ on the following parameter

$$\gamma = \frac{\bar{n}_e \cdot Z_{eff}}{I_{pl}^{1.5}}, \tag{2}$$

where $\bar{n}_e$ in m^{-3}, I_{pl} in kA. Obtained dependencies are shown in FIG.2a-c.

The peaking factor $P_{C^{6+}}$ increases with γ faster than the electron's density peaking factor P_e (FIG.2a) and the central density $n_{C^{6+}}(0)$ increase linearly with γ growth (FIG.2b). It is also noteworthy that carbon source Λ_C has no dependence on γ as it shown in FIG.2c.

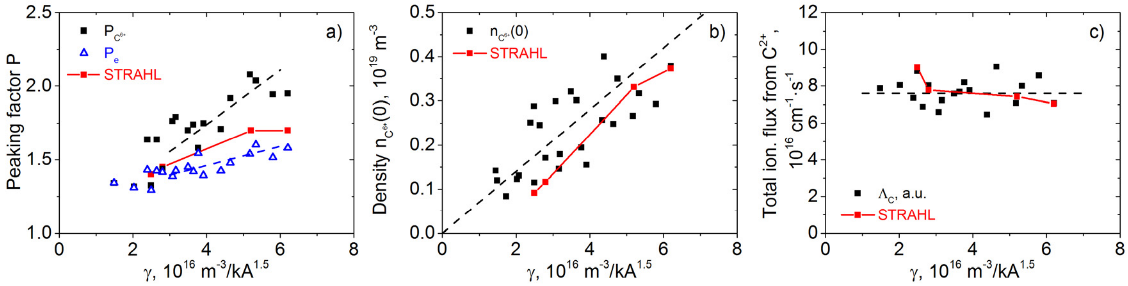

FIG. 2. The dependence of peaking factor (a), central carbon nuclei density (b) and carbon source (c) on γ parameter
dots – experiment; dashed line – fitting; solid red line – result of modelling

This fact means that transport processes, rather than impurity source changes, determine carbon behavior in OH plasmas. Therefore, the accumulation level $A_C(0)$ has linear dependence on γ parameter.

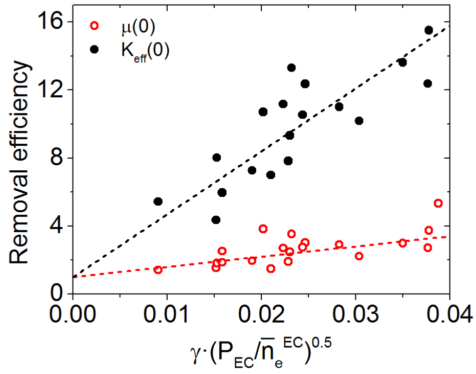

FIG. 3. Carbon nuclei removal efficiency
dots – experiment; dashed line – fitting

Consequently, initiated by the ECR heating removal begins with higher impurity density and more peaked profiles in plasmas with high γ. As it is shown in FIG.1 in discharge 65485 T_e and Λ_C reach steady state values in ≈40 ms after ECRH switch on. Steady state values of n_e are established in ~120 ms. At the first stage of the impurities removal C^{6+} density profile losses rapidly its excessive peaking and at the second stage a slow decay without significant changes of profile is observed. By other words, removal process occurs opposite the OH accumulation process. It is important to note that purely exponential decay of carbon nuclei, AXUV, and SXR signals is observed at the second ECRH stage with standing T_e and slowly changed n_e. Typical values of a decay characteristic time are τ_{EC}≈25 to 30 ms.

To describe quantitatively the impurity removal effect a parameter of the efficiency removal from plasma center $K_{eff}(0)$ is introduced here. $K_{eff}(0)$ is determined as a ratio of accumulation levels at the OH and ECRH stages:

$$K_{eff}(0) = \frac{A_C^{OH}(0)}{A_C^{EC}(0)} = \frac{n_{C^{6+}}^{OH}(0)}{n_{C^{6+}}^{EC}(0)} \cdot \frac{\Lambda_C^{EC}}{\Lambda_C^{OH}} = \mu(0)\frac{\Lambda_C^{EC}}{\Lambda_C^{OH}}, \tag{3}$$

where μ(0) is the lower limit of removal efficiency (since it does not take into account the source increase during ECRH). It is obtained that $K_{eff}(0)$ depends linearly on the parameter $\gamma \cdot \left(P_{EC}/\bar{n}_e\right)^{0.5}$ (see FIG.3). It is possible to see that $A_C^{EC}(0) \propto \left(P_{EC}/\bar{n}_e\right)^{-0.5}$, i.e. the

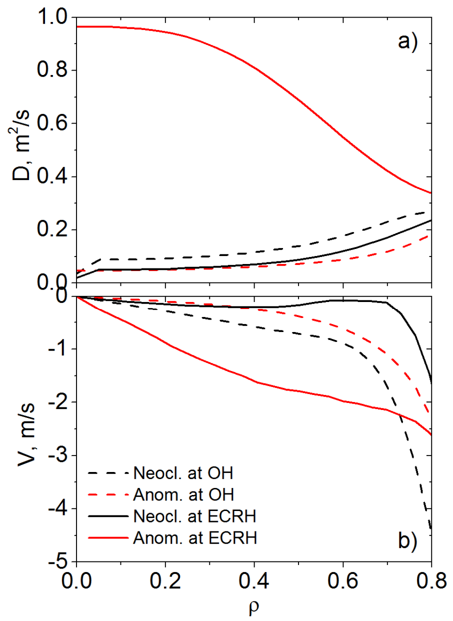

FIG. 4. Transport coefficients at OH and central ECRH in discharge 65283 γ=5.2·10^{16} m^{-3}/kA$^{1.5}$, $\bar{n}_e \approx 4.4 \cdot 10^{19}$ m^{-3}, I_{pl}=180 kA, P_{EC}=1 MW

accumulation level at the ECRH is basically determined by the heating power per plasma particle in comparison to $A_C^{OH}(0) \propto \gamma$ in the OH regime.

In order to describe experimental results numerical calculations in the transport code STRAHL [6] including neoclassical and anomalous transport are performed. Radial profiles of anomalous transport coefficients for OH are taken from T-10 experiments with argon and potassium injection [7, 8]. Sources of carbon and oxygen are varied to describe experimental density profiles of C^{6+} and O^{8+} obtained by CXRS in central plasma region ρ<0.8. Anomalous transport coefficients for ECRH stage are determined from modelling exponential decay of intrinsic impurities C and O at the second stage of removal.

Calculations show domination of neoclassical diffusion and convection over anomalous ones in OH plasma with a high γ (FIG.4 – dashed lines). Nevertheless, neoclassical pinch is insufficient to describe peaking of C^{6+} density profile at high γ (FIG.1a) due to flattening by temperature screening. Independent on γ carbon source Λ_C is described by modelling results (FIG.2c). At the ECRH stage anomalous transport of impurities increases significantly and exceeds neoclassical one (FIG.4 – solid lines). The shape of anomalous diffusion coefficients is changed drastically.

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