ECR heating and impurity radiative cooling of Tokamak Plasmas

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Radiative heating and cooling processes are of great interest for modern tokamaks as well as for future thermonuclear reactor. One of the most effective heating source is provided by the electron cyclotron radiation whereas the radiative cooling is due to radiative losses on impurities presented in plasma. The ECR heating is mostly related to the central hot plasma and it is strongly selective in minor radius. The energy balance between strong central heating and plasma periphery cooling can result in the sharp increase of electron temperature gradients and in the increase of transport coefficients both for electron thermal conductivity and impurity transfer. Besides the application of centrally deposited ECR heating flattens the electron profile in the core and consistently with higher diffusion can cause the impurities carrying out. The goal of the present paper is to make an analysis of a redistribution of impurity radiative losses under ECR heating for T-10 tokamak conditions.

The experiment and diagnostics

The radiation in the T-10 tokamak is measured by the diagnostic system based on silicon AXUV (Absolute eXtreme Ultra Violet) photodiode detectors [1]. The region from the center to the experimental measurements at 28 cm is under consideration in the calculations.

Time traces of unfolded signals (emissivity) in argon puffing shot are shown in Fig.1. Argon was injected into plasma (R/a = 1.5m/0.3m, I=250kA, Btor=2.5T) in Ohmic heating phase and ECR heating was switched on at t=700 ms. It is seen that after ECRH application the radiation signal after sharp jumping up decreases for central chords during approximately 50ms and keeps unchanging at the periphery (at r=26cm chord). Taking into account that the density and temperature keeps constant during this period in the EC regime it can be supposed that the radiation redistribution happens due to the impurity pump out from the plasma center. The emissivity change over minor radius for transition from OH to EC regimes is presented in Fig.2. Such radial redistribution of radiation losses can be connected with three reasons: (1) change of electron density and temperature profiles, (2) increase of neutral fraction in the ECR regime, (3) modification of impurity transport. The mechanisms responsible for changing of radiative losses profiles were under investigation below.

The analysis methods and results

The modeling of the effects has been done in the frame of the transport impurity code [2], and radiation losses were estimated using the model of average ion charge [3].

The radial transport equations together with ionization balance were used in the form for each impurity charge component density n_i^Z:

$$\frac{\partial n_i^Z}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}r\left(D(r)\frac{\partial n_i^Z}{\partial r} - V(r)n_i^Z\right) + S_{i-1}n_{i-1}^Z - S_i n_i^Z + R_{i+1}n_{i+1}^Z - R_i n_i^Z \qquad (1)$$

where $D(r)$ and $V(r)$ are diffusion coefficient and convection velocity for all impurity components, $S_i(Te,Zi)$, $R_i(Te,Zi)$ are ionization and recombination rates including the charge-exchange recombination for a specific ion with the charge Zi correspondently.

Simultaneously we modeled the heat transport with the help of transport code ASTRA [4] and TORBEAM code [5] for EC wave ray tracing and heating. The radial distribution of electron heat conductivity in the OH and ECRH regimes are presented in Fig.3. One can see an essential increase of heat transport in ECRH regime, both OH and ECRH heat conductivities dominating strongly the neoclassical value. As a result of analysis in a simplified treatment the diffusion coefficient and convection velocity profiles shown in Fig.4 (a,b) have been used to fit the experimental data. The diffusion coefficient in the ECRH regime is higher than in OH and the inward convection is less essentially. The increase of impurity diffusion coefficient in the ECRH regime in comparison with OH regime corresponds to the enhancement of electron heat conductivity. The different impurities species have been taken into account for the solution of Eq.(1). The emissivity data for intrinsic impurities iron and carbon together with argon seeded impurity are presented in Fig.5 (a,b). The impurity transport coefficients and the sources of the neutral atoms of impurities were determined also consistently with the value of Z_{eff} that was found with ASTRA code in the main components transport modeling using the experimental loop voltage. The Table demonstrates the contribution from different impurities species. It had been taken into account also that ECR heating causes the increase of the neutral flux into the plasma resulting in a change of the impurity ionization balance and enhanced cooling of the plasma periphery. Calculated and experimental emissivity profiles for OH and ECRH regimes replicate quite well as shown in Fig.6. Corresponding impurity density profiles show the impurity density decrease in the plasma center. The emissivity profiles resulting from the modeling for intrinsic carbon impurity are presented in Fig.7. It is seen that the change of neutral density and temperature

profile only without changing of impurity transport coefficients fails to explain the dramatic redistribution of radiative losses observed after ECRH switching on (see Fig.1).

Conclusion

On-axis ECR heating causes impurity transport increase whereas another effects on emissivity such as increased neutrals flow and changed T_e are less important. As a result the redistribution of impurities charge balance and densities profiles together with decrease of impurities density in the plasma center takes place. A strong increase of impurity diffusion coefficients under the condition of on-axis ECRH heating is in a qualitative correspondence with the increase of the heat transport coefficients. Our result for T-10 tokamak is in an agreement with the result for impurity transport analysis made for ASDEX-U tokamak in regime with the ECR heating [6]. The results data of impurity transport analysis are of importance for understanding the impurity behavior in future tokamak reactor with central heating.

References.

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St. Petersburg 2003 Vol 27A P-2.74
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[3] D E Post *et al*. Atomic Data and Nucl. Data Tables 20, 397-439 (1977)
[4]G.Pereverzev, P.Yushmanov. ASTRA Automated System for Transport Analysis in a Tokamak. IPP-Report 5/98 2002
[5]E.Poli *et al*. Computer Physics Communications 136 (2001) 90-104
[6]R.Dux *et al*. 30th EPS Conference on Contr. Fusion and Plasma Phys. St. Petersburg 2003 Vol 27A P-1.132
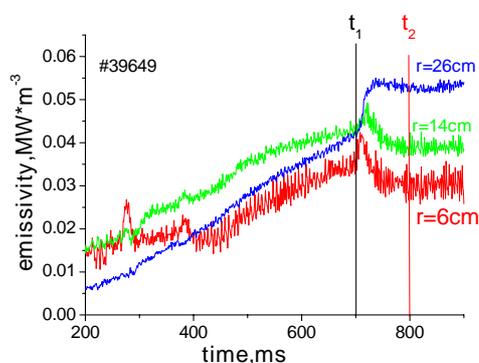

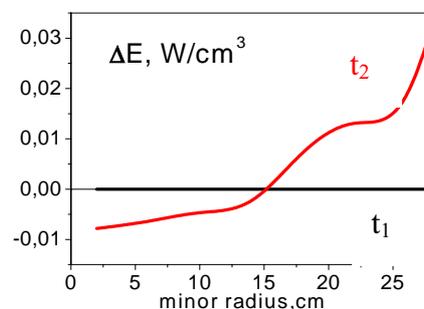Fig.1 Time traces of emissivity given at different radii.

Fig.2 Profiles of emissivity change ΔE after ECR heating switch on.
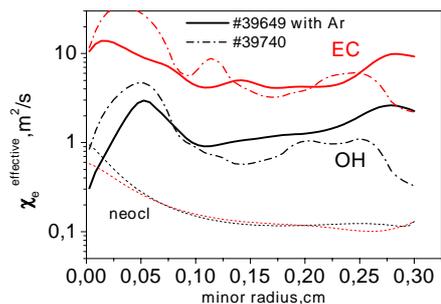
Fig.3 The radial distribution of electron heat conductivity in the OH and ECRH regimes.
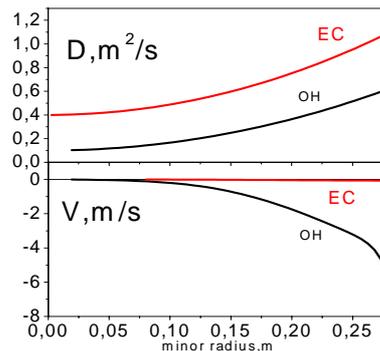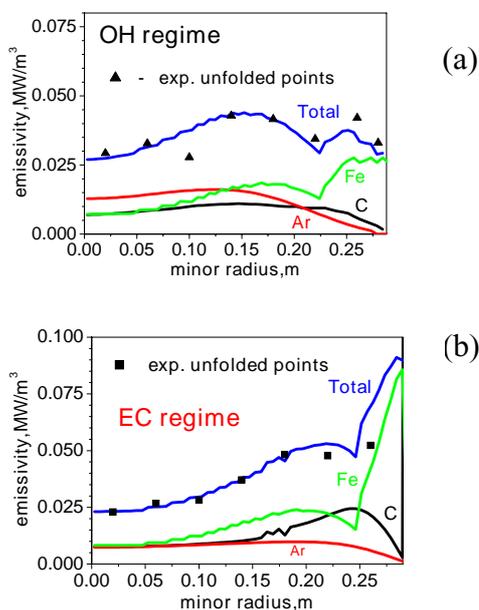
Fig.4 Impurities transport coefficients used in modeling

Fig.5 Impurity individual and total emissivity profiles for OH(a) and ECRH(b) regimes.
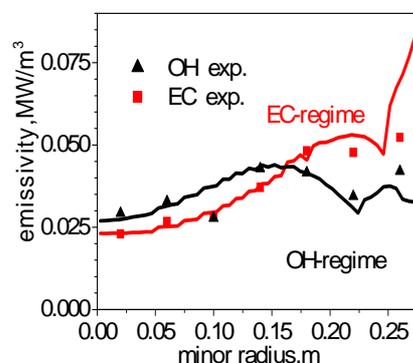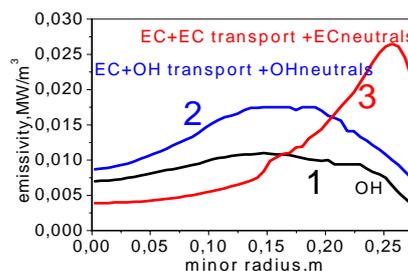
Fig.6 Total emissivity for OH and ECRH regimes.

Fig. 7.The emissivity profiles resulting from the modeling for intrinsic carbon impurity. The curve 1 corresponds to the OH regime, the curve 2 corresponds to the ECRH parameters with the same impurity transport coefficients as in OH regime and the curve 3 corresponds to ECRH regime with the modified impurity transport.

Table. Radiative losses, average density and Z_{eff} for different impurities species at ECRH.

	C	Ar	Fe	Sum	Photo-diodes
$P_{rad,kW}$	34	19	49	102	107
$<n>,\%$	3	0.1	0.03		
Z_{eff}	1.9	1.2	1.05	2.15	