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Simulation of Heavy Impurities Transport and Radiation for ITER Scenarios

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Last time attention is again attracted to the possibility of using high-Z materials in reactors (tungsten for the divertor plates coating and argon for reradiation of some power). In this case a danger of high-Z impurities accumulation in the plasma core is appearing. The purpose of the work is the analysis of the dynamics and radiation of tungsten and argon in the reference ITER scenarios at different suppositions on the impurities transport.

For the simulations we use the multi-species dynamic impurity code ZIMPUR [1], which models the behaviour of up to three impurities simultaneously. The dynamics of concentrations of impurity ions in different charge states n_k ($0 \le k \le Z$) is represented by the linked set of rate equations:

$$\frac{\partial (V' n_k)}{\partial t} + \frac{\partial}{\partial \rho}\left[V' < (\nabla\rho)^2 > \Gamma_k\right] = V' n_e \left\{ I_{k-1} n_{k-1} - \left(I_k + R_k\right) n_k + R_{k+1} n_{k+1} \right\}, \qquad (1)$$

where ρ is the radial coordinate, $V(\rho)$ is the volume inside the magnetic surface, Γ_k are radial fluxes of particles, I_k is ionization rate, and R_k is a sum of radiation and dielectronic recombination rates, which is enlarged on the value $R_k^{cx} = <\sigma V>_k^{cx} n^0/n_e$ to describe the charge exchange of impurity ions with hydrogen isotope atoms. The radiation of each sort of impurity after each time step is determined by the expression: $P_Z = \Sigma L_k n_k$, where L_k are including a sum of a bremstrahlung, linear and recombination radiation. The important component of the ZIMPUR code is the database of the elementary processes rates for impurity.

For the self-consistent simulations of the ITER scenarios this code has been integrated with the ASTRA transport code [2] to describe the dynamics of the background plasma parameters. For the calculation of the neoclassical impurity fluxes the NCLASS code [3] was utilized. It allows to calculate particle fluxes for the arbitrary aspect ratio and the arbitrary collisionality. It was supposed, that radial components of the ion impurity fluxes averaged over the magnetic surfaces include anomalous and neoclassical parts:

$$\Gamma_k = V_A n_k - D_A \partial n_k / \partial\rho + \eta \Gamma_k^{nc}, \quad k>0, \quad \eta = 0, 1.$$

In this work anomalous drift velocity V_A and a diffusion coefficient D_A have been taken the same, as for the main plasma. Diffusive approximation have been used for the simulation of impurity neutral atoms. We assume that its temperature equal T_0 =20eV. The relation between impurity ion fluxes Γ_k^x at $\rho_n=\rho/\rho_{max}=1$ and ion densities n_k^x was used as the boundary condition: $\Gamma_k^x = V_\perp n_k^x$. The value $V_\perp$ is equal to the velocity of the bulk plasma electrons. The impurity source was defined as the impurity neutral flux on the plasma boundary, which was fitted to produce the desirable impurity contamination in plasma.

Investigation of the tungsten and argon behaviour in the ITER inductive scenario.

The reference ITER inductive scenario is based on the ELMy H-mode regime with the fusion power $P_{fus} \sim 400$ MW, the fusion gain factor Q ≥10, toroidal magnetic field $B_o = 5.3$ T, plasma current Ip = 15 MA and average electron density $n_e \sim 1.1 \cdot 10^{20} m^{-3}$ [4]. The parabolic profiles of anomalous diffusion coefficients $\chi^{an} = \kappa_{an} * (1+3\rho^2)$ were assumed in the transport simulations of the main plasma and helium. The normalization coefficient k_{an} was fitted to obtain the correspondence of the integral energy confinement time to the H-mode IPB98(y,2) scaling [5]. It was supposed, that all plasma components have the same anomalous transport $D_e^{an} = D_{He}^{an} = \chi_e^{an} = \chi^{an}$, $\chi_i^{an} = 2\chi^{an}$. In the region of the H-mode external transport barrier, transport coefficients of the main plasma have been reduced to the ion neoclassical heat diffusivity level [6]. The beryllium was considered completely ionized and with concentration proportional to the electron plasma density ($n_{Be} \sim 0.02\ n_e$). The bulk plasma ion concentration was determined from a quasi-neutrality condition taking into account densities of electrons, of all impurities and helium. It was supposed, that 50/50 % mixture of deuterium/tritium will be used. The total content of high-Z impurity was selected by the boundary flux of impurity atoms to reproduce the necessary level of the total radiated power in the plasma column (as in the design [4]). The behaviour of impurities should be considered at different suppositions about the transport mechanisms.

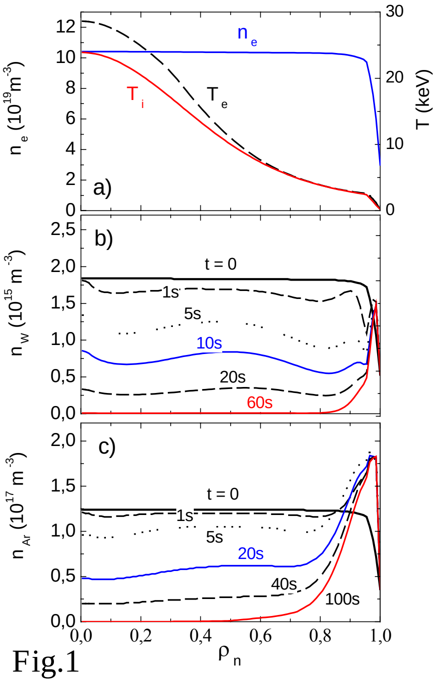

Fig.1

Fig. 1 demonstrates dynamics of impurity densities radial profiles when tungsten (b) or argon (c) were the main high-Z impurities and only neoclassical transport was assumed. Simulations have started from impurity distribution proportional to $n_e(\rho)$. Parameters of the main plasma in simulations when the main impurity was tungsten or argon have been similar and profiles of plasma temperatures and density are shown in Fig. 1a. In both cases high-Z impurities escape the plasma core and concentrate near the plasma column edge.

The anomalous part of the transport increases with the decrease of the impurity charge. Further, the behaviour of the argon impurity in this regime is considered at different assumptions about the ratio of the neoclassical and anomalous transport. Results of simulations for the case of the only anomalous diffusivity of argon are shown in the left-hand column of Fig. 2. Calculated profiles of electron and ion temperatures and the electron density are shown at the top of this figure. The anomalous diffusion coefficient $D_A = D_e^{an}$ is shown in the lower frame of this figure. Profile of the argon concentration is very flat and is close to the shape of the electron density profile. The main difference with previous simulations (using coronal approximation) is observed on profiles of the plasma radiation. near the plasma edge where it is about two times higher, than in the coronal approximation. Basically, it is the result of charge exchange of argon ions with hydrogen isotope neutrals. The flux of deuterium/tritium neutrals modelled a gas fuelling and was changed to provide a necessary level of plasma density in simulations with the above mentioned transport coefficients.

In the right column of Fig. 2, results of simulations are shown, when both the anomalous and neoclassical impurities transport were included in consideration. In the steady-state conditions the anomalous diffusion flux of impurities is balanced by the neoclassical thermal diffusion flux. This results in formation of a small positive gradient on

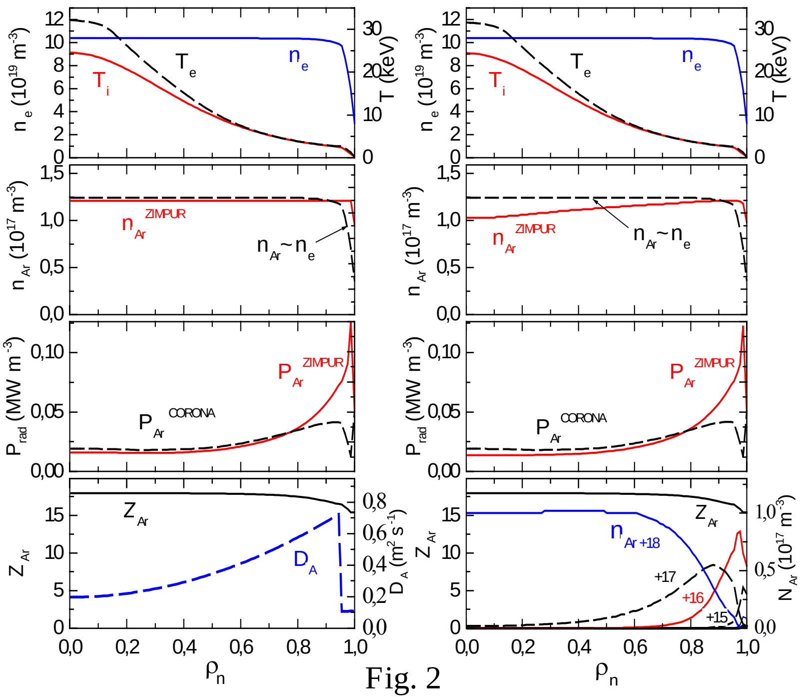

Fig. 2

impurity concentration due to more effective impurity penetration in the plasma core in comparison with the case without the anomalous diffusion.

Lower frame of Fig. 2 demonstrates radial profiles of concentrations of argon ions with different charges. The radiation near the plasma boundary in this case exceeds also approximately twice the radiation calculated in the coronal approximation. Despite of a smallness of the neoclassical fluxes in the contrast with anomalous in this case, they, nevertheless, prevent the impurity accumulation in the plasma core.

<u>ELM effect on impurity accumulation</u> The behaviour of impurities in considered scenario can be perturbed by MHD instabilities. The influence of sawteeth is insignificant because of the flat impurity concentration profiles in the central regions. The ELM instability results in periodic oscillations of plasma parameters near the edge and can redistributes impurity concentration. To estimate the characteristic time of the impurity profile re-organization after the ELM and possible frequency of this instability we considered the effect of ELM on the argon impurity transport (Figs. 3). We model plasma transport during the ELM by a sudden increase in the anomalous diffusion coefficient in the peripheral zones to ~15 m^2s^{-1} for a time interval of 1–5 ms (Fig. 3 right hand, lower). In ~ 100 ms after the ELM all perturbations vanish and all radial distributions return to their unperturbed values. It gives the characteristic time of ∇p restoration or possible ELMs frequency ≥ 10 Hz (for models where instability causes by ∇p). Simulations show that ELMs don't perturbed impurity density in the plasma core but only near the periphery. Due to the reduction of T_e near the

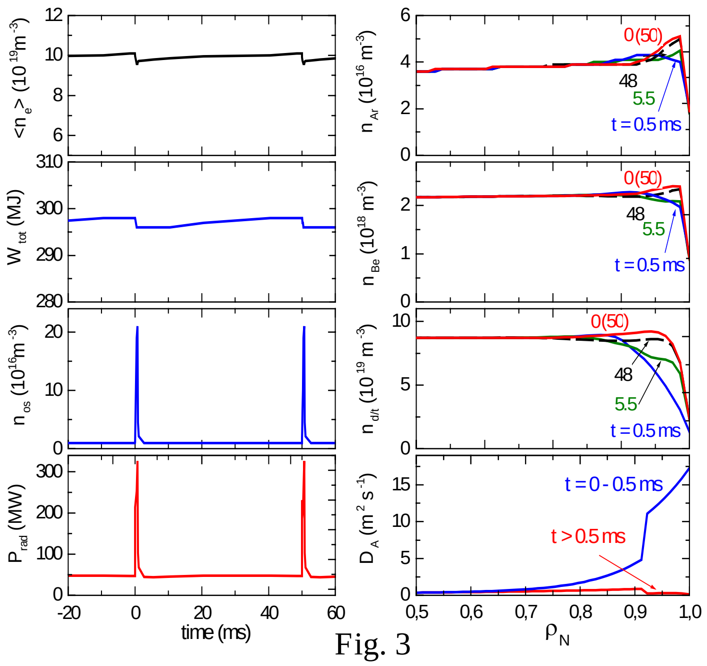

Fig. 3

boundary and increase of hydrogen isotope neutrals density there (n_{os} on Fig.3) in the ELM time, plasma radiation increases near the periphery (dynamics of the total radiated power is shown in Fig.3, left, lower). It can decrease power flux to the divertor in the ELM time what should be interesting for the experimental investigation. After the ELM we see some concentration of impurity in the region of edge transport barrier.

Transport and radiation of argon in the RS steady-state ITER scenario

The simulation has shown, that neoclassical effects play the higher role in the steady-state ITER scenarios with a broad zone of a reversed shear (RS) in the central regions of plasma. In such discharges, inside the ITB zone, as experiments show, the impurity transport is close to the neoclassical predictions.

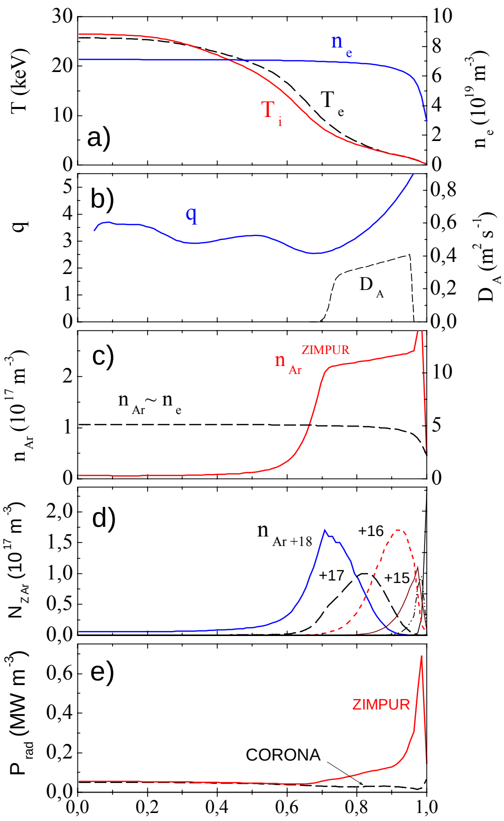

Fig. 4

The main results of the modelling of the steady-state ITER scenario with the plasma current 9 MA and average electron density $6.8 \cdot 10^{19} m^{-3}$ [4] are shown in Fig. 4. The temperatures profiles were taken according to the design [4] and were assumed fixed in this case. The electron density profile was calculated self-consistently, since it allows to determine the necessary deuterium/tritium neutrals density (which was fitted for a necessary plasma fuelling). In Figs. 4 a,b radial profiles of plasma temperature, density and stability margin q are presented. In the modelling the anomalous transport coefficient was decreased up to zero in the RS region and in the edge transport barrier region of the H-mode (Fig. 4b).

Profile of the total argon density simulated taking account of the neoclassical and anomalous coefficients is shown in Fig. 4c. Argon ions escape the plasma core with the RS region and concentrate to the plasma periphery where the anomalous diffusion effectively flattens their density. The radial distributions of concentration of argon ions with the different charges are presented in Fig. 4d. Plasma radiation in the peripheral regions in this case also higher than in the coronal approach (at $n_{Ar} \sim n_e$).

Thus, the modelling shows, that effective radiation of power from the plasma periphery is possible without the accumulation of heavy impurities in the plasma core for considered ITER scenarios. It supports the possibility of using heavy materials in ITER.

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