SIMULATION OF ANOMALOUS PINCH EFFECT ON IMPURITY ACCUMULATION IN ITER

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As our previous simulations of ITER scen arios showed [1], using only neoclassical pinch of the bulk plasma and impurities together with the anomalous diffusion in the impurity transport simulations gives flat radial profiles of impurity concentration. Neoclassical thermal diffusion at flat bulk plasma density profile helps to prevent impurities accumulation in the plasma core. However, experiments indicates possibility of anomalous pinch of the main plasma and impurities. It can result impurity accumulation. Anomalous pinch can influence the impurity accumulation by two ways: by increasing of the main plasma gradients and by the anomalous pinch of impurities themselves. The task of this work is to test a relative role of these two possibilities.

ASTRA transport code [2] was used for the description of the bulk plasma parameters evolution. In simulations we used artificial transport coefficients:

$$\chi_e = D_e = D_{an} \cdot F_{H-mode} + \chi_{ne}^{\text{nc}}$$,
$$\chi_i = 2 \cdot D_{an} \cdot F_{H-mode} + \chi_i^{\text{nc}}$$

where anomalous term had parabolic radial dependence

$$D_{an} = D_0 \cdot (1 + 3 \rho_N^2); \quad \rho_N = \rho/\rho_{\text{max}}.$$ 

In the region of the H-mode external transport barrier ($\rho_N > 0.92$) transport coefficients of the main plasma have been reduced to the ion neoclassical heat diffusivity level $\chi_i^{\text{nc}}$ [3] ($F_{H-mode} = 0$). The normalization coefficient $D_0$ was fitted to obtain the correspondence of the global energy confinement time to the H-mode IPB98(y,2) scaling [4] $\tau_E = \tau_E^{\text{H98(y,2)}}$. As the boundary conditions for the bulk plasma parameters we used some approximations on the basis of B2-Eirine results. Plasma fuelling by gas puffing was simulated using the kinetic equation for neutrals in the slab approximation.

ZIMPUR code [1] has been used for the modeling of transport and radiation of impurities (considering all impurity ions). Radial components of the impurity fluxes include neoclassical and anomalous parts:

$$\Gamma_k = \Gamma_k^{\text{nc}} - D_{an} \cdot \partial n_k / \partial \rho - V_{p,an} \cdot n_k,$$

where neoclassical impurity fluxes $\Gamma_k^{\text{nc}}$ for arbitrary aspect ratio and collisionality was calculated using the NCLASS code [5], $D_{an}$ is anomalous diffusion coefficient (in these simulations was the same as for the bulk plasma),

$$V_{p,an} = k_p \cdot g(k) \cdot D_{an} \rho/a^2$$

is the anomalous pinch velocity, $k$ is the ion charge and $k_p$ is the normalizing coefficient (was the same for all ions), $g(k)$ is the function of ion charge (we consider 3 version of this function: $g(k)=0$, $g(k)=1$ and $g(k)=Z_k/Z_{\text{eff}}$). Relations between impurity ion fluxes $\Gamma_{k}$ through the separatrix and ion densities $n_k$ were used as the boundary conditions $\Gamma_{k} = V_{\perp} \cdot n_k$, where velocity $V_{\perp}$ was equal to the velocity of the escaping plasma column bulk plasma electrons for the automatically satisfaction of the ambipolarity requirement. Impurity atomic flux through the boundary was fitted to produce necessary impurity contamination in plasma (for example for necessary level of plasma radiation). The bulk plasma ion concentration (50%D + 50%T) was determined from a quasi-neutrality condition taking into account densities of electrons and of all
impurity and helium ions. Thermalized helium pumping speed on the boundary was fitted to produce relation $\tau_{\text{He}}^* / \tau_{\text{E}} = 3$.

Investigations have been done for the basic inductive ITER scenario with the plasma current $I_p = 15\text{MA}$, average plasma density $<n_e> = 10.1 \times 10^{19}\text{m}^{-3}$ and fusion power $P_{\text{fus}} = 400\text{MW}$.

Two problems have been considered: 1) variation of the radial profiles of the bulk plasma parameters and different impurity concentrations (Ar, Be, He) with change of the anomalous pinch velocity value and 2) checking the possibility to control the main characteristics of this regime within the operational limits, and to determine the maximum value of anomalous pinch velocity when control is possible.

These simulations were performed keeping some main discharge parameters constant (to keep the scenario performance): fusion power $P_{\text{fus}} = 400\text{MW}$ (by changing of average plasma density by boundary neutral flux control) and radiated power $P_{\text{rad}} = 47\text{MW}$ (by changing of Ar impurity flux through the separatrix). This helps to keep constant level of power through the separatrix $P_{\text{loss}}$. In this scan boundary conditions for Be and He concentrations were fixed as in the reference inductive scenario.

To characterize different profiles we used peaking factor $f_x = x(0) / < x >$, where $< x >$ is a volume averaged $x$ value.

We produce 3 scans: 1) addition of anomalous pinch in the electron density equation only $g(k) = 0$ (to test the effect of the bulk plasma density profiles picking on the impurities accumulation); 2) addition of the identical anomalous pinch in all plasma components (in the bulk plasma and impurities) $g(k) = 1$ and 3) addition of the anomalous pinch which is proportional to the ion charge $g(k) = Z_k / Z_{\text{eff}}$ into all plasma components.

In the left hand side of Fig.1 one can see dependence of normalized density profiles of bulk plasma and impurities versus the value of anomalous pinch ($k_p$ variation) which
was introduced in the electron density equation only \( (g(k) = 0) \). In this case change of He density profile was small. Simulations for this case showed that increase of the bulk plasma density profile peaking does not result in the impurities accumulation (impurity density profiles stay flat). The reason of this is the prevailing of the anomalous impurity diffusion under the neoclassical impurity pinch. Right hand side demonstrates some decrease of \( < n_e > \) and increase of the Ar contamination in plasma which were necessary for the discharge quality keeping. It results in increase of \( < Z_{eff} > \) value due to increase of argon and helium contamination. In the same time \( Z_{eff} (\rho) \) profile peaking factor \( f_{Z} \) slightly decreases.

Fig.2 demonstrates dependence of plasma parameters versus anomalous pinch value when the identical anomalous pinch has been added to all plasma components (for the bulk plasma and impurities) \( g(k) = 1 \). Normalized density profiles of bulk plasma and impurities at different anomalous pinch values are shown in the left hand side of this figure. One can see that change of He density profile is small. In this case impurity density profiles are similar to the bulk plasma density profiles. Increased accumulation of impurities is absent. Peaking factors of the bulk plasma density profiles and impurities density profiles are similar and profile of \( Z_{eff} \) stay flat. He contamination increases.

Results of addition of the anomalous pinch with the velocity, proportional to \( (Z_k / Z_{eff}) \), for all plasma components (bulk plasma and impurities) are shown in Fig.3. Change of He density profile in this case was small. Impurities accumulation and impurities profiles sharpening increases with impurity charge. Be and He percentage increases and some sharpening of \( Z_{eff} \) profile and increase of \( < Z_{eff} > \) takes place. Discharge quality can be keeping in this case by some increase of \( < n_e > \) and control of Ar seeding into the plasma.
CONCLUSIONS

The modeling of the parametric dependencies of impurity accumulation versus the value of anomalous pinch velocity showed that:

Increase of the bulk plasma density profile peaking (without increasing of the anomalous pinch of impurities) has small effect on the impurities accumulation (impurity density profiles stay flat). The reason of this is the prevailing of anomalous impurity diffusion under the neoclassical impurity pinch. In this case discharge quality can be keeping by some decrease of \(< n_e >\) and increase of the Ar flux into the plasma.

In the case of equal anomalous pinch velocities of the bulk plasma and impurities, impurity density profiles are similar to the bulk plasma density profiles and profile of \(Z_{\text{eff}}\) stays flat (increased accumulation of impurities is absent). To keep the total radiation power in this case it is necessary to increase the Ar seeding into the plasma.

If anomalous pinch velocity proportional to the ion charge one indicates impurities accumulation which increases with impurity charge (It results in some sharpening of \(Z_{\text{eff}}(\rho)\) profile). Change of He density profile is small. Some increase of \(< n_e >\) and control of the Ar seeding into the plasma help to keep the discharge quality in this case.

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