Assessment of impurity radiation for ITER reference scenarios

V. Leonov, V. Zhogolev

NRC "Kurchatov Institute", Moscow, Russia.
E-mail: *Leonov_VM@nrcki.ru*

Plasma-surface interaction is one of the key issues in predictions of ITER performance. Recently, special attention was attracted to using of tungsten as a material of divertor elements. Impurities can penetrate into plasma column from plasma facing components and can be injected to control plasma radiation for preventing the overheating of the divertor plates. It is important to avoid accumulation of impurities in the plasma core to prevent radiation losses and fuel dilution. In this study maximal permissible concentrations of different impurities (W, Be, Ar, C, He), which are characteristic for ITER, are estimated for the reference ITER scenarios [1]. At the exceeding of these concentrations, discharge parameters leave the declared ITER operation domain and then discharge can transfer to the L-mode what results in plasma cooling.

For the description of the evolution of bulk plasma parameters ASTRA transport code [2] was used with scaling based transport model. Anomalous transport terms had a parabolic radial dependence $D_{an}= \chi_{an}= D_o\cdot(1+ 3.\rho_N^2)$. The normalization coefficient D_o was fitted to obtain correspondence of the global energy confinement time to the ITER scalings. In the region of the H-mode external transport barrier ($\rho_N > 0.94$) and RS ITB region transport coefficients of the main plasma have been reduced to the ion neoclassical heat diffusivity level. As the boundary conditions on the separatrix for the bulk plasma parameters we used empirical relation $n_s = 0.3\cdot \langle ne \rangle$ and approximations on the basis of B2-Eirine results: $T_s(eV) = (90.P_{loss}(MW)/n_{s19})^{2/3}$. Plasma fuelling by gas puffing was simulated using the kinetic equation for neutrals in the slab approximation. At the modeling of profiles of the bulk plasma and impurities anomalous pinch velocity $V_p = 0.25\ D_{an}\ (\rho/\rho_{max}^2)$ has been added. The thermalized helium pumping speed at the plasma boundary was fitted to provide $\tau_{He} / \tau_E = 3$. ZIMPUR code [3] was used for the modeling of transport, ionization states and radiation of impurities. Radial components of the impurity fluxes include neoclassical and anomalous parts: neoclassical impurity fluxes was calculated using the NCLASS code [4], anomalous coefficients were the same as for the bulk plasma. The impurity source was defined as the impurity neutral flux on the plasma boundary, amplitude of which was fitted to provide the desirable impurity contamination in the plasma.

Radial profiles of the main plasma parameters for the inductive ITER scenario based on the ELMy H-mode regime [1] with toroidal magnetic field B_o=5.3T, plasma current I_p = 15 MA, average electron density $n_e \sim 1.1 \cdot 10^{20} m^{-3}$ and fusion gain factor Q ≥ 10 are presented in Fig.1. In this regime auxiliary heating power is equal to 53 MW (33 MW of NBI and

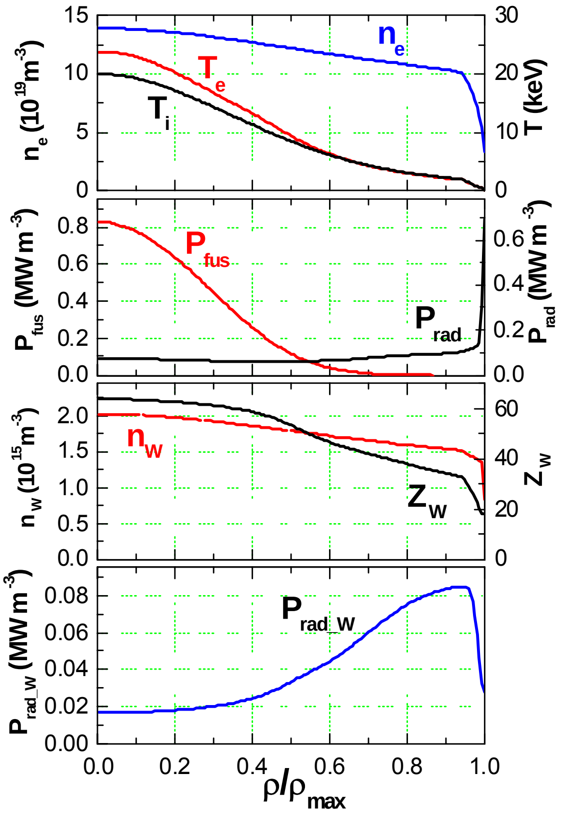

Fig. 1 Radial profiles of plasma parameters for the inductive ITER scenario

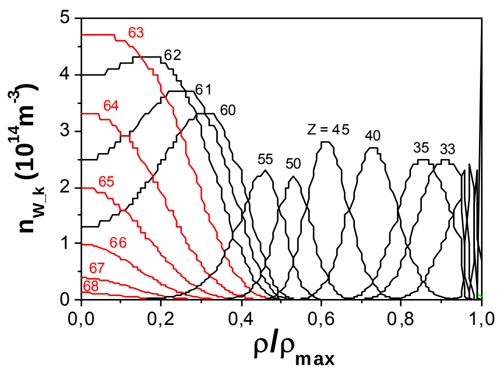

Fig. 2 Radial profiles of concentrations of different W ions for inductive ITER scenario

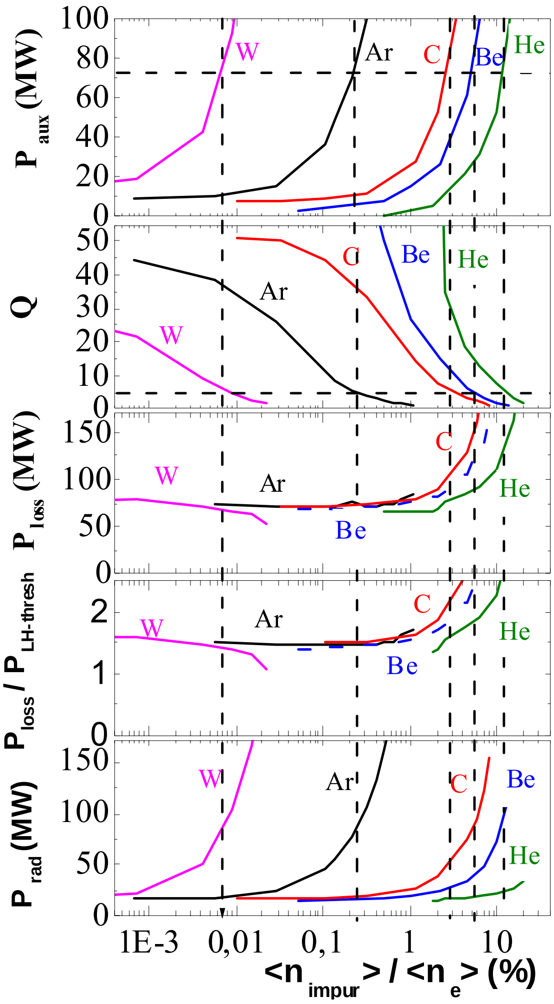

Fig. 3 Change of plasma parameters vs. impurity concentrations for inductive ITER scenario

20 MW of ECR) and radiated power is equal to 77.4 MW (< 100MW what is acceptable for divertor operation). In our simulations due to some influence of neoclassical thermal diffusion on flat enough plasma density profiles picking factor of tungsten and electron density profiles are similar one to other and tungsten does not concentrate in the plasma core. Pick of the tungsten radiation shifted to the boundary regions. Fig.2 demonstrates radial profiles of concentrations of different tungsten ions for this discharge.

As one can see W is not fully ionized in this case. Highest charge of ions is 68 (maximum possible charge is 74).

Increase of impurity concentrations in plasma results in plasma cooling due to rise of radiation and fuel dilution. One can keep fusion power by raising the auxiliary heating power but in this case fusion gain coefficient Q reduces and discharge parameters leave declared operational window of the reference regime. Besides, the level of P_{aux} is limited. It means that minimal permissible Q ~ 5 value and maximal accessible level of P_{aux} =73 MW define critical (maximal permissible) impurity concentration. For this scenario these concentrations are: n_W/n_e ~ $7{\cdot}10^{-3}$%; n_{Ar}/n_e ~ 0.25%; n_C/n_e ~ 3%; n_{Be}/n_e ~ 5%; n_{He}/n_e ~ 11% (see Fig.3).

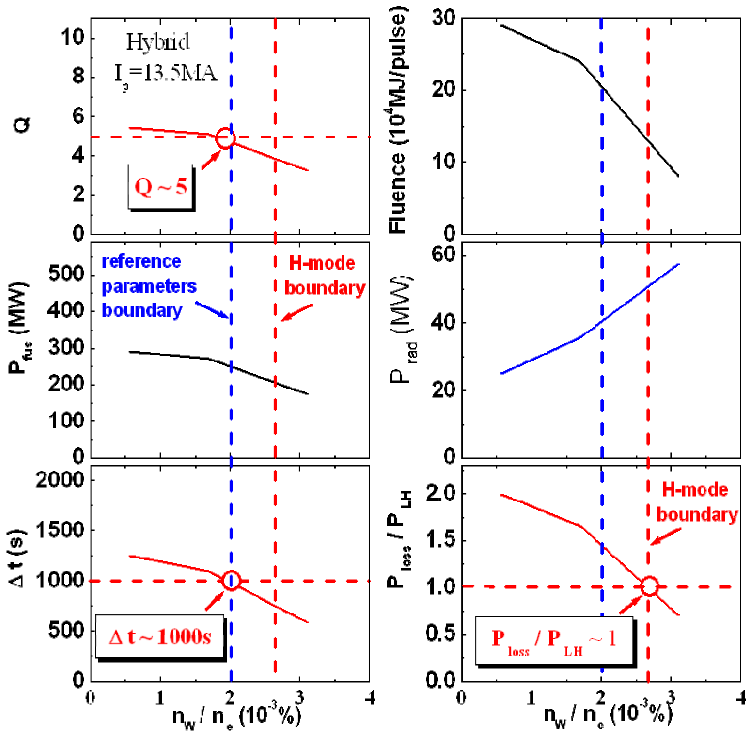

Fig.4 Dependence of hybrid scenario performance on W contamination

In hybrid scenario [1] noticeable part of plasma current is driven by non-inductive methods. Main parameters for this scenario are Q ≥ 5 and discharge duration Δt ≥1000 s. Dependence of this discharge performance on W concentration is shown in Fig.4. There are two boundaries for this discharge. First boundary is determined by the declared parameter region Q ~ 5 and Δt ≥ 1000s (blue dashed line), and second is more strict boundary set by the transition into the L-mode (red dashed line), when loss power reduces to the value less than threshold power of reversed H-L transition. As a result of simulations for this scenario we obtained such critical concentrations: n_W/n_e~ (2-3)10^{-3}%; n_{Ar}/n_e ~ (0.12-0.2)% and n_{Be}/n_e ~ (3-4)%.

Results of simulations for the steady state scenario [1] are presented in the Fig.5. In this scenario additional requirement due to the total CD by non-inductive methods is appeared. . Reduction of plasma temperature at plasma cooling results in reduction of CD efficiency and requires enhanced confinement for compensation of this reduction. As a result maximum impurity contaminations for realization of SS scenario were found to be: $n_W/n_e \sim (3 - 3.5)\cdot10^{-3}\%$, $n_{Be}/n_e \sim (8 - 9.5)\%$, $n_{Ar}/n_e \sim (0.18 - 0.22)\%$.

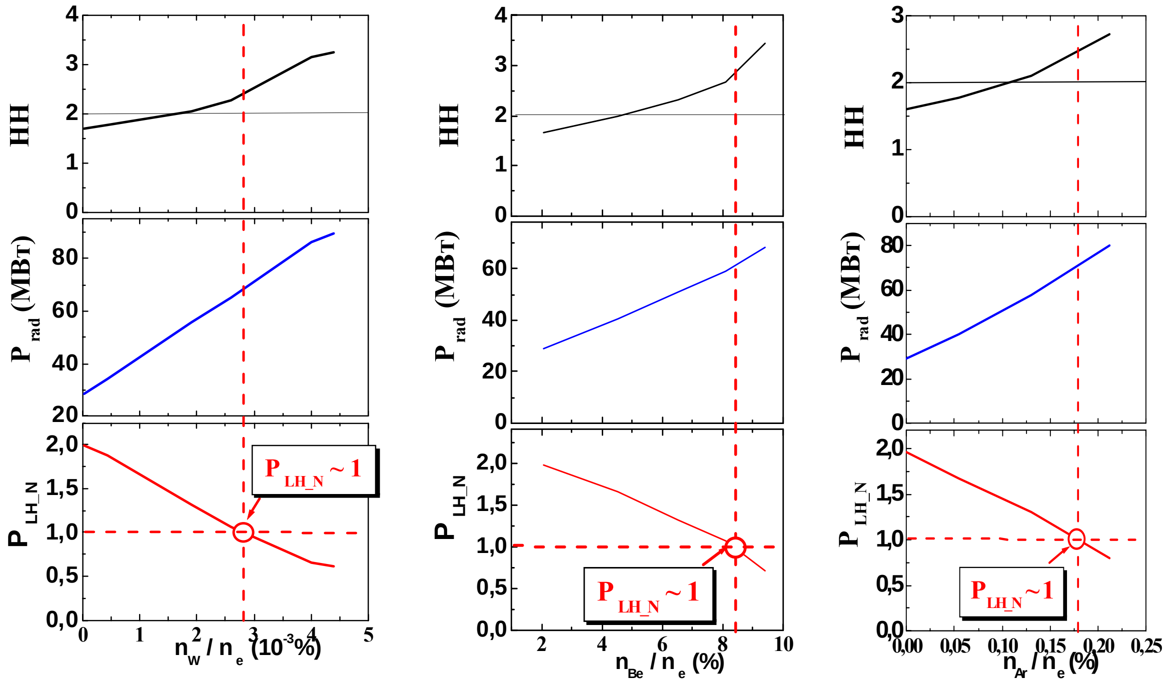

Fig.5 Dependence of steady state scenario performance on W, Be and Ar contamination

Conclusions. Results of simulations of dependences of plasma parameters on the main impurities contamination for the reference ITER scenarios are presented. Critical (maximal permissible) concentrations of different impurities were estimated for the flat-top stage of these scenarios. These relative concentrations are presented in the Table 1.

Table 1. Critical relative concentrations of different impurities for the reference ITER scenarios.

	W	Ar	Be
Inductive	$7\cdot10^{-3}$ %	0.25 %	~ 5 %
Hybrid	$(2-3)\cdot10^{-3}$ %	(0.12-0.2)%	(3-4)%
Steady State	$(3-3.5)\cdot10^{-3}$%	(0.18-0.22)%	(8-9.5)%

At the exceeding of these concentrations discharge parameters leave the declared ITER operational space. Further rise of impurity contamination can result in discharge transition to the L-mode and plasma cooling.

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