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Influence of Impurity Seeding on Plasma Burning Scenarios for ITER

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ITER expects to produce fusion power of about 0.5GW when operating with tungsten (W) divertor and beryllium (Be) wall. The influx of W from divertor can have significant influence on the discharge performance. This work describes predictive integrated numerical modeling of ITER discharges using the COREDIV code, which self-consistently solves the 1D radial energy and particle transport in the core region and 2D multi-fluid transport in the SOL. Calculations are performed for inductive ITER scenarios with intrinsic (W, Be and He) impurities and with seeded impurities (Ne and Ar) for different particle and heat transport in the core and different radial transport in the SOL. Simulations show, that only for sufficiently high radial diffusion (both in the core and in the SOL regions), it is possible to achieve H-mode mode plasma operation (power to SOL > L-H threshold power) with acceptable low level of power reaching the divertor plates. For argon seeding, the operational window is much smaller than for neon case due to enhanced core radiation (in comparison to Ne). Particle transport in the core characterized by the ratio of particle diffusion to thermal conductivity) has strong influence on the predicted ITER performance.

Keywords: ITER, impurity, integrated modeling, core plasma, edge plasma

1. Introduction

The reduction of the power load to the ITER divertor plates to an acceptable level is an important and critical issue, in particular for full tungsten ITER divertor. In present day experiments, stable discharges with different seeding species (N, Ne, Ar), radiative divertor cooling and strong reduction of the power to the W targets have been achieved so far on JET and AUG [1, 2]. Corresponding simulation results [3, 4] as well as modeling studies of ITER auxiliary heated (RF, NBI) hybrid scenarios [5] (with neon seeding) show that the core-SOL-divertor coupling in tokamak plasmas is very strong in presence of W impurity and it might reduce the operational domain for considered scenarios, as compared to the unseeded cases.

This work describes integrated numerical modeling applied to ITER scenarios with tungsten (W) divertor plate and beryllium (Be) wall using the COREDIV code, which self-consistently solves the 1D radial energy and particle transport in the core region and 2D multi-fluid transport in the SOL in the slab geometry. The model is fully self-consistent with respect to the influence of impurities on the α-power level (dilution, radiation) with simplified anomalous impurity transport and not taking into account the effect of ELM flushing from the confined region into plasma edge and impurity accumulation in the core. The code has been successfully benchmarked with a number of JET discharges, including the nitrogen seeded type I and type III ELMy H-mode discharges [6, 7, 8] and recently, JET ILW configuration [9]. COREDIV has also been applied to ASDEX discharges in the full W environment [3]. An impact of two important constraints - operation above the LH power threshold, radiating divertor and with low power arriving in the divertor - on the operational domain with high fusion gain is analyzed here for ITER baseline inductive scenario taking into account strong core-SOL-divertor coupling caused by W impurity. The impact of the different impurity seeding species (Ne, Ar) are compared.

2. Modeling results-sensitivity analysis

The physics model used in the COREDIV code has been already presented elsewhere [10, 11)].

It should be noted that anomalous transport in the core is based on an energy confinement scaling law. The ion and electron conductivities are defined by the formula: $\chi_{e,i}^{an} = C_e(a^2/\tau_E)\times F(r)$, where r is radial coordinate, a is the minor plasma radius, τ_E is energy confinement time calculated from the IPB98(y,2) scaling law. It should be noted that this scaling law was obtained for type I ELMy H-modes in carbon wall tokamaks and might not be valid for ITER with W divertor. The parabolic-like function *F(r)* describes the profile of transport coefficients and takes into account also the conductivity drop near the separatrix due to H-mode barrier formation. The constant C_e is adjusted to keep the calculated confinement time obtained in simulations equal to the value defined by the scaling law. The source term in the background ion transport equation takes into account the attenuation of the neutral density due to ionization processes and its intensity is determined by the internal iteration procedure in such a way that the average electron density (n_e) obtained from neutrality condition is kept constant (input parameter). For all ions, background plasma and impurities (including tungsten), we have used the same anomalous transport coefficient defined by: $D_i = \zeta\chi_{e,i}$; $V_i^{pinch} \sim C_p D_i$, where D_i is

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anomalous particle diffusion, $\chi_{e,i}$ is anomalous heat conductivity and the coefficient ζ is an input parameter. C_p is the density peaking coefficient for the main plasma ions. For impurities, an optimistic assumption is used with $C_p^{IMP} = 0$ (no impurity pinch) in our simulations. We note, that this assumption is consistent with the experiments on the ASDEX-U, where the ECRH control of the central electron temperature leads to the mitigation of W accumulation in the core [12] as well as to experiments with central RF heating in JET [13]. Moreover, the effect of impurity pinch on the ITER performance has been already analyzed in the ref. [5, 11].

In the SOL, the 2D multifluid equations are solved for the DT plasma and equations for each ionization state of each impurity species in the simplified slab geometry (poloidal and radial directions) with classical parallel transport and anomalous radial transport ($D^{SOL}_{perp} = 0.5\chi_e = \chi_i$). An analytical description of the neutrals is implemented in COREDIV which allows for the inclusion of plasma recycling as well as the sputtering processes at the target plates. This model is applicable for highly recycling and semi-detached plasma conditions in divertor, however full divertor detachment cannot be properly accounted for. The hydrogen recycling coefficient is iterated to obtain the prescribed plasma density at the separatrix and the particle source in the core is adjusted to achieve assumed electron plasma density which is the input parameter for the code.

We are mostly interested in the global behavior - in terms of fusion power and of the power load to the divertor target plates - of ITER seeded plasmas and we have focused our work to evaluate the effects induced on the discharge by tungsten. It should be noted however, that due to simplifications of our model (slab divertor geometry) we are not able to resolve the real ITER-divertor structure with W baffles/dome and W target plates. The beryllium wall is simulated in our model assuming uniform influx of beryllium atoms from the side walls ($\Gamma_{Be} = 10^{21}$ s^{-1}) in agreement with estimations given in Ref.[14] which leads to beryllium concentrations below 0.1%. It should be noted, however, that even 10 times larger Be influx has only small influence on the simulation results. We note that only direct influence of Be on the plasma parameters (due to radiation and dilution) is considered in the present paper and all the effects related to Be deposition and material mixing are neglected.

We have considered the standard ITER inductive reference scenario [15] with I_p = 15 MA, (B_T = 5.3 T), line average density $<n_e>_{line} = 0.85 n_{GW} = 1.01 \times 10^{20} m^{-3}$, auxiliary heating P_{aux}=52 MW and we have modeled the effect of neon and argon seeding. Slightly reduced enhancement factor with respect to the ITER H-98P(y,2) confinement scaling H98P(y;2) = 0.95 has been chosen, to be consistent with the temperature profiles as obtained in the recent ITER simulations with transport codes [16].

For these conditions, the electron temperature (T_e) and density (n_e) on the pedestal is 4.6keV, and $9.2 \times 10^{19} m^{-3}$, respectively.

2.1 Influence of the particle transport in the core

In our model, the ratio between particle diffusion and heat conductivity in the core plasma is a free parameter for the transport simulations. In Ref. [16] ζ = 0.1 ($\zeta = D/\chi_e$) was used whereas in our old simulations for ITER

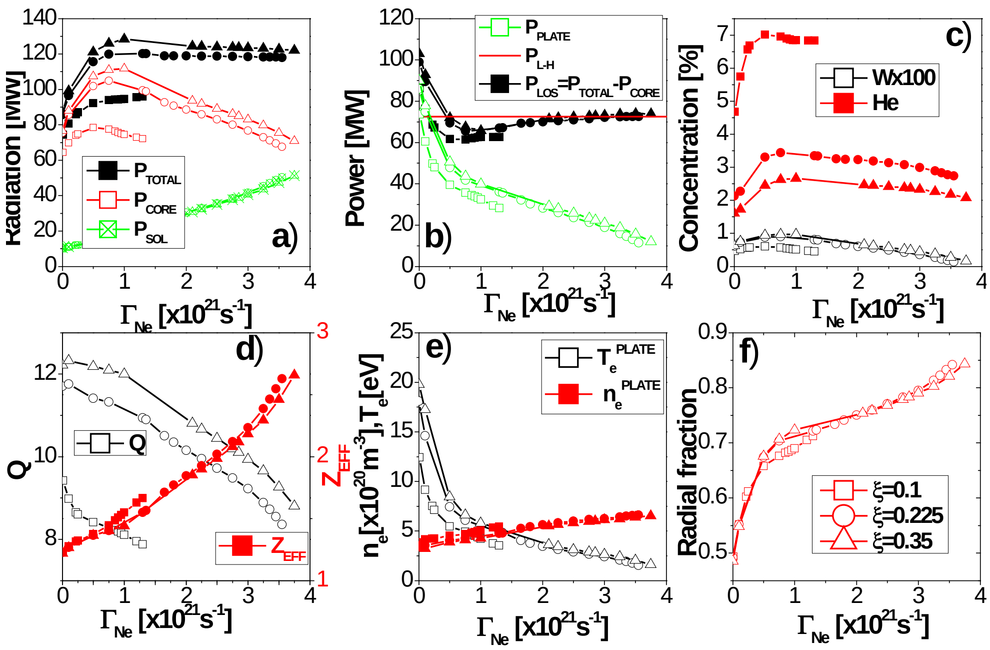

Fig. 1. Plasma parameters in ITER inductive scenarios versus neon gas puff for three different transport coefficient: ζ=*0.1; 0.225* and 0.35: (a) total, core and SOL radiative power; b) power to plate, L-H power threshold and power through the separatrix; (c) W and He concentrations (d), Z_{EFF} and fusion gain Q; (d) temperature and density at the divertor plate and (e) radiation fraction. Reference D^{SOL}_{perp} = 0.25 m^2/s is used.

[5, 17], ζ =0.35 was assumed. The particular value of the ζ parameter has relatively small influence on the simulations of present day experiments, however it might affect strongly the fusion reactor performance where the effect of helium ash accumulation could be important. Therefore, we have analyzed, how the assumption about particle transport in the core influences the simulation results assuming three different values of the ratio of particle diffusion coefficient to thermal electron conductivity: ζ = 0.100, 0.225 and 0.350, respectively.

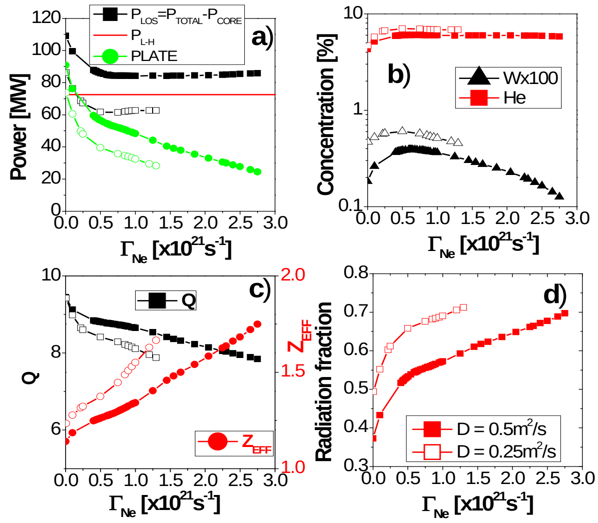

Fig. 2. Plasma parameters for ITER inductive scenario versus neon gas puff for ζ =0.1 and for two values of $D^{SOL}{}_{RAD}$ = 0.25 and 0.5m^2/s: (a) power to plate and power through the separatrix; (b) W and He concentrations (c), Z_{EFF} and fusion gain Q; (d) radiation fraction.

The main plasma parameters: total (P_{TOTAL}), core (P_{CORE}), and SOL (P_{SOL}) radiations, power to the plate (P_{PLATE}), L-H power threshold (P_{L-H}) and power through the separatrix (P_{LOS}), W and He concentrations, effective charge state (Z_{EFF}) and fusion gain (Q), temperature (T_e^{PLATE}) and density (n_e^{PLATE}) at the divertor plate and radiation fraction are shown in the Fig. 1 for the reference value of the plasma transport in the SOL $D^{SOL}{}_{perp}$ = 0.25 m^2/s and neon seeding.

Without impurity seeding (Fig.1b), the power load density to the W plate is always above 10MW/m^2 (assuming 40 MW power to the divertor and 4m^2 of the wetted area) and therefore impurity seeding is needed to reduce divertor heat load to the acceptable level. The coefficient ζ, have strong influence on the ITER performance, which is related to helium transport. If the particle transport is reduced (lower ζ) then the helium concentration (C_{He}) builds up.

This is strongly non-linear effect as can be seen in Fig.1c. In the case with ζ =0.1, C_{He} is ~3 (~2) times higher than for ζ =0.350 (0.225). Increased helium concentration, leads to plasma dilution and strong reduction of the alpha power and fusion gain Q (Fig.1d) and consequently the power crossing the separatrix is reduced, falling below the L-H threshold power (72.5MW). The operational window in terms of the allowed seeding level is also narrowed, in particular for the lowest ζ=0.1.

2.2 Influence of the radial transport in the SOL

Predictive COREDIV modeling for hybrid scenario, shows that the high perpendicular diffusion in the SOL is beneficial for an increase of the ITER operational space[5]. Figures 2 and 3 show the influence of the radial transport in the SOL on plasma parameters for the inductive scenario for two different values of $D^{SOL}{}_{perp}$, equal to 0.25 and 0.5 m^2/s, respectively and for two different assumptions regarding the core transport: ζ =0.1 (Fig.2) and ζ =0.35 (Fig. 3).

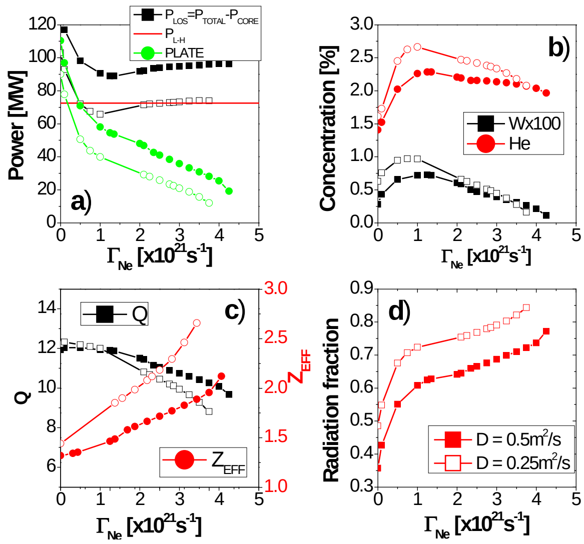

Fig. 3 Plasma parameters in ITER inductive scenarios versus neon gas puff for ζ =0.35 for two different transport coefficient: $D^{SOL}{}_{RAD}$ = 0.25 and 0.5m^2/s.: (a) power to plate, L-H power threshold and power through the separatrix; (b) W and He concentrations (c), Z_{EFF} and fusion gain Q; (d) radiation fraction.

With the increased diffusion in the SOL, the screening efficiency of the edge region is improved, leading to the decrease of W concentration (and radiation) in the core and consequently to the increase of the power across the separatrix (P_{LOS}), which stays well above the P_{L-H} threshold. It can be seen that for ζ =0.1 and for relatively small seeding (Γ_{Ne}> 1.75x10^{21}s^{-1}) it is possible to achieve H-mode operation (P_{LOS} > P_{L-H}) and simultaneously P_{PLATE}<40MW), but the Q-factor is below nine. For the case with ζ=0.35, stronger seeding is required to reduce the heat load below 40 MW limit due to much better fusion performance (Q > 10 for Γ_{Ne}< 4x10^{21}s^{-1}).

2.3 Influence of the different impurity type

Since the simulations show, that with the reduced particle transport (ζ =0.1 and $D^{SOL}{}_{RAD}$ = 0.25m^2/s) achievement of the stable operational window might be problematic in the case of neon seeding, we have studied also the influence of argon seeding on the ITER performance. Simulation results for argon seeding for two extreme ζ values (= 0.10 and 0.35) and for the optimistic situation with stronger SOL transport ($D^{SOL}{}_{RAD}$ = 0.5m^2/s) are presented in Fig.4. It can be seen that the fusion performance for both gasses is quite similar (in terms of Q-factor and alpha power production) but for argon we do not observe reduction of the Q–factor with increased seeding as in the Ne case (small dilution effect for Ar). There is not a stronger degradation of the pedestal in the case of Ar because of the high assumed pedestal temperature (~4 keV) which means that Ne and Ar are mostly radiating outside of the separatrix.

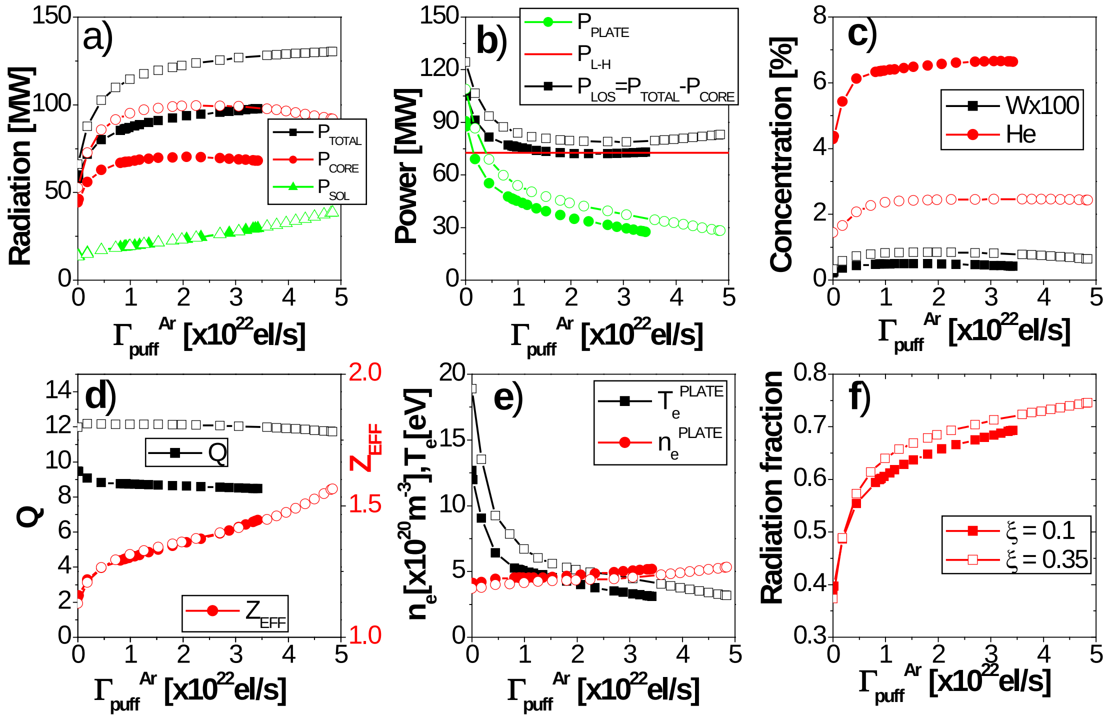

Fig. 4. Plasma parameters in ITER inductive scenarios versus Ar gas puff for D^{SOL}_{RAD} =0.5m^2/s: (a) total, core and SOL radiative power; b) power to plate, L-H power threshold and power through the separatrix; (c) W and He concentrations (d), Z_{EFF} and fusion gain Q; (d) temperature and density at the divertor plate and (e) radiation fraction. Reference ζ *=0.1* are used for different impurity seeding: ζ = 0.1 (full symbol) and ζ = 0.1 (open symbol)

However, the power crossing separatrix is significantly reduced in the case of Ar due to additional contribution from argon to the core radiation (in addition to W losses).The H-mode operation is only marginally possible for ζ =0.1 close to the maximum allowed seeding level (Γ_{Ar} > 3.5x10^{21}el/s). For the case with higher core diffusion (ζ =0.35), the operational window in terms of seeding level starts from Γ_{Ar} > 2.7x10^{21}el/s, where the power to plate falls below 40MW.

3. Summary and Conclusions

The COREDIV code has been used to analyze ITER standard inductive scenario. Since the operational limit for the divertor target plates is 10MW/m2, seeding is mandatory to reduce the heat load to target plates, simulations have been performed comparing neon and argon seeding for different assumptions regarding particle transport in the core and edge regions.

It has been found that in order to achieve wide operational window with the power crossing separatrix above the H-L threshold and simultaneously with tolerable heat load to target plates (< 40 MW) relatively strong impurity transport in the core and SOL regions is necessary. In particular, the particle (impurity) diffusion has very strong effect on the fusion gain due to plasma dilution by helium [18]. It has been found that with low diffusion in the core (ζ = 0.1) and SOL (D^{SOL}_{RAD} =0.25 m^2/s) no operation space for ITER for Q=10 is possible under the assumptions made in the COREDIV simulations. An increase of the perpendicular diffusion in the SOL or core region helps to achieve the H-mode operation with tolerable power to the target plates. In particular, for ζ = 0.35 and D^{SOL}_{RAD} =0.5 m^2/s wide operational window can be achieved for neon and argon seeding, but it should be noted that for Ar the operational range is stronger limited than for neon seeding.

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