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Influence of core–edge coupling and impurities on the operation regimes of a fusion reactor

R. Stankiewicz *, R. Zagórski

Institute of Plasma Physics and Laser Microfusion, P.O. Box 49, 01-908 Warsaw, Poland

Abstract

The extended version of the COREDIV code has been used to analyze the combined effect of different impurity species on the ITER–FEAT operation regimes. The core plasma is treated in the frame of 1D radial transport model whereas in the edge the 2D multifluid code EPIT is used. The steady states of ITER–FEAT reactor have been studied numerically and the influence of the core–edge coupling due to the production of the sputtered impurities has been analyzed for nickel and carbon plasma facing components. The effect of injected impurities on the divertor operation and heat removal is addressed.

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1. Introduction

The power load to divertor plates in the fusion reactor strongly depends on the operation regime in both the core and the SOL plasma and on the radiation losses of impurities. The detailed treatment of the edge plasma is very important particularly for ITER–FEAT and requires the 2D modelling of the boundary layer. Two basic approaches are usually used in order to tackle the problem. In the first one the time evolution of the whole system is studied with various levels of approximation and complexity of the model applied to both parts of the system [1–4]. A review of the different models is presented in [3]. The attempt to model all physical details and the geometrical complexity of the problem leads to huge and computer time consuming codes. On the other hand simplified models can also lead to satisfactory results, e.g. simple 0D core and 1D SOL model reproduced surprisingly well some of the FTU experimental data [1]. The second approach is based on parametrization of either the core or SOL region response to the signal obtained from the second part of the system [5].

In this paper, operation regimes of a fusion reactor in the presence of seeded impurity are analyzed with the help of the COREDIV code [4], which was recently extended to include the transport of several sputtered and/or injected impurities. An efficient iteration procedure has been developed for finding the stationary solution of the problem [4]. The possibility of using the seeded impurities to reduce the power load in ITER–FEAT is analyzed. The results are presented for carbon and nickel plasma facing components and neon and silicon are considered as seeded impurities.

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* Corresponding author.
E-mail address: romsta@ifpilm.waw.pl (R. Stankiewicz).

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1.1. In the core

The 1D radial transport equations for bulk ions, each ionization state of impurity ions, electron and ion temperatures are solved. It is assumed that all ions have the same temperature. The energy sources due to alpha heating, Ohmic heating and additional heating (e.g. NBI, RF) are included. The energy losses are determined by Bremsstrahlung and line radiation. The electron and ion energy fluxes are defined by the local transport model proposed in Ref. [6] reproducing the prescribed energy confinement law [7]. In particular, the heat conductivity is given by the formula

$$\kappa_{\mathrm{e,i}} = -n_{\mathrm{e,i}} C_{\mathrm{e,i}} \frac{a^2}{\tau_{\mathrm{E}}} \left(5.5 - \frac{r}{a}\right)^{-1}, \tag{1}$$

where τ_{E} is the energy confinement time defined by the ELMy H-mode scaling law [7], $n_{\mathrm{e,i}}$ is the electron (ion) density, a is the plasma radius and $C_{\mathrm{e}} = 2C_{\mathrm{i}}$ is an adjustable coefficient. The value of $C_{\mathrm{e}} = 1.8$ used in calculations gives good agreement between the energy confinement time obtained in calculations and that calculated from the energy scaling law. The radial impurity transport is described by standard neoclassical and anomalous transport. The profile of the main plasma ions is modelled by the solution of the radial diffusion equation with the diffusion coefficient of the form $D_{\mathrm{i}} = D_{\mathrm{i0}}/(1 + 2(\frac{r}{a})^2)$ and the source $S_{\mathrm{i}} = S_{\mathrm{i0}}[1 - \exp(-(\frac{r}{a})^{16})]$, yielding flat density profiles [7]. The internal iteration procedure is applied to determine the source intensity S_{i0} in order to fulfill the condition that the averaged electron density obtained from neutrality condition equals the value assumed in the ITER–FEAT project.

1.2. In the SOL

We use the 2D boundary layer code EPIT, which is primarily based on Braginskii-like equations for the DT plasma and rate equations for each ionization state of each impurity species. In the past the EPIT code was used to analyze some FTU experiments giving satisfactory agreement between the calculated and measured values [8]. In the model, for sake of simplicity, the drifts have not yet been included. Since the plasma density in a reactor would be high we expect a relatively small influence of drifts on the ignition condition and global plasma balance. The effect of drifts would be concentrated to the SOL and to the boundary region close to the separatrix. The drifts, which are connected with the radial electric field and its shear would strongly influence the transport in the edge (L–H transition). However these problems are still outside the scope of our model. Since the model has been described elsewhere [9], only the main points are discussed here. For every ion species we solve the continuity, parallel momentum and energy equations. An analytical description of neutrals allows the inclusion of plasma recycling as well as the sputtering processes at the target plates. We assume that the divertor is in attached mode and the recycling coefficient R is an external parameter in the model. Since the temperature at the plates is high at the strike point, the physical sputtering is dominating and the contribution of the additional chemical sputtering is less important and has been neglected. The radiation losses caused by the impurity ions (intrinsic and seeded) are included self-consistently in the model. A slab geometry with radial and poloidal direction is used. The transport along field lines is assumed to be classical whereas the radial transport is anomalous. The standard sheath boundary conditions are imposed at the plates, whereas at the wall, the boundary condition are defined by the decay lengths [9]. The parallel velocities and the gradients of densities and temperatures are assumed to be zero at the midplane (stagnation point). The coupling between the core and SOL is realized by imposing continuity of energy and particle fluxes as well as particle densities and temperatures at the separatrix.

2. Results

The operation regimes of the reactor have been studied for two plate and wall materials: carbon and nickel. Neon and silicon have been chosen as seeded impurities. An ITER–FEAT [7] reference case ($R_{\mathrm{T}} = 6.20$ m, $a = 2.0$ m, $I_{\mathrm{p}} = 15$ MA, $\langle n_{\mathrm{e}} \rangle = 1.01 \times 10^{20}\ \mathrm{m}^{-3}$, 3.2% He) has been assumed. Prescription of the averaged electron density $\langle n_{\mathrm{e}} \rangle$ and recycling coefficient R (= 0.99 in our calculations), together with the injected impurity gas-puff rate determines the self-consistent solution of the problem.

In order to analyze the operating regimes of ITER–FEAT tokamak the coupling between the core and SOL region is modified by varying the background ions diffusion coefficient from 0.3 m^2/s to 3 m^2/s. In all calculations the uniformly distributed additional heating $P_{\mathrm{add}} = 30$ MW has been assumed. In Figs. 1–3 the alpha power (P_{alpha}), the heat load to the plates (P_{plate}), the power flowing from core to edge (P_{inp}), the line radiation losses in the edge ($P_{\mathrm{lin}}^{\mathrm{edge}}$) and in the core ($P_{\mathrm{lin}}^{\mathrm{core}}$), the averaged effective charge (Z_{eff}) in the core, the total density at the separatrix of sputtered impurity (n_{zs}) and seeded impurity (n_{seeded}) are presented as functions of the electron density n_{es} at the separatrix. In Figs. 1 and 3 nickel is considered as the wall and plate materials whereas Fig. 2 presents the results for carbon. It is assumed that seeded impurities are introduced to the edge plasma by localized gas puffing. They are modelled by time independent local neutral source of impurity atoms with prescribed space distributions with the intensity

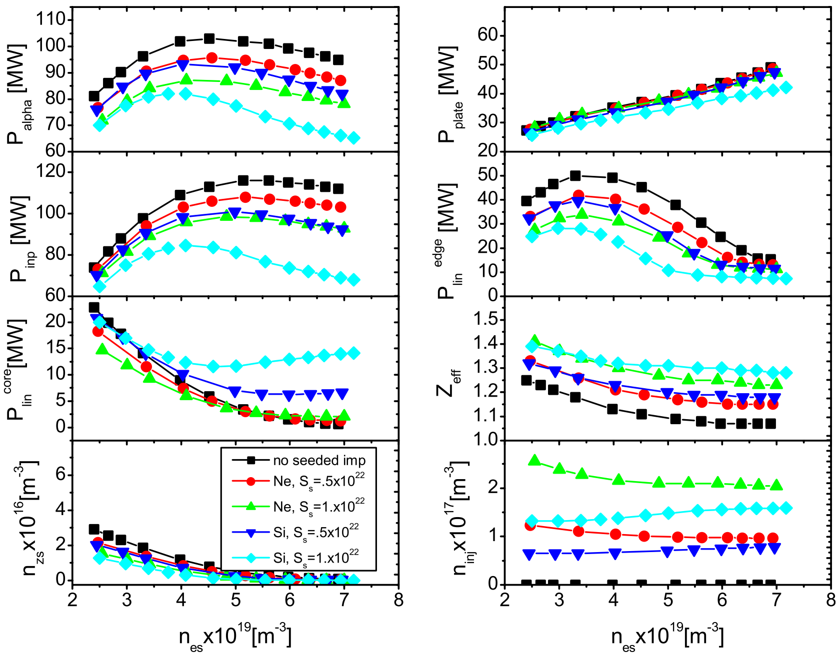

Fig. 1. Results for nickel plate for various intensities of impurity gas-puff source (S_s).

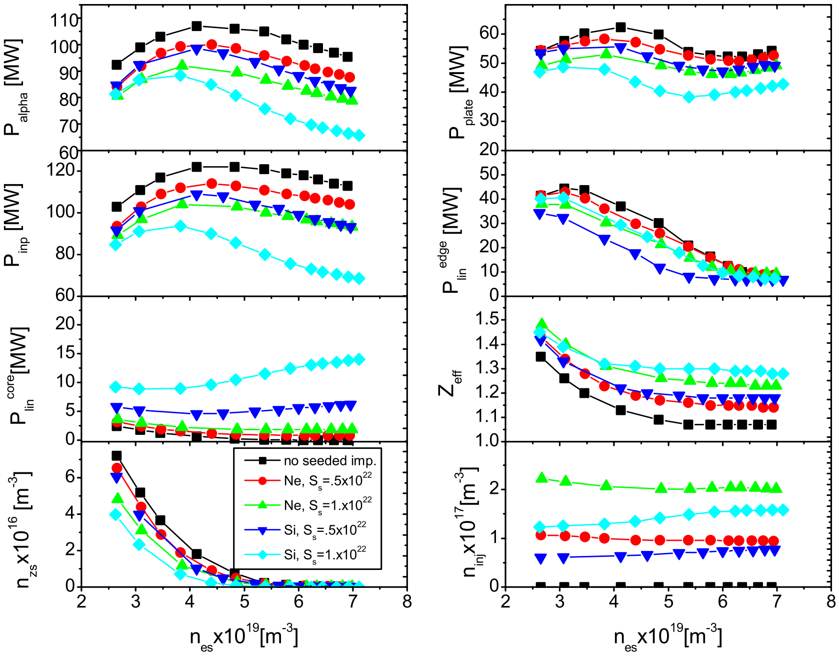

Fig. 2. Results for carbon plate for various intensities of impurity neutral source (S_s).

S_s ([s^{-1}]). In Figs. 1 and 2, results for the case when the impurity source is located close to the stagnation point are presented. Two factors strongly influence the reactor operation: the cooling and dilution of the core plasma by impurities. Therefore, with increasing of the intensity of the gas-puff source the Z_{eff} in the core increases and the alpha power and energy flowing to the SOL decreases. It should be noted that in all considered cases

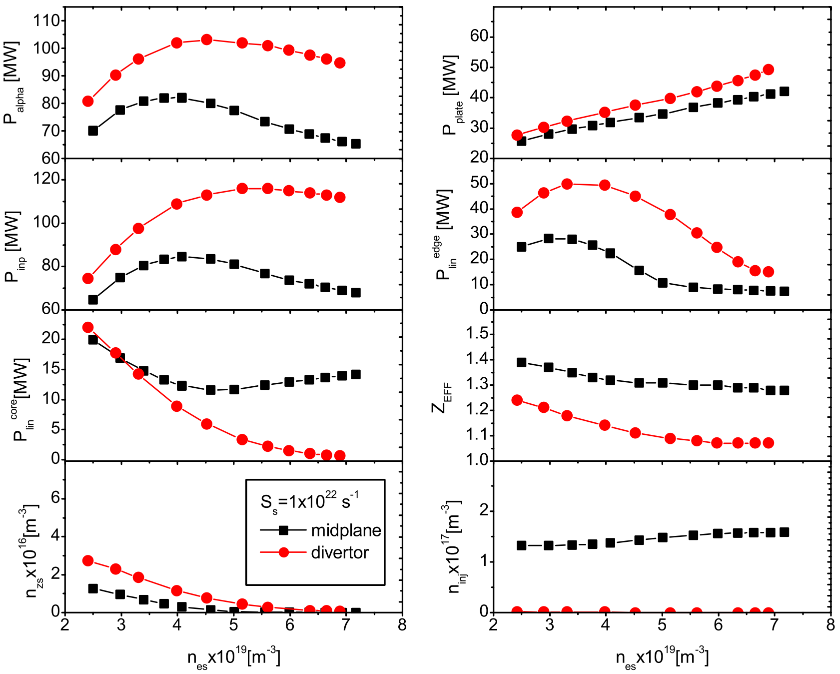

Fig. 3. Results for nickel plate and silicon as seeded impurity. Gas-puff source located near midplane and in the divertor.

the averaged Z_{eff} remains within assumed limits for ITER–FEAT (<1.8).

In the case of nickel plate, there is a very weak influence of the injected impurity on the heat load. It can be seen in Fig. 1 that the power load to divertor plates (P_{plate}) is almost independent on the type of seeded impurity and intensity of its source. This effect is associated with the strong coupling between core and edge plasma for Ni target [2]. Since the sputtering of nickel strongly depends on the plate temperature especially when the self-sputtering yield is close to unity, then even small changes in the power load can lead to significant changes of sputtering yield. If the power input to the SOL P_{inp} increases (smaller gas puff) then, in turn, the higher energy input leads to a higher sputtering at the plate and efficient cooling of the plasma in the SOL, in particular for lower edge plasma densities. With the gas puff some of the nickel ions are replaced by the seeded impurity ions leaving the power balance in the discharge more or less unchanged.

In contrast, for carbon plate (Fig. 2) the seeded impurities can significantly reduce the power load to the divertor. The sputtering of carbon is also reduced with the increase of the seeded impurity density but, due to the weak carbon radiation, the decrease in the carbon density results in the smaller change of the total power losses in the edge in comparison to the case of the nickel plate. The reduction of the power flowing to the edge leads to the reduction of the power loads to the plate and the plate erosion.

In Fig. 3 two cases are compared for nickel plate and silicon as seeded impurity. In first case, the silicon source is located close to midplane (one of the cases presented in Fig. 1) and in the second case the gas-puff source is in the divertor near the target plate. The simulation results indicate that the influence of seeded impurities on global performance of fusion reactor is stronger if the impurity source is located close to the stagnation point. In that region the plasma velocity is small and the friction force dragging the impurities towards the plates is small. Therefore the impurities travel more efficiently to the core. If the gas-puff source is located close to target then impurity ions are simply pushed by the strong plasma flow to the target plate. For the gas-puff source located close to the target the overall plasma behavior is almost the same as for the case without gas-puff (see Fig. 1), meaning that the core power balance is not affected by injected impurities. Consequently, the reactor performance improves and the alpha power is higher than in the case of the injected impurity source located near the stagnation point. It should be noted, however that the heat loads to the plate in both cases are similar, due to effective cooling by the nickel line radiation.

3. Conclusion

Results of calculations for ITER–FEAT show that the stationary solutions with burning plasma can be achieved in ITER–FEAT for both low Z (C) and middle Z (Ni) plate materials. For both plate materials the effect of the seeded impurities is equivalent to shifting part of the edge radiation to the core and the simultaneous reduction of the alpha power and plate erosion. It should be noted that the power load to the nickel divertor plate is only slightly reduced by introduction of the seeded impurities. However, the plate erosion can be efficiently reduced by injected impurities. In contrast, in case of carbon plates, the seeded impurities can significantly reduce the power load and plate erosion. It should be stressed that our results have been obtained with the help of a model which is still developing and not fully justified. In particular, for the SOL we have used a simplified slab model neglecting plasma drifts with rather simple analytical model for neutrals. The effect of chemical sputtering was also neglected and a simplified transport in the core was assumed. At the moment it is difficult to say which simplifications are essential and therefore the results should be treated rather as indication of some trends.

Acknowledgments

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