Role of the radiation opacity in divertor plasma detachment

A.A. Pshenov[1,2], A.S. Kukushkin[1,2], E.D. Marenkov[2], S.I. Krasheninnikov[3]

[1] *NRC "Kurchatov Institute", Moscow, Russian Federation*

[2] *National Research Nuclear University MEPhI, Moscow, Russian Federation*

[3] *University of California San Diego, San Diego, USA*

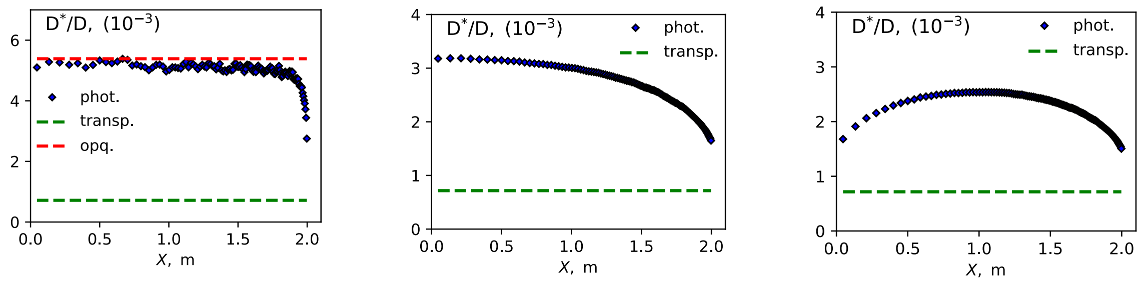
I. Introduction

Transition to the detached divertor regime that allows lowering the peak heat loads on the divertor targets in an ITER size tokamak-reactor to the tolerable level of 5-10 MW/m^2 [1] is closely connected to the onset of the volumetric recombination process [2], which in turn requires low temperature $T_e \sim 1$ eV and high density $n_e \sim 10^{21}$ m^{-3}. Plasma in such conditions is opaque to the Lyman lines of the hydrogen isotopes [3] and radiation transport becomes an important part of the problem [4]. Radiation trapping results in reduction of both the hydrogen "ionization cost" and the electron ion recombination rate, which can make reaching the detached plasma regime more difficult.

Nevertheless, almost all 2D edge plasma transport codes used to study the detachment physics treat the divertor plasma as fully transparent for the line radiation of both hydrogen and impurities. One noticeable exception is the radiation transport block developed by V. Kotov for the SOLPS code package, which allowed to study the effect of hydrogen line trapping on the neutral kinetics in a tokamak divertor [5]. It was shown that for the similar values of the neutral pressure P_{neut} in the divertor, the control parameters (such as the peak heat load q_{pk}, the electron density at the separatrix n_e^{sep}, the impurity concentration at the separatrix c_{imp}, etc.) remain largely unaffected, in spite of the significant changes in the divertor plasma profiles. However, because of extreme computational demands this study was conducted for a very limited range of the input parameters. In the present work, we "revive" the radiation transport block in SOLPS4.3 and study divertor plasma detachment in the limiting cases of the opaque divertor plasma with the collisional-radiative model (CRM) incorporated into the code.

II. Radiation transport block tests

Since the radiation transport block in SOLPS has not been used for a long time now, it is important to test its integrity before applying it to the edge plasma modeling. For this purpose, radiation transport in a specific 1D formulation of the SOLPS4.3 code package has been studded. The computational domain is represented by a slab of the length L = 2 m and width d = 2 cm. The two sides and the “left” end (corresponding to X = 0 in Fig. 1) of the domain are “mirror” (i.e. reflecting) surfaces, whereas the “right” end (X = 2 m in Fig. 1) is completely absorbing in Fig. 1a and 1b. In Fig. 1c, the “left” end boundary condition is changed to the complete absorption. A specific iterative rescaling procedure has been developed to study the radiation transport on the prescribed background plasma and neutral profiles. For the background, a pure deuterium plasma with $T_e = T_i = T_{neut}$ fixed at 5 eV and $n_e = n_i = 10^{14}$ cm^{-3} was used. Radiation transport in Lyman–α has been studied. Only the natural and Doppler line broadening mechanisms were taken into account. The neutral density n_{neut} of 10^{14} cm^{-3}, which corresponds to the mean free path of the emitted photons λ ~ 1 cm (λ << L), was used to obtain Fig. 1a, whereas $n_{neut} = 10^{12}$ cm^{-3} (λ ~ 1 m ~ L) was used for Fig. 1b and 1c.



a) b) c)

Figure 1. Fractional abundance of the first exited state (n = 2) of the deuterium neutrals obtained in the slab geometry described in Section II.

The resulting fractional abundance of the first exited state (n = 2) of the deuterium neutrals is shown in Fig. 1. The full transparency limit (zero photon absorption rate, green dashed line) and the complete L_α opaqueness limit (zero spontaneous decay rate A_{21}, red dashed line) are also shown. When λ ~ L and both ends of the slab are absorbing (Fig. 1c), a symmetrical, bell-like profile of the abundance is obtained. If the boundary condition on the “left” end is changed to complete reflection (Fig. 1b), the profile changes to the gradually decreasing (along X) one with zero gradient on the “left”. Finally, when λ << L (Fig. 1a), the fractional abundance is close to the opaqueness limit everywhere except for the very end of the slab, close to the absorbing surface. All the obtained results are physically justified, thus confirming the self-consistency of the radiation transport module in EIRENE.

III. Detachment in opaque divertor plasma

To determine, which changes in the divertor plasma detachment process can be expected due to intense radiation trapping, a series of parameter scans has been conducted in a DIII-D-like geometry similar to the one used in [6]. A pure deuterium plasma with the input power from the core Q_{SOL} = 8 MW was studied. The total number of the deuterium particles (both ions and neutrals) outside the separatrix N_D^{edge} was taken as the input parameter determining the edge plasma density. Three limiting cases were studied: the transparent edge plasma, the edge plasma completely opaque to the Lyman–α radiation (A_{21} = 0) and the edge plasma completely opaque for the whole Lyman series (A_{n1} = 0).

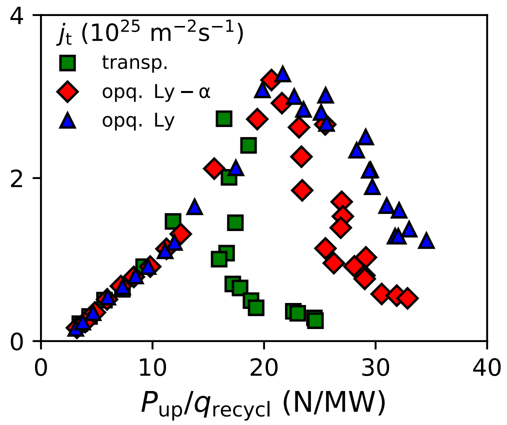


Figure 2. Specific ion saturation current reaching the outer target in chosen flux tube against parameter determining the degree of detachment.

Increasing the opacity results in decreasing radiation from the deuterium neutrals, therefore reducing the "ionization cost" E_{ion}. It was shown in [2,7] that the degree of the detachment is determined by the ratio of the upstream plasma pressure P_{up} to the specific power flux entering the recycling region q_{recycl}. In turn, critical value of P_{up}/q_{recycl} increases with decreasing E_{ion} approximately as $(E_{ion})^{-1/2}$. Since in the absence of impurities q_{recycl} remains largely unaffected by the changes in the edge plasma opacity, increasing radiation trapping should result in higher P_{up} necessary to reach detachment. This effect is indeed observed in the modeling. In Fig. 2, the specific ion saturation current in one of the flux tubes connecting the power flux stagnation point to the outer divertor target j_{sat} is plotted against the P_{up}/q_{recycl} parameter. It can be clearly seen in Fig. 2 that the critical value of P_{up}/q_{recycl} (after which j_{sat} changes its trend from increasing to decreasing) goes up with increasing the opacity.

Therefore, in opaque plasma, because of the decreasing radiation losses (Fig. 3a), the transition to the detached plasma regime (especially in the more loaded outer divertor) requires substantially higher N_D^{edge} (Fig. 3b,c) and n_e^{sep} (Fig. 3d) compared to the transparent case. This is largely caused by suppression of the volumetric recombination (Fig. 3e) due to both the decrease in the reaction rate with increasing the abundances of the higher excited states of deuterium neutrals and the increasing plasma temperatures in front of the target plate compared to the transparent case (Fig. 3f).

Note also that the difference in the threshold of the transition to the detached plasma regime between the opaque to the Lyman–α and the opaque to the whole Lyman series cases is rather marginal. Therefore, in the future studies with the full radiation transport model, taking into account Lyman–α alone should be sufficient to capture the effect.

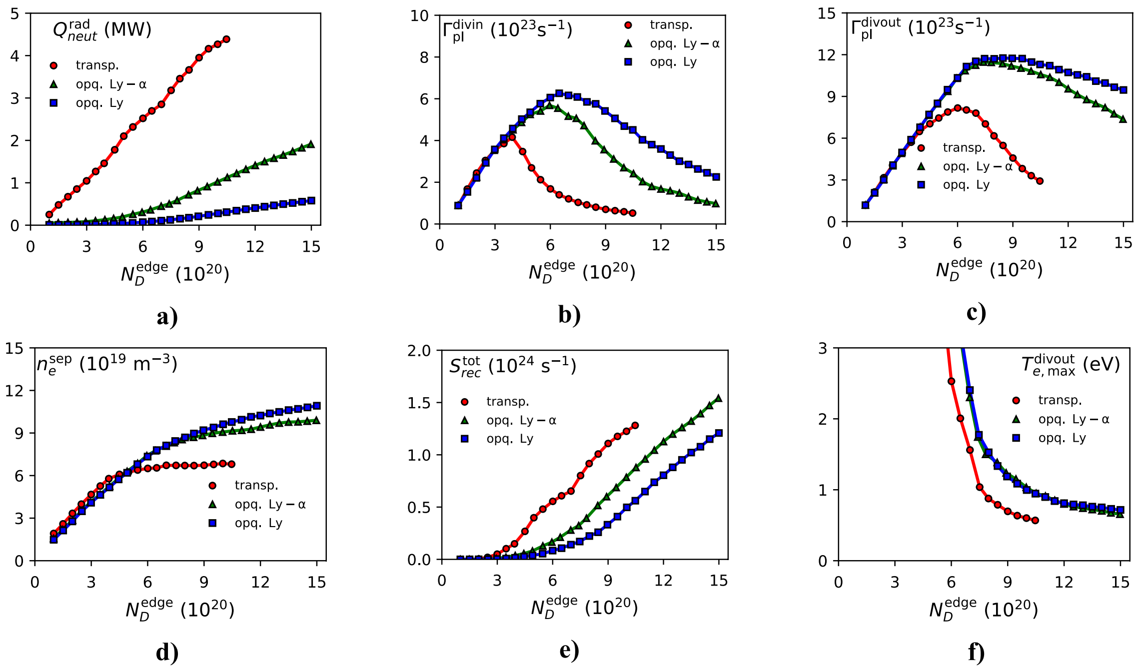


Figure 3. Dependence of the a) radiation losses from deuterium neutrals, b) total ion flux to the inner divertor target, c) total ion flux to the outer divertor target, d) average electron density at the separatrix, e) total recombination sink in the divertor volume and f) maximum T_e in the vicinity of the outer target on the N_D^{edge}.

IV. Conclusions

i) The integrity of the radiation transport model incorporated in the SOLPS4.3 version of the Monte-Carlo code EIRENE is verified with a series of fixed-background 1D calculations. ii) A possible influence of radiation trapping on the transition to the detached divertor regime is studied. iii) It is shown that the decrease of the “ionization cost” of the deuterium atoms results in suppression of the volumetric recombination, which can further stiffen the requirements to the separatrix plasma pressure or the fraction of power radiated in the scrape-off layer.

Acknowledgments This paper is based upon the work supported by the Russian Science Foundation, grant 18-12-00329.

References

[1] A. Loarte et al., Nucl. Fusion 47 (2007) S203–S263.

[2] S.I. Krasheninnikov et al., Phys. Plasmas 23 (2016) 055602.

[3] J.L. Terry et al., Phys. Plasmas 5 (1998) 1759–1766.

[4] D. Reiter et al., J. Nucl. Mater. 313–316 (2003) 845–851.

[5] V. Kotov et al., Contrib. to Plasma Phys. 46 (2006) 635–642.

[6] A.A. Pshenov et al., Phys. Plasmas 24 (2017) 072508.

[7] A.A. Pshenov et al., Nucl. Mater. Energy 12 (2017) 948–952.