

## Cross-field plasma transport in divertor and divertor plasma detachment

A.A. Pshenov<sup>1,2</sup>, A.S. Kukushkin<sup>1,2</sup>, S.I. Krashennnikov<sup>2,3</sup>

<sup>1</sup> *NRC “Kurchatov Institute”, Moscow, Russian Federation*

<sup>2</sup> *National Research Nuclear University MEPhI, Moscow, Russian Federation*

<sup>3</sup> *University of California San Diego, San Diego, USA*

### I. Introduction

Detached (or partially detached) divertor regime is currently considered mandatory for ITER and future tokamak-reactors [1]. Its realization relies on intensive power loss by the impurity radiation from divertor volume [2]. In tokamaks with carbon PFCs the main radiation loss is usually due to carbon, sputtering of which is virtually uncontrollable. In tokamaks with metal walls (e.g. JET) radiation loss with impurity generated by sputtering of the PFCs is relatively small. In order to reach divertor detachment, one has to inject impurities (e.g. nitrogen or neon). As a result, the amount of impurity becomes a controllable parameter. However, impurity localization and, therefore, the radiation loss in divertor volume is determined by an interplay of drifts and classical parallel and anomalous cross-field transport. Simple models (see for example [3]) predict that the cross-field heat transport can significantly enhance the impurity radiation loss in relatively cold divertor plasma, where parallel heat conduction is limited.

While there are some experimental data on and theoretical models of the physics of anomalous cross-field plasma transport in the main chamber of the scrape-off layer (SOL), the information on anomalous cross-field plasma transport in divertor volume is very limited. Meanwhile turbulent transport in divertor volume can differ from the one in the main chamber of the SOL dramatically due to strong magnetic shearing in vicinity of the X-point and very different plasma conditions in the divertor. To shed some light on the consequences this difference might have for the divertor plasma detachment process we perform scoping studies using the SOLPS4.3 code suite [4] as the test bed.

### II. Modeling setup

We use two different geometries in the present study. One is built around DIII-D-like magnetic equilibrium (Fig. 1a) and is characterized by the relatively short divertor legs, the other one is built around AUG magnetic equilibrium (Fig. 1b) with the divertor legs elongated significantly. “Closed box” approximation is used. Hence it is natural to describe

the edge plasma parameters as a function of total hydrogen inventory in the edge (including

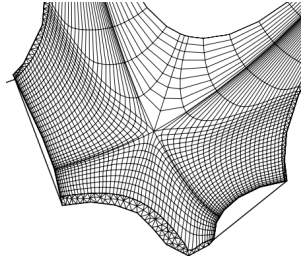


Fig. 1a. DIII-D like divertor configuration

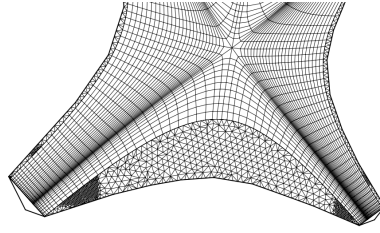


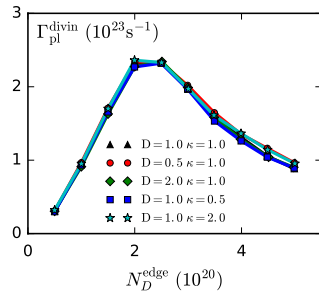
Fig. 1b. AUG-like divertor configuration

both ions and neutrals),  $N_D^{\text{edge}}$ .

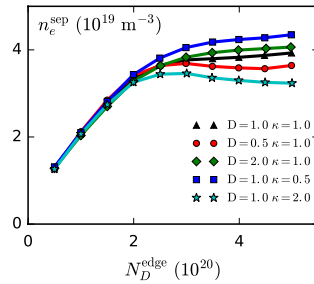
Whereas more relevant to the experiment  $n_e^{\text{sep}}$  description can be deduced afterwards. Neon is chosen as the seeded impurity; its inventory in the

edge is fixed at  $N_{\text{Ne}}^{\text{edge}} = 0.02 \times N_D^{\text{edge}}$ . Power coming to the edge through the separatrix,  $Q_{\text{SOL}}$ , is set to 4 MW for pure deuterium cases and 8 MW for impurity seed ones. The anomalous cross-field particle and heat diffusivities are set constant,  $D_{\perp} = 0.3 \text{ m}^2/\text{s}$ ,  $\kappa_{\perp}^{(e,i)} = 1 \text{ m}^2/\text{s}$  in the main chamber SOL for both deuterium and neon. In the divertor volume multipliers are applied increasing/decreasing  $D_{\perp}$  or  $\kappa_{\perp}^{(e,i)}$  by factor of 2. The SOLPS4.3 code package is used; therefore neither drifts nor currents are present in the modeling reported here.

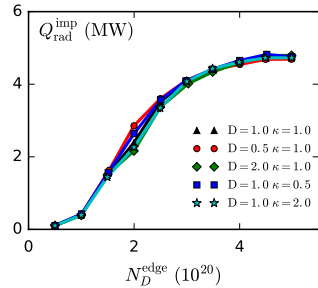
### III. Pure deuterium plasma



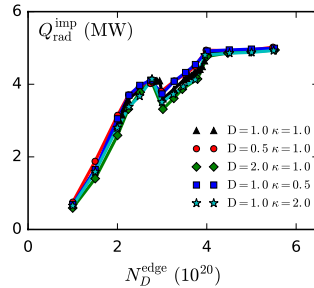
**Figure 2.** Plasma flux to inner target as a function of  $N_D^{\text{edge}}$  for DIII-D like configuration.



**Figure 3.** Separatrix electron density as a function of  $N_D^{\text{edge}}$  for DIII-D like configuration.



**Figure 4.** Neon impurity radiation loss as a function of  $N_D^{\text{edge}}$  for AUG like configuration.



**Figure 5.** Neon impurity radiation loss as a function of  $N_D^{\text{edge}}$  for AUG like configuration.

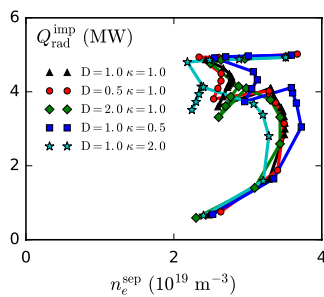
For the pure deuterium plasma changes in divertor cross-field heat and particle transport have no impact on the plasma flux to the divertor target,  $\Gamma_{\text{pl}}$ , and the detachment onset as a functions of  $N_D^{\text{edge}}$  for both DIII-D and AUG like configurations (Fig. 2). That is not surprising since the energy available for the ionization remains the same and deuterium “ionization cost” is not too sensitive to the cross-field transport coefficients. On the other hand “upstream” (i.e. separatrix) parameters are

noticeably affected by the changes in the cross-field transport. In Fig. 3 the average electron

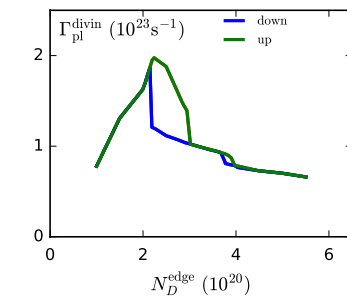
density at the separatrix,  $n_e^{\text{sep}}$ , as functions of  $N_D^{\text{edge}}$  is shown for the different values of the divertor heat and particle cross-field transport coefficients in the DIII-D like configuration. One can see (Figs. 2,3) that difference in the “upstream” parameters becomes especially pronounced after the inner divertor detachment. This result can be explained with the local detachment criterion introduced in [2], where it was shown that the detachment onset is controlled by the ratio of the “upstream” plasma pressure,  $P_{\text{up}}$ , to the specific power flux entering recycling region,  $q_{\text{recycl}}$ . For example, with the increase of the cross-field heat transport in divertor  $q_{\text{recycl}}$  would decrease, leading to decrease of  $P_{\text{up}}$ . Associated decrease of the “upstream” plasma density,  $n_{\text{up}}$ , with  $\kappa$  in the main chamber SOL remaining unaffected by the divertor cross-field transport multipliers, would result in weakening of the radial heat transport in main chamber SOL and increase of the “upstream” plasma temperature,  $T_{\text{up}}$ . This in turn would increase  $n_{\text{up}}$  even further. Decrease of the anomalous particle transport coefficient would have similar effect since increasing density on the most loaded flux tubes, where the ionization source is localized, would increase cross-field heat conduction in the divertor. Though this effect is not as pronounced as the direct heat conductivity scaling.

### III. Neon seeded plasma

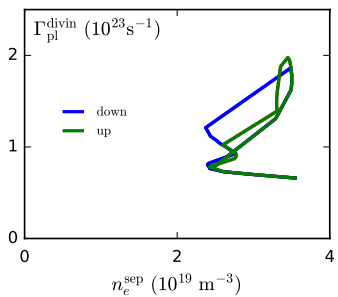
Seeded cases also demonstrate no impact of cross-field transport coefficients in divertor on the detachment onset. Furthermore from Figs. 4 and 5 one can conclude that the impurity radiation loss,  $Q_{\text{imp}}$ , also remains virtually unaffected by the changes in the divertor cross-field transport coefficients.



**Figure 6.** Neon impurity radiation loss as a function of  $n_e^{\text{sep}}$  for AUG like configuration.



**Figure 7.** Plasma flux to the inner divertor target as a function of  $N_D^{\text{edge}}$  for AUG like configuration.



**Figure 8.** Plasma flux to the inner divertor target as a function of  $n_e^{\text{sep}}$  for AUG like configuration.

However, if one looks at the very same scans from the more experiment relevant perspective, where an “input” parameter is  $n_e^{\text{sep}}$ , one can see a strong impact of cross-field

transport on  $Q_{\text{imp}}$  as a function of  $n_e^{\text{sep}}$  (see Fig. 6). Moreover, we find multiple values of  $Q_{\text{imp}}$  for the same  $n_e^{\text{sep}}$ . Furthermore, AUG like configuration shows signs of strong bifurcation-like behavior during transition to the detachment. It is especially pronounced for the onset of the inner divertor detachment (see Fig. 7). The cause of such an abrupt transition is related to the neon transport and localization. At small densities while both divertors remain attached neon is not confined inside the divertor volume and is mostly localized at the low field side (LFS) in SOL and outer divertor. Whereas at sufficiently high densities and small temperatures in the inner divertor large portion of neon becomes locked in the divertor volume. Associated redistribution of radiation causes a jump in densities and temperatures inside divertor volumes. Needless to say that this in turn leads to abrupt change in separatrix parameters. This physical picture being rather clear in terms of  $N_D^{\text{edge}}$  becomes complex when it is expressed through  $n_e^{\text{sep}}$  (Fig. 8).

#### IV. Conclusions

i) Total impurity radiation loss (at least for mid-high Z impurities such as neon) seems to be insensitive to the changes in the divertor cross-field heat and particle transport if it is expressed in terms of total particle inventory  $N_D^{\text{edge}}$ . ii) “Upstream” plasma parameters on the other hand change significantly especially after the inner divertor detachment. Therefore the same data for  $Q_{\text{imp}}$  plotted as a function of more experiment relevant  $n_e^{\text{sep}}$ , demonstrate a strong impact of cross-field transport in divertor volume. iii) AUG like configuration exhibits bifurcation-like behavior during transition to detachment. Abrupt transition to the detached/attached inner divertor state results from the peculiarities of neon transport in the edge plasma. Analyzing such processes from the  $n_e^{\text{sep}}$  perspective is difficult since  $n_e^{\text{sep}}$  is no longer monotonic function of plasma inventory, whereas dependences on  $N_D^{\text{edge}}$  allow more direct interpretations.

**Acknowledgments** This paper is based upon the work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under Award Numbers DE-FG02-04ER54739 at UCSD and the Russian Ministry of Education and Science grant No. 14.Y26.31.0008 at MEPhI.

#### References

- [1] A. Loarte *et al.*, Nucl. Fusion **47** (2007) S203–S263.
- [2] S.I. Krasheninnikov *et al.*, Phys. Plasmas **23** (2016) 055602.
- [3] S.I. Krasheninnikov *et al.*, Phys. Plasmas **5** (1998) 2297.
- [4] A.S. Kukushkin *et al.*, Fusion Eng. Des. **86** (2011) 2865–2873.