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Interpretation of partially detached divertor operation with and without impurity seeding in JET with EDGE2D-EIRENE

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Radiative power exhaust with extrinsic impurities is necessary in ITER to maintain the divertor surface heat fluxes below 10 MW/m^2 while producing 500 MW of fusion power [1]. Reliable prediction of these scenarios for the next step devices relies on model validation with existing experimental facilities. To address these needs, partially detached divertor operation with N_2 and Ne injection in high-triangularity, high confinement mode JET plasmas with both strike points on vertical targets have been experimentally investigated at toroidal magnetic field of 2.7 T and plasma current of 2.5 MA with about 16 – 25 MW of NBI and 3 – 5 MW of ICRH heating [2, 3]. In this study, the divertor characteristics in these plasmas are further dissected and simulated with the multi-fluid code package EDGE2D-EIRENE [4, 5, 6]. The EDGE2D-EIRENE setup, including cross-field transport coefficients, is similar to that used in [7]. The simulation grid in this study corresponds to a high triangularity, vertical target configuration, whereas the grid in [7] corresponded to a high triangularity equilibrium with the low-field side (LFS) strike point on the horizontal target. Further details about the configurations can be found in [2]. Deuterium is injected into the computational domain at the high-field side (HFS) divertor into the common SOL with the puff rate adjusted to provide a LFS mid-plane separatrix electron density of 4.1e19 m^{-3}, at which the model captures the measured LFS divertor saturation currents and strike point electron temperatures in the unseeded plasmas at medium deuterium fuelling rates (about 2.2 – 2.6e22 electrons/s). As in the experiment, the deuterium puff level is not changed when increasing the impurity injection rate in the model. With this setup, the predicted LFS mid-plane electron density and

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[1] *See the appendix of F.Romanelli et al., 25th IAEA FEC, St. Petersburg, Russia, 2014.*

temperature profiles are consistent with the JET high resolutions Thomson scattering measurements in the unseeded plasmas [8]. However, the scrape-off layer (SOL) densities further than 0.5 cm away from the separatrix are underestimated by a factor of 2 compared to the JET Lithium beam (Li-beam) measurements [9]. This is presumably caused by unaccounted SOL transport processes as well as underestimated deuterium ionization sources in the far SOL. These mechanisms are subject to further studies in forthcoming publications. In this contribution, overlapping scans with N and Ne injection, based on this unseeded reference plasma simulation, are conducted and compared to experimental observations. Both impurity species are assumed fully recycling.

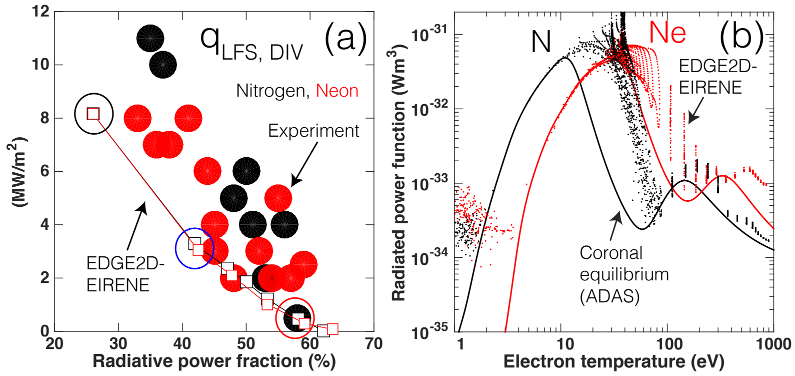

Figure 1. (a) Measured (solid circles) and predicted (connected hollow squares) LFS divertor peak heat flux as a function of radiated power fraction. Since the EDGE2D-EIRENE simulation grid includes only the pedestal and SOL regions, the radiated power fraction used as the x-axis for the simulations is calculated according to the formula $f_{rad}^{EDGE2D\text{-}EIRENE} = (P_{rad}^{EDGE2D\text{-}EIRENE} + 4\ MW)/18MW$, where 4 MW stands for the unaccounted core radiation contribution. The simulation cases representing the unseeded (black), medium-N_2/Ne (blue) and high-N_2/Ne (red) injection cases are circulated with color-coded circles b) The radiated power function for N (black), and Ne (red), as a function of electron temperature in coronal equilibrium (solid lines) and in EDGE2D-EIRENE simulations (dots) in the medium-N_2/Ne injection cases.

The simulations show that, changing only the radiating species while maintaining all the other input parameters unchanged, the LFS divertor peak heat flux, $q_{LFS,DIV}$, is reduced in similar fashion with either N_2 or Ne injection (fig. 1a). This result is qualitatively consistent with experimental observations and obtained in the simulations when adjusting the impurity injection rate to reproduce the experimentally measured levels of radiation. However, whereas the radiative potential of nitrogen peaks around electron temperatures of 10 – 40 eV, reducing to low values at temperatures above this region, the peaking region for neon extends from 20 eV up to 100 eV (fig. 1b). Furthermore, for electron temperatures inside the pedestal ($T_e > 500$ eV), the radiative potential of neon is about a factor of 5 – 10 higher than that of nitrogen. As a result, at impurity injection rates producing partially detached divertor conditions at the LFS divertor plate (the cases with the red circle in the fig. 1a), more than 90% of nitrogen radiation in the computational domain, which extends about 12 cm inside the separatrix at the LFS mid-plane, is predicted to occur in the divertor chamber below the vertical height of Z = -1.2 m, and more than 92% outside the separatrix. Therefore, nitrogen seeding is predicted to enable seeded, partially detached divertor operation in JET with a very minor reduction of the power crossing the separatrix, P_{SOL}. Increasing the nitrogen injection further in the simulations, leads to a transition to a radiation-condensation, X-point MARFE, formation inside the X-point. Once this formation occurs, the nitrogen radiation zone shifts inside the X-point and more than 50% of nitrogen radiation occurs inside the separatrix. However, due to numerical difficulties, these simulations do not reach a converged state. On the other hand, in partially detached divertor conditions with neon injection, less than 50% of radiation is predicted to occur below the vertical height of Z = -1.2 m, and less than 60% outside the separatrix. As a result, at neon injection rates required for substantial reduction of $q_{LFS, DIV}$, substantial reduction of P_{SOL} is also predicted. These findings are qualitatively consistent with experimental observations, where in partially detached nitrogen seeded plasmas (JPN 85274) about 43% of the total radiated power is estimated occur below the vertical height of Z = -1.2m. In contrast, in partially detached neon seeded plasmas (JPN 87181) about 16% of the total radiated power is estimated to occur in this region. Estimating the radiation inside and outside the separatrix, the difference between two seeding species becomes smaller: 34% outside the separatrix with N, 30% with Ne. However, this type of analysis is susceptible to large error-bars due to spatial uncertainties of the bolometric reconstruction in the vicinity of the X-point. The exact divertor radiation fractions differ between the model and the experiment due to the missing core radiation contribution inside the pedestal in the EDGE2D-EIRENE simulations, due to spatial uncertainties in the experimentally estimated radiation distribution, as well as due to possible disagreement in the detailed radiation distribution between the model and the experiment. Nevertheless, a qualitative agreement between the experiment and the model is obtained, and overall these findings are also consistent with recent ITER prediction, conducted with the SOLPS code package, where the operational space with neon seeding is predicted to be more conservative than the operational space with nitrogen seeding, due to the proximity of P_{SOL} in ITER to the H-to-L back transition threshold [10].

When adjusting the impurity injection rate to reproduce the measured radiated power, the simulations capture the experimentally observed particle and heat flux reduction at the LFS divertor plate (fig. 2 a,b). With both nitrogen and neon injection, the dominant particle flux reduction in the detachment assisted by impurities is caused by reduced deuterium ionization and recycling rate, which is possible due to reduced power reaching the deuterium ionization front. The recombination sink is less than 10% of the LFS ionization source in all of the simulated cases. However, the divertor D_α-emission is underestimated by about a factor of 2 in the unseeded plasmas, and about a factor of 3 – 5 in the partially detached conditions, even though the LFS divertor particle fluxes are consistent with measured values. This indicates a shortfall in the deuterium radiation, which is presumably caused by underestimated recombination emission, unaccounted emission related to deuterium molecules, as well as due to other unaccounted D_α-emission channels in the post processing routine in EDGE2D-EIRENE. While in the unseeded plasmas, the overall divertor radiation is underestimated by a factor of 2, with increasing seeding rate the overall measured divertor radiation levels are obtained with both nitrogen and neon. However, as this happens, it is very likely that the deuterium radiation contribution is underestimated throughout the impurity injection scan, as is also indicated by the underestimated deuterium alpha emission levels.

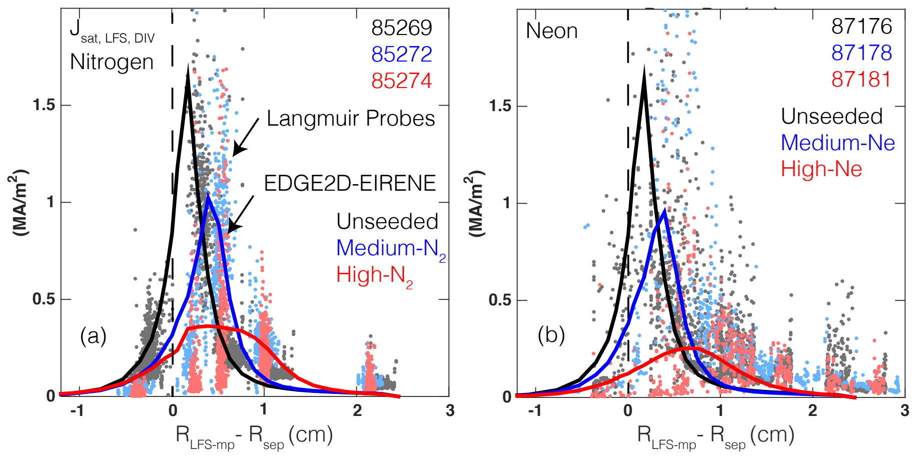

Figure 2. Measured (dots) and predicted (solid lines) LFS divertor saturation currents in the unseeded (black), medium seeding rate (blue), and high seeding rate (red) plasmas with nitrogen (a) and neon (b) injection. The illustrated simulation cases are circled in the figure 1a.

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