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Possible influence of near SOL plasma on the H-mode power threshold[☆]

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ABSTRACT

A strong effect of divertor configuration on the threshold power for the L-H transition (P_{LH}) was observed in recent JET experiments in the new ITER-like Wall (ILW) [1–3]. Following a series of EDGE2D-EIRENE code simulations with Be impurity and drifts a possible mechanism for the P_{LH} variation with the divertor geometry is proposed. Both experiment and code simulations show that in the configuration with lower neutral recycling near the outer strike point (OSP), electron temperature (T_e) peaks near the OSP prior to the L-H transition, while in the configuration with higher OSP recycling T_e peaks further out in the scrape-off layer (SOL) and the plasma stays in the L-mode at the same input power. Code results show large positive radial electric field (E_r) in the near SOL under lower recycling conditions leading to a large $E \times B$ shear across the separatrix which may trigger earlier (at lower input power) edge turbulence suppression and lower P_{LH}. Suppressed T_e's at OSP in configurations with strike points on vertical targets (VT) were observed earlier and explained by a geometrical effect of neutral recycling near this particular position, whereas in configurations with strike points on horizontal targets (HT) the OSP appears to be more open for neutrals (see e.g. review paper [4]).

1. Introduction

There is growing experimental evidence for a strong effect of divertor configuration on the threshold power for the L-H transition (P_{LH}) (see e.g. [1–3] and refs. therein). Recent experiments in JET in the ITER-like (Be/W) wall showed a factor of two reduction of P_{LH} in a configuration with the outer strike point (OSP) on the horizontal tile 5 (hence, 'HT' configuration of pulse #81883) compared to that with the OSP on the vertical target (hence, 'VT' configuration of pulse #84727), see Fig. 1, observed in the high density branch where P_{LH} increases with plasma density. The two magnetic configurations with the plasma current 2.0 MA and toroidal field 2.4 T, as well as plasma parameter profiles, were similar in the core, inside of the magnetic separatrix. Sometimes traces for a pulse similar to the #81883 pulse in the VT configuration can be found in [5].

With no significant difference between global parameters in these two pulses, it was concluded that the explanation for the difference in P_{LH} may be related to a difference of plasma parameters in the extreme edge: in the scrape-off layer (SOL) and divertor. EDGE2D-EIRENE [6–8] simulations reproduced a large difference in experimental target profiles which are described below, leading to a large difference is radial electric field (E_r) which, in turn, may influence plasma turbulence around the separatrix location via $E \times B$ shear [3].

It has to be noted that large differences between target profiles in divertor configurations with strike points on horizontal and vertical tiles were observed earlier in different machines and attributed to different neutral recycling patterns: in VT configurations, neutrals recycling from the target had larger probability to be ionised on flux surfaces hitting the target near the strike point, compared with HT configurations, which appeared to be more open to neutrals (see e.g. review paper [4]). Consequently, measured electron temperature (T_e) had a tendency to peak near the strike point in HT configurations, while being lower at the strike point in VT configurations. One expects similar behaviour in configurations shown in Fig. 1, just that this difference should apply

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[1] See the Appendix of F.Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia.

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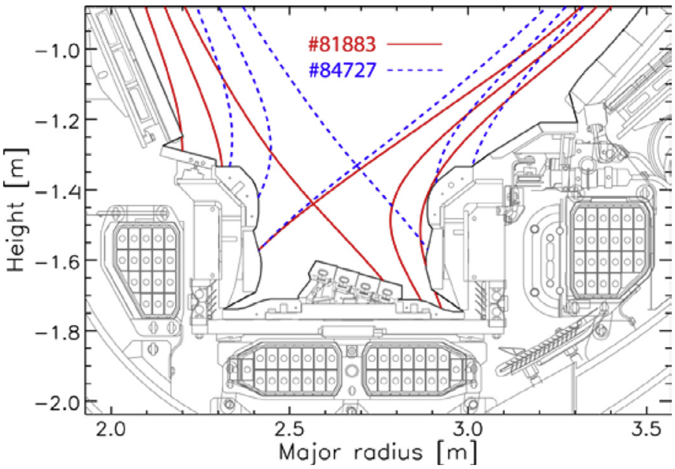

Fig. 1. Magnetic configurations of the HT (#81883) and VT (#84727) discharges in the divertor.

only to OSP, since inner strike points (ISP) are on vertical tiles in both configurations.

2. Setup of EDGE2D-EIRENE cases

EDGE2D-EIRENE grids were built using magnetic equilibria of JET pulses shown in Fig. 1. The grids were optimised for numerical stability of the code runs in the presence of parallel currents and drifts. The optimisation was mainly aimed at avoiding very narrow separation between radial 'rows' in some parts of the grid, e.g. along the row connecting the X-point with the inner target along the separatrix, which resulted in very small cell sizes. Since sharp switching of drifts often leads to numerical instabilities, they were switched on gradually across the entire computational domain. All drifts velocities were multiplied by the coefficient α, which was raised linearly from 0 to 1 over 1 ms time period, which is a standard drift-related option in EDGE2D-EIRENE. Material surfaces in the code runs were assumed as in the ITER-like wall (ILW), and ion species included deuterium (D) and beryllium (Be) with the latter being physically sputtered from the wall. Tungsten (W) was not included in the ion mixture, as W concentrations inside of the plasma covered by the EDGE2D-EIRENE grid were found to be negligible. A neoclassical self-consistent model for E_r was implemented in the core which impeded surface averaged radial currents.

The EIRENE version with Kotov-2008 model [9] was used to describe neutral behaviour. The plasma density was controlled by a combination of gas puff from the PFR and wall recycling ('puff+recycling' option in EDGE2D-EIRENE), aiming at maintaining a specified electron density at the outer midplane (OMP) position of the separatrix, $n_{e,sep}$. Due to some difference in line average electron density (larger by ~8.5% in the HT pulse), a somewhat higher electron separatrix density at OMP in the HT case, $n_{e,sep} = 1.2e19\,m^{-3}$, compared to $1.0e19\,m^{-3}$ in VT, was specified. These choices were partly motivated by the known effect of a non-linear dependence of $n_{e,sep}$ on line-average density at low to medium densities, and partly by the desire to match target profiles measured by Langmuir probes.

The input power into the grid was set at 2.7 MW in both cases, to match experimental power balance. In the code, the input power was equally split between ion and electron channels.

Divertor and target plate parameters in EDGE2D-EIRENE cases are strongly influenced by arbitrarily specified anomalous transport coefficients. Between ion and electron heat conductivities, and particle diffusion coefficient, often the relation $\chi_{e,i} = 2/3D_\perp$ is assumed. At the same time, in recent EDGE2D-EIRENE simulations of JET -L-mode plasmas it was found that better match with target Langmuir probe measurements can be achieved if $\chi_e \approx D_\perp$ across most of the SOL and PFR is assumed, with $D_\perp$ being reduced in the outer core and SOL regions around the separatrix position [10]. In the simulations described here, the following transport coefficients were assumed: $D_\perp = 1\,m^2\,s^{-1}$ and $\chi_i = 2\,m^2\,s^{-1}$ across the whole grid, $\chi_e = 1\,m^2\,s^{-1}$ everywhere except for the main SOL (not including the divertor) where it was reduced to $0.5\,m^2\,s^{-1}$.

Physical sputtering model for Be impurity was assumed. In all EDGE2D-EIRENE cases, however, Be radiation represented only a few percent of the total radiated power which was dominated by the deuterium Lyman alpha radiation. The same result comes from the experiment [11]. Also, target $T_{e,i}$ and n_e profiles in cases with Be were quite close to those with pure deuterium.

Catalogued EDGE2D-EIRENE cases can be found in: alexc/edge2d/jet/81883/nov1015/seq#1 for HT and alexc/edge2d/jet/84727/nov1015/seq#1 for VT configurations.

3. Comparison between EDGE2D-EIRENE output and experimental results

Fig. 2 shows experimental Langmuir probe and EDGE2D-EIRENE simulated target profiles of T_e, n_e and ion saturation current j_{sat} along inner and outer targets in both configurations, mapped to radial positions at OMP. The profiles are plotted vs. distance from the separatrix (strike points on both targets) which are indicated by horizontal dash-dotted lines mapped to positions at the OMP. Due to uncertainties in the equilibrium reconstruction experimental profiles were arbitrarily shifted (IT profiles by 0.5 cm in both HT and VT cases, and OT profiles by 1.2 cm in the HT and 1.7 cm in the VT case, all shifts towards the high field side) and their positions on the targets were converted into distances from the separatrix using linear interpolation based on EDGE2D-EIRENE positions.

The most important feature of the code results is a much more peaked T_e at OT in the HT configuration, obtained for the same input parameters as in VT (even, in the more challenging setup, with a 20% higher $n_{e,sep}$). This is related to the recycled neutrals being ionised more strongly along the separatrix in the VT, compared to HT configurations, which is a purely ballistic effect of recycling neutrals [4]. This results in lower target T_e and higher target n_e near strike points at outer target (OT) in the VT compared to the HT configuration. At the inner target (IT), the situation regarding code to the experiment comparison is similar for the two configurations, since the configurations are almost the same on the inner (high field) side. It has to be noted that results analyzed in [4] were obtained in machines with carbon walls, while experimental and code results presented here are obtained in the ILW environment on JET. One of the consequences of this change is the loss of the intrinsic radiator (C) in ILW: W concentrations in the SOL and divertor are negligible, while some Be sputtering from the main chamber (Be) wall doesn't lead to high enough radiation losses which would strongly influence the radiation pattern established by the main working gas (usually D) radiation. As a result, an introduction of non-intrinsic impurities (N, Ne etc. gases) is required to increase radiation in the SOL and divertor. All these aspects, focusing on the difference between the C and ILW environments are discussed in the review paper [12].

In the HT configuration, all code OT parameters are more peaked near the strike point and larger than experimental ones in the common flux region (CFR), on the main SOL rings. According to the probes, there exists the plasma in the private flux region (PFR), especially at the outer target, which is not seen in the code output. The reason for this strong discrepancy may be related to deficiencies of the transport model used in the code or the neglect of neutral leakages from divertor structures (see [12] and refs.

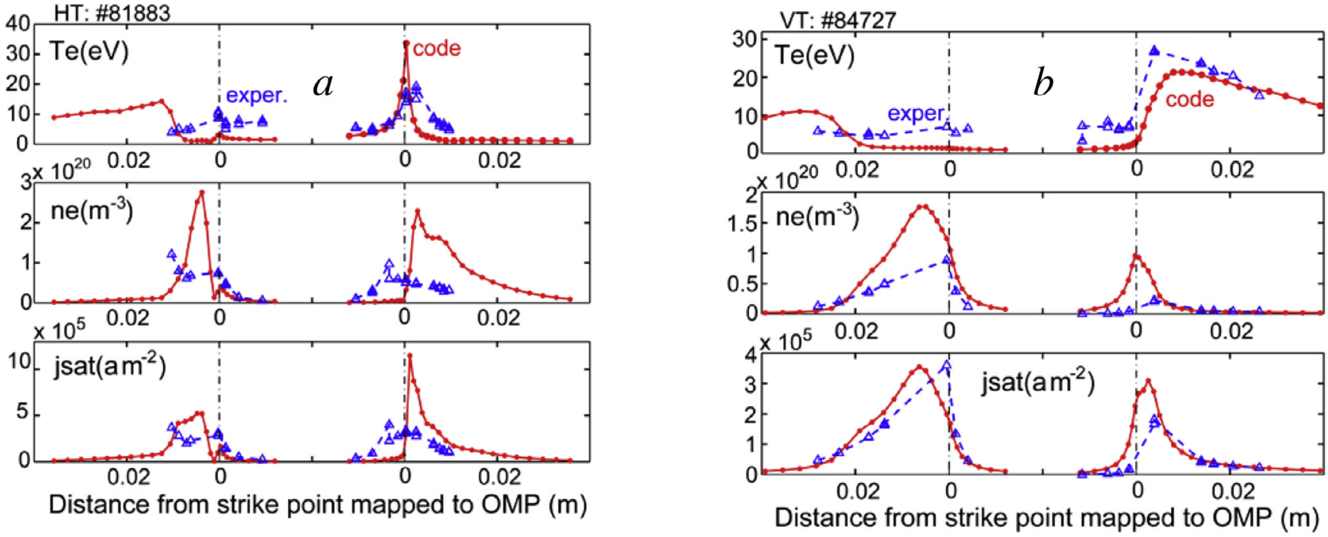

Fig. 2. Experimental (triangles) and EDGE2D-EIRENE (dots) target profiles of electron temperature (T_e), electron density (n_e), and ion saturation current density (j_{sat}) in HT (a) and VT (b) configurations. Note the inverted X-scale for the left target.

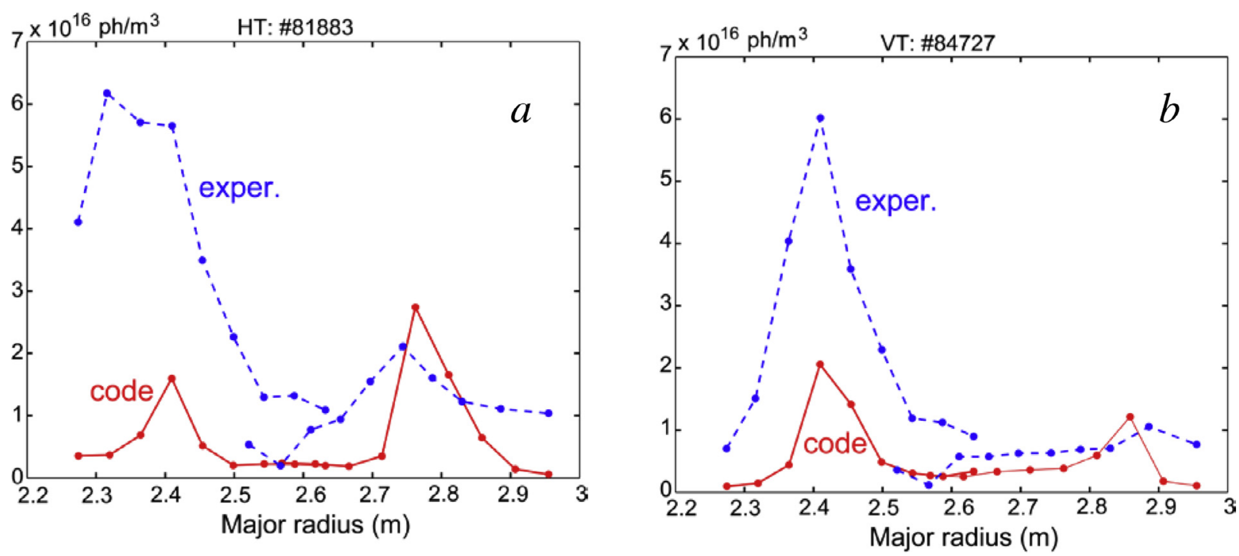

Fig. 3. Measured (blue dotted line) and simulated (red solid line) D_α emission profiles in the divertor in HT (a) and VT (b) configurations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

therein). The probe point with the largest j_{sat} at OT is unreliable. At IT probe target T_e's near the strike point and in the PFR are much greater than the code values. It is known however that Langmuir probe T_e's below ~5 eV are unreliable. This may partly explain the discrepancy in IT n_e, as lower experimental T_e would imply higher n_e, closer to the code values (note that j_{sat} values are fairly well matched at IT). At OT in both cases, the code n_e is much greater than experimental values, which can be attributed to an underestimate of the degree of detachment in the code, evidenced by factor two higher j_{sat} in the code than in the experiment. The degree of detachment at the target is often underestimated in 2D fluid codes (see e.g. [13]).

A better match between the code and experiment is achieved in the VT configuration. Still, at OT j_{sat} is overestimated by the code, and due to somewhat lower code T_e, n_e is overestimated even stronger. Again, as in the case of the HT configuration, probe T_e's do not fall significantly below 10 eV and, as commented above, such relatively high values can't be trusted, especially deep in the PFR.

Fig. 3 shows experimental and simulated D_α emission profiles along vertical channels looking into the divertor. Fairly reasonable match between the experiment and simulations is seen at OT in both configurations, taking into account all uncertainties associated with the neutral model and perpendicular transport coefficients adopted in EDGE2D-EIRENE runs. A considerable discrepancy can be seen at IT, with experimental D_α emission being much higher, indicating a much stronger degree of detachment at this target in the experiment compared to the code simulations. The D_α radiation shortfall in the modeling has been reported earlier and related to an insufficient target T_e drop in the code, which, in turn, may be related to molecular power loss terms which are presently not properly accounted for in EDGE2D-EIRENE, see e.g. [14–16].

4. Radial electric field (E_r) profile along outer midplane from EDGE2D-EIRENE output

Experimental E_r data for the pulses analysed in this paper are unavailable. Fig. 4 shows E_r profile vs. distance from the separatrix

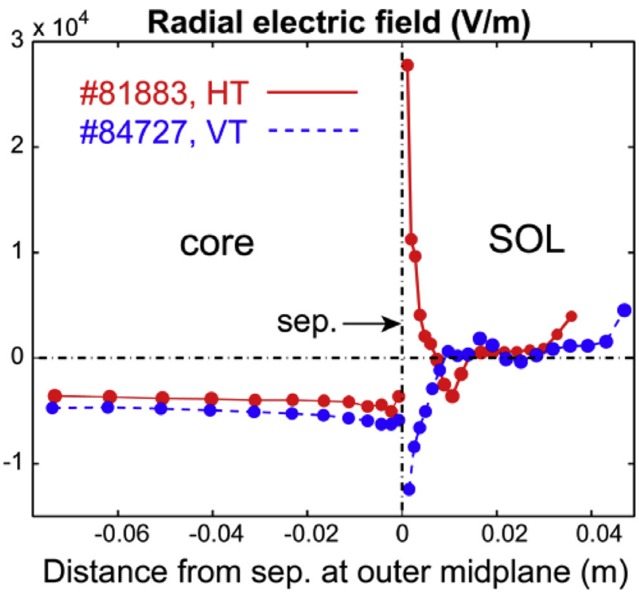

Fig. 4. Simulated E_r profiles along OMP for HT and VT configurations.

along OMP calculated by EDGE2D-EIRENE. The clear difference between the two cases can be seen, with the case in HT configuration showing a large positive E_r spike near the OSP, with large positive values also in a few other, adjacent positions in the near SOL. This can be related to a spike in T_e in this configuration causing positive plasma potential upstream of the target which is to a large extent attributed to the potential sheath drop at the target $|eV_{sh}| \sim 3T_e$. Since an electrically conducting target (W) has constant potential, positive $E_r \equiv -\nabla_r V_{sh}$ in the plasma emerges for radially decaying T_e in the SOL. In contrast, in the VT configuration E_r is negative in the near SOL, since T_e rises radially. In the outer core $E_r < 0$, caused by ion pressure and temperature gradients (no toroidal momentum input was assumed in the code runs). A particularly large shear of poloidal $E_r \times B$ rotation is therefore formed near the separatrix in the HT configuration.

In Fig. 4 E_r values at the first SOL ring outside of the separatrix (ring 's01') are not plotted. This has to do with the way E_r is calculated in the code. On the core (poloidal) rings the primary value is E_r: the self-consistent neoclassical solution for E_r ensures zero surface averaged radial electric currents between rings. Plasma potentials are calculated later using E_r values. In contrast, in the SOL electric potential is the primary quantity, calculated assuming zero target potential and taking into account parallel electron momentum balance equation and a possibility of electric currents to the target surface. E_r in the SOL is then calculated by subtracting potentials between neighboring rings. Calculation of E_r on ring s01 therefore requires subtraction of the potential on the outermost core ring (c01) from that on ring s02, which is the second ring in the SOL. In EDGE2D-EIRENE no model is used to electrically connect the two topologically disconnected regions: core and SOL, and an arbitrary value can be added to potentials in the core. For plotting the potential across both core and SOL, potentials are assumed equal on rings c01 and s01 at the OMP position. This arbitrary electrical link between the regions creates an uncertainty in the E_r calculation at ring s01. For this reason E_r values on rings s01 are ignored. Positions of points c01, s01, s02 and s03 at the equatorial plane with respect to the separatrix position are: −0.07, 0.04, 0.11 and 0.19 cm, which ensure good spatial resolution even in the absence of the E_r data at position s01.

5. Discussion

The main purpose of the EDGE2D-EIRENE modeling activity was to compare HT and VT configurations for the same modeling assumptions about power flow into the computational domain, separatrix density, plasma-wall interaction, neutral behaviour etc., since the focus was on the effect of neutrals in the two different magnetic configurations. At the same time, code results were to be obtained under conditions which are relevant to JET pulses at power levels where the plasma in the HT configuration goes into the H-mode, while in VT configuration it stays in the L-mode. This determined the choice of separatrix densities and transport coefficients in EDGE2D-EIRENE simulations.

The clear difference in T_e profiles at outer targets between the two configurations has been observed and interpreted earlier, as explained in the Introduction section. In the present code simulations strong difference in target profiles expected in HT and VT configurations is seen even though $n_{e,sep}$ was chosen to be higher in HT compared to the VT configuration, emphasising a very strong impact of the divertor configuration on neutrals behaviour and their impact on target T_e profiles and E_r at the OMP.

It is worth noting that the peak T_e value at OT is probably not so important, from the viewpoint of the mechanism of turbulence suppression by the $E \times B$ shear, if it is achieved farther in the 'outer SOL', where plasma densities and temperatures are much lower than in the 'near SOL'. The main difference in E_r profiles between the two configurations, with the much larger $E\times B$ shear around the separatrix location in the HT configuration, is due to different neutral behaviour at the OSP and immediately upstream of this position, which seem to be the key locations for this mechanism.

In JET experiments it is observed that, as the input power is raised, the L-H transition is preceded by detachment at the inner target [3]. EDGE2D-EIRENE runs were unable to simulate the inner target detachment, and the inner target T_e was constantly increasing with the input power. This may indicate missing elements in the plasma or neutral models of the code, or the need to higher transport coefficients at high input powers. Test EDGE2D-EIRENE cases with transport coefficients varied proportionally to the input power have however failed to simulate stronger inner target detachment with increase in the input power.

6. Summary

There is growing experimental evidence from a number of machines for a strong effect of divertor configuration on the threshold power for the L-H transition (P_{LH}). Recent experiments in JET in the ITER-like (Be/W) wall showed a factor of two reduction of P_{LH} in a configuration with the outer strike point (OSP) on the horizontal target (HT) compared to that with the OSP on the vertical target (VT) observed in the high density branch where P_{LH} increases with plasma density (for the 'high density branch' see e.g. linearly rising part of P_{LH} vs. multi-machine Martin's scaling for input powers above 2.5 MW in [17]). The two magnetic configurations and plasma parameters were similar in the core.

In search of a possible explanation for the P_{LH} difference, EDGE2D-EIRENE code simulations with drifts aimed at reproducing Langmuir target profiles and D_α emission in the divertor, but having the same transport coefficients for the two configurations, were carried out. Both in the experiment and in the code simulated outer target T_e shows a spike at the OSP and then decay across the SOL in the HT configuration, whereas in the VT configuration T_e is low at the OSP and rising in the near SOL (first ~0.7 cm), with peak target T_e's being similar in the two cases (20–25 eV). The effect of recycling neutrals on target T_e profiles in different divertor configurations was studied earlier and attributed to the ionisation pattern of recycling neutrals: whether they are recycled towards the field line striking the target at the separatrix location or away from it.

The difference in target T_e profiles results in the difference of E_r profiles in the SOL, due partly to the effect of the potential sheath drop: $|eV_{sh}| \sim 3T_e$, hence $E_r \equiv -\nabla_r V_{sh} > 0$ for the HT and < 0 for the VT configuration, for constant target potential. With negative E_r in the outer core, a positive E_r spike in the near SOL, just outside of the separatrix, generates a particularly large poloidal $E \times B$ shear in the HT configuration. It is hypothesised that the extreme edge $E \times B$ shear effect on the local turbulence suppression may have an impact on the L-H transition, leading to lower P_{LH} in divertor configurations with less ionisation of recycled neutrals at the strike point and upstream of it.

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