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ABSTRACT:

The ITER-like Wall project in JET is replacing its Plasma Facing Components (PFCs) currently made of Carbon-Fibre Composite (CFC) with bulk beryllium main-chamber limiters and full tungsten divertor. Experiments on JET have prepared to explore the domain of moderate exhaust for acceptable impact upon plasma performance on standard high δ ELMy H-mode discharges. Systematic studies were carried out on the individual effects of deuterium fuelling and seeding with two extrinsic impurities, as well as their interplay. An operational domain was achieved where this baseline scenario suffers less than 10% decrease in the pedestal stored energy and is both compatible with the ILW engineering limits and in the domain of low W sputtering. Nitrogen (N2) may be preferable as an extrinsic radiator to neon (Ne) as it mostly affects the divertor radiation without significantly increasing core radiation. In the non-carbon machine, deuterium fuelling alone is unlikely to reach this operational domain as it is just able to reach it in the present machine, hence extrinsic impurities would then have to be used.

1. INTRODUCTION

The ITER-like Wall (ILW) project in JET is replacing its Plasma Facing Components (PFCs) currently made of Carbon-Fibre Composite (CFC) with bulk beryllium main-chamber limiters and a full tungsten (W) divertor, the material selection for the DT phase in ITER [1]. This poses a severe challenge for scenario development. The first direct concern is to reduce PFC steady-state power loads in order to keep within the engineering limits for the ILW [2]. The second concern is to limit the impurity production from the new PFCs to maintain plasma performance, in terms of dilution by beryllium (Be) but more acutely in terms of core radiation from tungsten (W) by reducing the target plasma temperature (target T_e) which governs the sputtering yield for W. Strategies are being developed to address both concerns with the least impact on confinement for the present scenarios. It becomes all the more important in the ILW where the exclusion of carbon, an excellent divertor radiator, will be apt to lead to an increase in power loads and target temperature from present values. Added to that, the concurrent upgrade of the JET neutral beam power from 24MW to 34MW will necessitate active reduction of the exhaust power. An attractive option would be to reduce both power load and target plasma temperature via fuelling and/or radiative impurity seeding.

Since the last IAEA FEC, experiments on JET have explored the domain of moderate exhaust power for the least impact on plasma performance [3,4] for a high-δ 2.7T/2.5MA H-mode scenario. Systematic studies were carried out on the individual effects of deuterium fuelling and seeding with two extrinsic impurities, as well as their interplay. An operational domain was achieved where this baseline scenario suffers less than 10% decrease in the pedestal stored energy (W_{ped}) and is both compatible with the ILW engineering limits and in the domain of low W sputtering [3]. It is shown that to reach this operational domain, nitrogen (N) may be preferable as an extrinsic radiator to neon (Ne) as it mostly affects the divertor radiation without significantly increasing core radiation. In the non-carbon machine, deuterium fuelling alone is unlikely to reach this operational domain as it is just able to reach it in the present machine, hence extrinsic impurities would then have to be used. The plasma transition to type III ELMs sets an upper boundary on the fuelling and seeding levels required to access this operational domain. It is expected that the presence of W will set in addition a lower boundary to moderate the W source and its transport to the separatrix.

2. EXPERIMENTAL SETUP AND COMPATIBILITY OF REFERENCE BASELINE SCENARIO WITH JET ILW

This paper concentrates on the baseline ELMy H-mode scenario at 2.7T/2.5MA, q_{95}~3.5, P_{in} ~ 16MW with high triangularity δ~0.4, and at Greenwald density fraction f_{GDL} ~ 1. The divertor configuration has been developed such that the outer strike-point is moved to the tile capable of bearing highest power loads, in preparation for the JET ILW. Enhanced diagnostic capabilities to monitor the Outer Target (OT) heat flux by means of a fast Infra-Red thermographic camera (IR) [5], OT ion flux from Langmuir Probes (LP) [6], pedestal and core Te and ne profiles with High Resolution Thomson Scattering [7], ion temperature profiles and impurity concentration with Charge Exchange Spectroscopy [8]. Steady-state discharges were obtained with the requisite range of fuelling and impurity seeding levels in feed-forward scans of deuterium (4×10^{21} to 6×10^{21} el/s), nitrogen (0.0 to 4.3×10^{22} el/s) and neon (0 to 4×10^{21} el/s) fuelling rates. Throughout the experiments, reference discharges were used to monitor possible legacy effects due to the seeding of N_2 in particular.

The ILW divertor will consist of a W-coated CFC side with a bulk W main plate, composed of 4 toroidal rings or “stacks” to receive the outboard strike point [1]. The ILW engineering limits to steady-state and transient power loads on the W-divertor are complex and described in details in [2]. A simplified description of those limits directly relevant to the reference discharge is as follows. The bulk W limits are, in a first phase, to keep the surface temperature below 1200^oC, inclusive of ELM-periods, and in a second phase, when this limit will have relaxed to 2200^oC, the incident energy on each stack will be restricted to 50MJ [2]. The W-coated CFC tile on which the inner strike point is located for high-δ scenario will be limited to a surface temperature below 1200^oC including ELM-period and incident ELMs should not exceed $330kJ/m^2$. For the reference discharge considered, the surface temperature of the OT stays below 900^oC, the estimated incident energy on each stack would not rise above 9MJ. Although, no IR measurement of the IT are available due to viewing restriction of the inner divertor [5], strong detachment of the IT is suggested with line integrated radiation measured with bolometry combined with Dα line intensity. Finally, the average peak energy density on the OT (ε_{max}) of $45kJ/m^2$ is an order of magnitude below the limit of incident energy for the IT. The reference scenario considered here is already within the steady-state limits, in the present carbon machine. The power crossing the separatrix P_{sep} (= $P_{in}-P_{rad,core}$, respectively 16MW and 5MW) is about 11MW. In the inter-ELM-period, a fraction of 0.22-0.30 of P_{sep} ($f_{div,OT} = P_{Div,OT}/P_{sep}$) is incident on the outer divertor target, where it is deposited on a wetted area of 0.3m2, leading to a peak heat flux of $\sim 11MW/m^2$.

The second aspect to consider is to maintain plasma confinement by limiting the impurity production from the new PFCs. The W concentration cW needs to remain below 10^{-5} to avoid excessive radiation losses in the core plasma [9]. The W release is governed by impurity ions due to their threshold energy for W sputtering being an order of magnitude lower than that for deuterium. The sputtering yield for impurity ions such as C^{4+}, Ne^{4+}, rises dramatically for plasma temperature above 3-5eV. In other words, the inter-ELM-period the W source will be minimized for plasma conditions with partial or full detachment. Once this is achieved, the W source will be primarily determined by ELMs [10]. A peak target Te of 45eV was measured in the inter-ELM-period for the reference discharge. This measurement can be quoted with enhanced confidence as the power load measurements of the LP are in good agreement with those obtained from IR thermography. This means that although the reference discharge is compatible with the ILW power limits, it is unlikely to be able to maintain its energy confinement with the ILW PFCs, without steps to reduce the W source.

3. DOCUMENTATION OF IMPACT OF FUELLING AND SEEDING IN ELMY H-MODE DISCHARGES

Scans of fuelling and seeding rates were performed for the reference ELMy H-mode scenario in order to identify the domain of compatibility with the JET ILW with the acceptable impact on plasma performance. As a criterion for comparing the effects of fuelling and seeding, target conditions compatible with ILW operation were sought for a decrease of less than 10% in W_{ped} value from the reference-discharge value. In this paper, W_{ped} is the sum of both electron and ion contribution. Deuterium fuelling: With deuterium fuelling alone at a level up to 4.5×10^{22} el/s, it is possible to decrease moderately the inter-ELM-period fraction $f_{div,OT}$ reaching the OT for the inter-ELM-periods from 0.22-0.30 down to 0.17. However, the increase in the IR measured wetted area by 40% from 0.35 to 0.6 m^2 leads to a decrease of the peak heat flux density by 3.6 from ~11 to 3MW/m^2. More importantly for the expected W influx, the target Te decreases from 45eV during the inter-ELM-period down to ~ 10eV with no degradation in W_{ped}. It should be mentioned that the value quoted here is not measured by the LPs, as the latter measurement is affected at deuterium fuelling levels higher than the reference level [11]. Rather, it is determined from the ratio of IR power flux profiles and ion saturation current assuming a sheath transmission factor of 7. Excellent agreement between these two values was achieved for the reference discharge giving confidence in the use of this method. At the highest level of fuelling of ~ 6×10^{22} el/s, a 20% decrease in W_{ped} from the reference scenario is observed, with ELMs exhibiting a compound nature as shown from their frequency, a common sign of approaching the type III ELM regime [12]. In the present carbon machine, deuterium fuelling alone is only just able to increase divertor radiation enough to reduce the target T_e below 10eV whilst keeping within 10% of the Wped reference value. As carbon is a powerful radiator in the temperature range typical of the divertor plasma, its exclusion or drastic reduction with the ILW will be apt to lead to higher power loads and target temperatures. It is unlikely that deuterium fuelling alone will allow an acceptable operational domain to be achieved, ie extrinsic impurity seeding will have to be used in addition. During this fuelling scan from the reference level to 4.5×10^{22} el/s, a recognized transition from type I to I/II ELM is observed for this high δ scenario [13] with increased Wped (via increased pedestal density), unchanged core stored energy and, importantly for this discussion, with decreased ELM frequency and increased ELM size from 180kJ to 300kJ, although εmax keeps above 45 kJ/m^2. The radiative fraction is only just increasing from 0.45 to 0.55 in this scan. It is interesting to note that the compound ELMs appear in the deuterium fuelling scan when the ion flux has saturated marking onset of detachment.

3.1.NITROGEN SEEDING

An operational domain of compatibility with the ILW has been identified with nitrogen seeding at a rate of ~2×10^{22} el/s and deuterium fuelling at 2×10^{22} el/s (see Figure 2). The fraction $f_{div,OT}$ reaching the OT during the inter-ELM-period can be reduced from 0.22-0.30 down to below 0.10, corresponding to a peak power below 1MW/m^2 and within the measurements uncertainty of the IR camera. An increase is observed in wetted area by 70% from 0.35 to ~1.3 m^2 is also observed and the target Te is reduced down to below 10eV. The sharp drop in the OT ion flux observed between the 1.3×10^{22} to 2×10^{22} el/s fuelling levels is indicative of the onset of inter-ELM detachment, see Figure 2. In fact, the OT ion flux profiles show that when inter-ELM-period peak ion flux drops below 0.5 MA/m^2, the ionisation front has moved away from the strike-point position, and the plasma is either partially or fully detached. In this operational domain, the average ELM size is comparable to the reference discharge of ΔW_{ELM}~13% Wped and with εmax in the range of 40-60kJ/m^2. At the highest level of N_2 seeding of 4×10^{22} el/s and for all deuterium fuelling levels, W_{ped} drops by 30% from its reference value, indicating a transition to the type-III ELM regime. This is confirmed by MHD stability analysis of the pedestal profiles, which shows that the pressure gradient and current density stay well below the critical pressure gradient and current density as calculated by peeling-ballooning stability theory [14][15]. As in the case of deuterium fuelling only, the radiative fraction is increased modestly from 0.45 to 0.55 when reaching the operational domain and then to 0.6 at the transition to type III ELM regime.

3.2. NEON SEEDING

A scan of the neon seeding and fuelling rates was also carried out, although only a subset of the data is shown in Figure 3 for which the input power is comparable to the nitrogen series and within the range of 16 to 17.5MW. Focusing on the search for an operating domain for the ILW with a Wped within 10% of the reference value, the best parameters were with a neon seeding of rate 0.15×10^{22} el/s and a fuelling rate of 2.5×10^{22} el/s. At this point, the fraction $f_{div,OT}$ between ELMs is only reduced to 0.13 and not below 0.1 as was the case for nitrogen. Due to poor quality, the LP ion flux measurement are not available from this seeding scan to confirm that the plasma was still attached. But in support of this, the inter-ELM-period wetted fraction is below 1m^2, in contrast to above 1.5m^2 for a fuelling level of 4×10^{22} el/s. At this highest level of fuelling, W_{ped} drops by 30% from the reference value, indicative of a transition to the type-III ELM regime, a result also confirmed by stability calculation. As a result, it is unlikely that the domain considered at the fuelling level of 2.5×10^{22} el/s is compatible with a low target temperature. Even more important for the use of this impurity as an extrinsic radiator, depending on the fuelling level, at the same level of seeding of 0.15×10^{22} el/s, the ELMy H-mode can either, reach a type III regime with partial detachment, or stay in a type I regime with increased core radiation (see figure 3). At this neon seeding level, as shown in Figure 4, the core neon concentration decreases from 0.73% down to 0.43% at fuelling levels between 2.5 to 4.5×10^{22} el/s. In the nitrogen series, a moderation of the nitrogen concentration is also observed with deuterium fuelling as shown in Figure 4, but nitrogen is not able to radiate strongly at pedestal temperature and has little capacity to affect core radiation as is the case with neon seeding.

3.3. CORE PURITY

To reach the operational domain compatible with the ILW identified experiments with nitrogen seeding, Z_{eff} is either at a similar level of ~2 as in the reference discharge, or even reduced to ~1.7 at the highest fuelling level as shown in Figure 4. The reason for this is that the carbon concentration in the core plasma is reduced from 3% down to 1.5% whereas the nitrogen concentration is increased from below 0.4% up to 0.6-0.8%.

3.4. DISCUSSION

An operational domain was achieved where the baseline H-mode scenario suffers less than 10% decrease in the pedestal stored energy (W_{ped}) and is compatible with the ILW limits and within the domain of low W sputtering. It is shown that to reach this domain, nitrogen may be preferred as an extrinsic radiator to neon as it mostly affects the divertor radiation without radiating in the main plasma boundary. In contrast neon is able to cause both divertor radiation or radiation in the main plasma boundary depending on the deuterium fuelling level, and as a result complicates the design of a robust scenario.

4. PREDICTION OF SEPARATRIX W CONCENTRATION IN REFERENCE SCENARIO

Above, an operational domain was identified in the machine with a carbon wall for the high-δ baseline scenario at 2.7T/2.5MA compatible with the ILW engineering limits and with a target T_e in the domain of low W sputtering. In these conditions, a scenario would have the lowest W influx, however it could cope with a higher source as long as the W concentration c_W is below 10^{-5} to avoid excessive radiation within the main plasma boundary [9]. The absence or reduction of C in the ILW and the exact impurity mix is difficult to predict, hence it is difficult to give an estimate c_W to be expected in the reference discharge. An estimate cw in the most favourable case can however be attempted as a guide of what can be expected in ILW. It is estimated that even in the most favourable case, i.e. the conditions of reference scenario in the carbon wall, will require additional fuelling to keep the average c_W below 10^{-5}. This estimate has been calculated with the 2D Monte-Carlo code DIVIMP [16], with an updated W sputtering model [17], from EDGE2D-EIRENE background plasmas.

Predictive modelling has been carried out to assess the EDGE2D-EIRENE capability to reproduce both the upstream and target profiles for the reference ELMy H-mode discharge studied here [18], as well as to bolometric measurements and carbon spectroscopy. Match of both the outer target profiles (ion saturation current and electron temperature) and heat loads measured by the infra-red camera, as well as the measured radiated power in the vicinity of the outer target. Although it was already remarkable to achieve such a match for the outer target, the simulated plasma conditions at the inner target are less detached than what is experimentally observed. The EDGE2D-EIRENE predictions were tested in the deuterium fuelling scan carried out in the nitrogen seeding experiment for scenario considered here. It was shown that without altering any input other than fuelling rate, the plasma response for the upstream and target profiles were well reproduced [16]. The simulations provides the background plasma for which cW is estimated with DIVIMP.

DIVIMP W transport calculations were done first for the EDGE2D-EIRENE reference case with carbon, but assuming W target. Tungsten was predominantly sputtered by C^{4+} ions assumed in these simulations at a fraction of 1%. Parallel-B transport is modelled using a force balance between friction and temperature-gradient forces exerted by the background plasma on the W ions, and an ad-hoc radial transport. For the latter, a perpendicular diffusion coefficient is taken of $1m^2/s$. The time evolution of approximately 50000W particles was followed until steady-state was achieved, which provided 2D map of the W density distribution of all 74 ion charges-states, including those along the separatrix. The inter-ELM-period plasma conditions of the reference discharge is estimated to lead to a W influx of $\sim 7\times10^{18}$ particles per s and unit of toroidal length at the targets, as shown in Figure 5. For such a source, the poloidal average of the W concentration would be close to a level of 10^{-4} for the reference case, as shown in Figure 5. This is the lowest estimate of c_W to be expected in the ILW for the reference scenario. Indeed, the absence of carbon in the ILW (or drastic reduction) will lead to increase in $f_{div,OT}$ and target Te. And this estimate does not take into account the W sputtering by ELMs. The reference ELMy H-mode discharges will require at least deuterium fuelling to keep cw low enough. The DIVIMP calculations show that c_W can be decreased by roughly an order of magnitude with the highest deuterium fuelling, down to c_W of $\sim 10^{-6}$ at the separatrix, see Fig.5. This decrease is due both to a decrease of W influx via a decrease of target T_e but also due to a transport effect. In DIVIMP, it is shown that the fraction of the source impurity ions entering the plasma within the separatrix is reduced with deuterium fuelling from ~8% down to 0.3%, as shown in Figure 5.

CONCLUSIONS

Experiments on JET have explored the domain of moderate exhaust for acceptable impact on plasma performance for a high-δ 2.7T/2.5MA H-mode scenario. An operational domain was identified where this baseline scenario suffers less than 10% decrease in the pedestal stored energy and is both compatible with the ILW limits and in the domain of low W sputtering. It is shown that to reach this operational domain, nitrogen may be preferred as an extrinsic radiator to neon as it mostly affects the divertor radiation without significantly increasing core radiation. Deuterium fuelling alone in the absence of carbon will be unlikely to reach this operational domain. The presence of tungsten will modify the identified operational domain by setting a lower limit on the deuterium fuelling and seeding level in order to be able to control its source due to sputtering and transport to the core plasma. Indeed, even more so than neon, W will be able to produce core radiation and probably degrade W_{ped}. A key aim of the ILW project is to determine whether an operating window will still exist between the type III ELM regime and a regime with degraded W_{ped} due to W radiation from the main plasma boundary. The demand of a metal target, essential for fusion reactor in the long terms, present severe challenge to scenario development and strategies for coping with those demands will be one of the aspect investigated with the JET ILW project.

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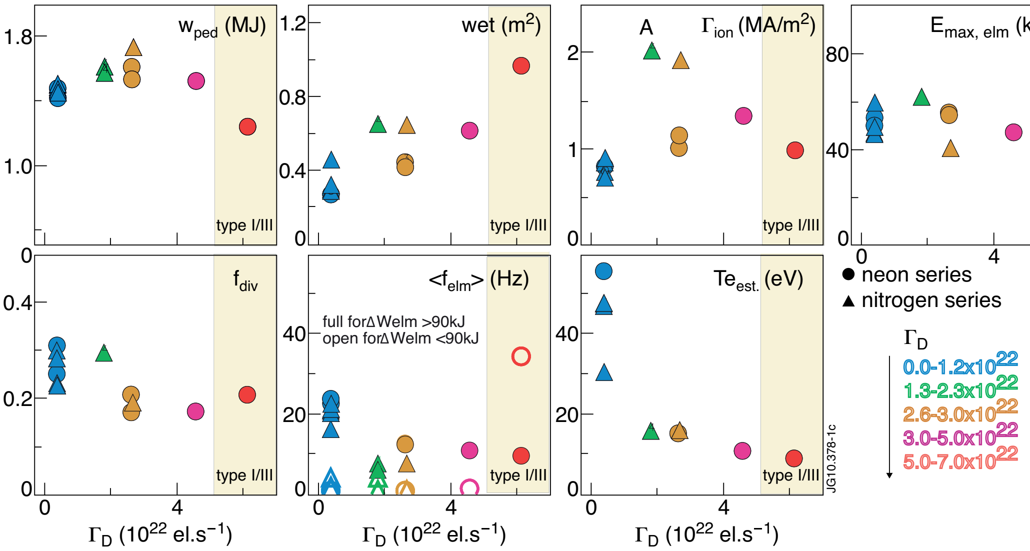

Figure 1: Impact of deuterium fuelling on reference ELMy H-mode: (from top right to bottom left) average stored pedestal energy derived from kinetic profiles, outer target inter-ELM-period wetted area and peak ion flux, average peak ELM energy density at outer target, fraction of Psep delivered to outer target in inter-ELM-period, average ELM frequency for stated criterion of ΔELM, inter-ELM-period peak electron temperature estimated from IR and LP data.

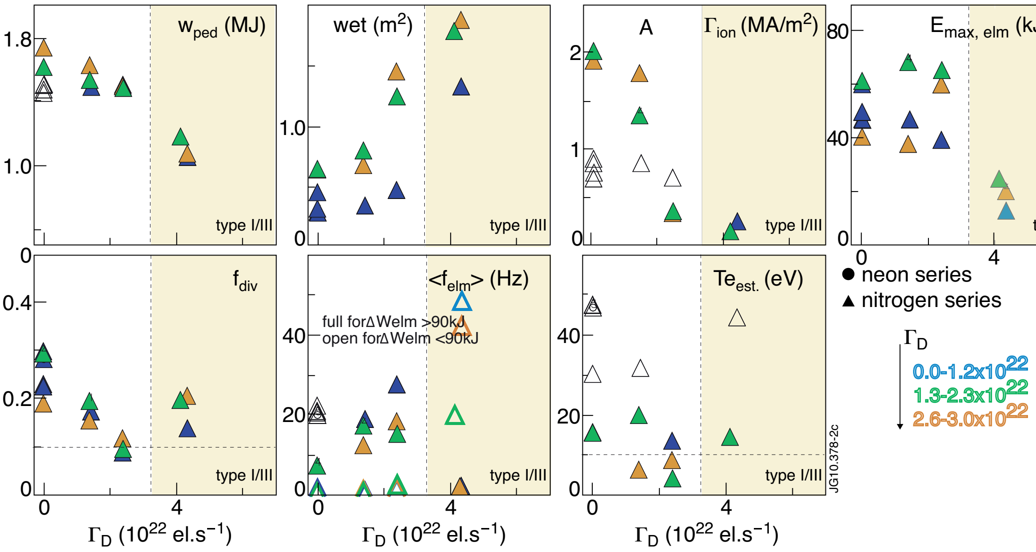

Figure 2: Impact of nitrogen seeding and deuterium fuelling on reference ELMy H-mode: caption same as figure 1.

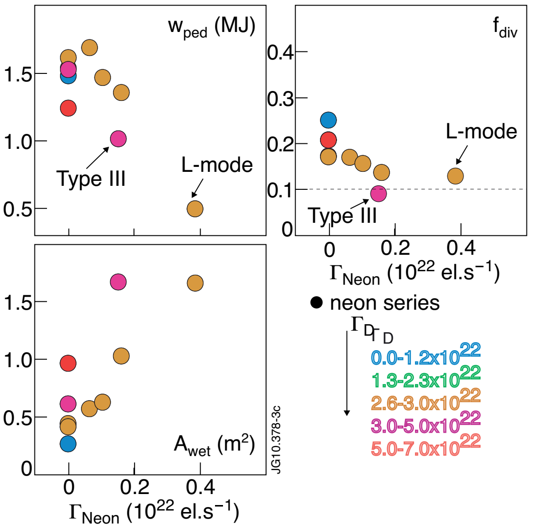

Figure 3: Impact of neon seeding and deuterium fuelling on ELMy H-mode: (from top left to bottom right) average pedestal stored energy and inte-ELM-period wetted area and fdiv,OT (see caption Figure 1).

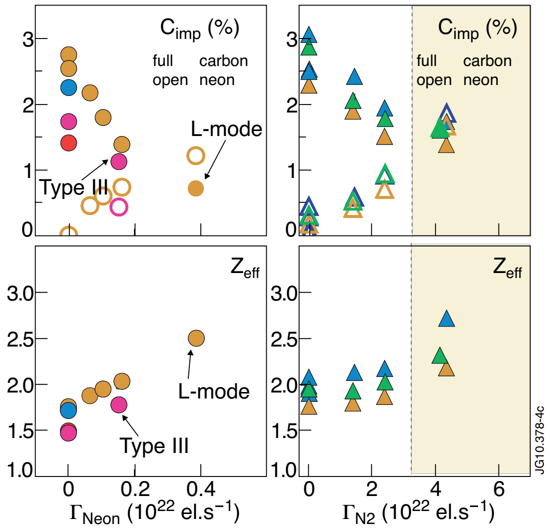

Figure 4: Impact of seeding and fuelling on impurity concentration and Zeff: (from top left to bottom right) averaged carbon and neon concentrations from mid-radius to edge and Zeff from neon series and nitrogen series respectively. Legend same as in Figure 3.

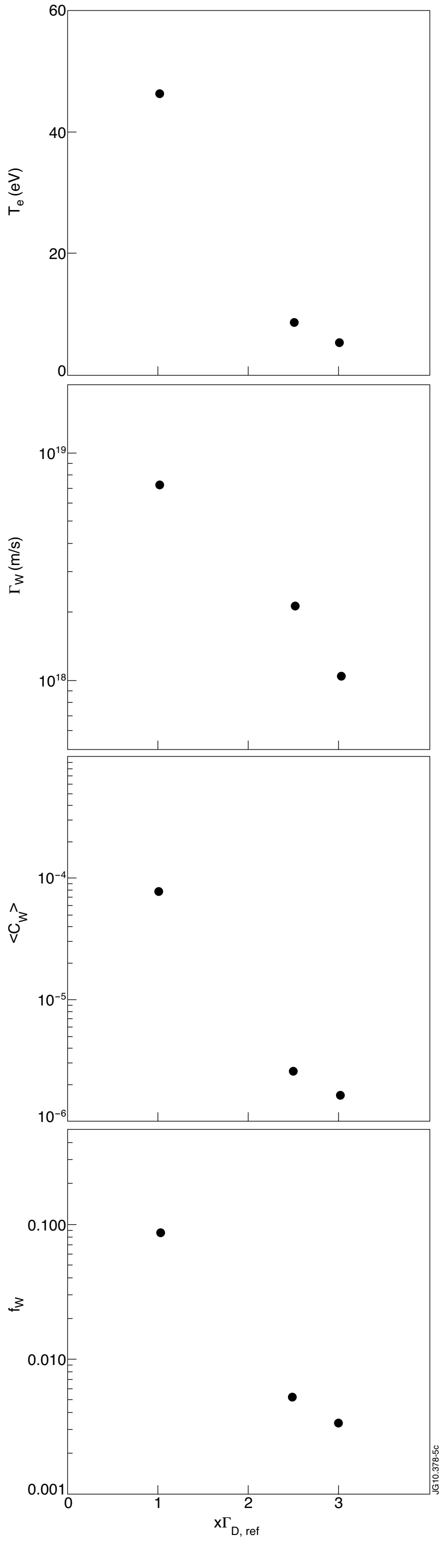

Figure 5: DIVIMP/EDGE2D-EIRENE simulation result: (from top to bottom), peak electron temperature at outer target plate simulated by EDGE2D-EIRENE, used in DIVIMP, total W source, average W concentration and fraction of impurity ion entering the plasma within the separatrix.