ITER Fuelling Requirements and Scenario Development for H, He and DT Through JINTRAC Integrated Modelling

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Abstract. The most efficient ways to fuel ITER baseline H, He and DT plasmas with gas and/or pellet injection have been investigated self-consistently with the integrated core and SOL/divertor suite of codes JINTRAC. Our simulations suggest that pellets may be essential for the density rise in L-mode, but should preferably be kept moderate or even be switched off during the L-H transition until ELMy H-mode is reached. Gas fuelling could complement the Ne seeding during the H-L transition to keep the power loads to the divertor reasonable but precise control over radiation will be needed to keep the plasma within the allowed operational range.

1. Introduction

The ITER Research Plan[1] proposes a sequence of plasma operation in hydrogen, helium, deuterium, and ultimately deuterium-tritium mixtures for fusion power production. In the non-active phase commissioning of diagnostics, fuelling, heating and current drive systems, coils and plasma control systems will take place. Early studies in H, He, and D will also give insights on strategies to optimise DT plasma scenarios, which is crucial to ensure ITER's success in its primary goal of achieving high fusion performance. The density profile and its evolution will be key in determining the best route to achieve the target fusion gain, Q=10, in ITER H-modes using the available heating.

In present devices gas can efficiently fuel the core as the edge plasma is fairly transparent to neutrals, but in contrast, the ITER edge plasma will be hotter and denser so that more gas will be ionised in the far scrape-off-layer (SOL) and will not penetrate to the separatrix [2][3]. Thus, pellet injection, even if it is peripheral, will be vital to fuel the core plasma in ITER. Here, for the first time, we exploit coupled core-edge transport calculations that track the entire plasma evolution from just after X-point formation, to find the most effective ways of fuelling and heating H, He and DT plasmas on ITER without exceeding operational limits for neutral beam (NB) shine-through (species dependent) and divertor power fluxes (10MW/m^2).

We have focused our L-mode H and He simulations on achieving robust scenarios with sufficient density to safely operate and commission the NB at maximum beam voltage. In H there is the possibility of using pellets if gas fuelling is insufficient. In He only injection of H pellets is foreseen on ITER, but this carries the risk of diluting of the He plasmas to the point where the NB shine-through density limit increases from its lower He value towards its higher

H value. The L-H threshold also increases with the H dilution in He plasmas [4][5][6][7]. So, we have kept the H dilution in our He simulations low to optimise our chances of reaching an ELMy H-mode, which can be used to commission the ITER ELM mitigation systems.

In our simulations of 15MA/5.3T ITER baseline plasmas with 50/50 DT mixture, the initial aim was to reach sufficient density in L-mode to safely add the NB at full power and thereby cross the L-H transition power threshold. However, from previous studies it was known that over-fuelling during the L-H transition may lead to a temperature drop[8]. This reduces the fusion power and may cause a back transition to L-mode as the auxiliary power on ITER is not sufficient to sustain the H-mode. During our L-H transition studies we optimised the fuelling rate to reach ELMy H-mode in an as short time as possible, and then increased the fuelling rate to obtain a Greenwald density fraction of 85%, which achieves Q=10. Up until this point we kept the divertor power fluxes below 10MW/m^2 with no or fine-tuned Ne seeding. However, the SOL power fluxes change rapidly during the H-L transition and we had to adjust the Ne seeding level frequently to keep the divertor sufficiently hot to avoid triggering a MARFE, but not so hot as to melt the divertor plates.

To model this comprehensively and self-consistently, we have used the integrated suite of core and SOL/divertor transport codes JINTRAC[9] (see references therein for each JINTRAC module) developed at JET. JINTRAC couples JETTO/SANCO, a 1.5D core transport solver that includes impurities, with EDGE2D/EIRENE, a 2D SOL/edge multi-fluid solver that includes plasma interactions with the ITER Be wall and W divertor. For simplicity, the only impurities we have modelled are Be and Ne.

In the initial phase of the project, we carried out an extensive benchmark between EDGE2D and SOLPS 4.3[10] to ensure that the SOL/divertor physics was consistent between the two codes[11]. Moreover, we extensively modified EDGE2D to handle plasmas with He as a majority species. Here we present the first fully integrated core-edge simulations of He plasmas. Another noteworthy consequence of this development work is that EDGE2D is now able to handle plasmas with two main hydrogenic species, essential for DT mixture studies.

The outline of the paper is as follows: In Section 2 we describe the JINTRAC modelling suite and our modelling assumptions. Our results for the non-active phase are captured in Section 3 and the DT results in Section 4 with summary and conclusions in Section 5.

2. JINTRAC Modelling Assumptions

Generally, the main focus of our simulations in He and DT has been on the fuelling requirements to obtain sufficient density to 1) use the NB in L-mode to trigger the L-H transition; 2) reach ELMy H-mode; and 3) reach a Greenwald density fraction of 85% in DT to obtain Q=10. However, for H plasmas the main aim was to achieve the minimum density allowed for acceptable NB shine-through losses (4.3x10^{19}m^{-3}), which is considerably larger than for DT (2.5x10^{19}m^{-3}) so these simulations have been done at constant field and current.

In JINTRAC the core plasma is fuelled, apart from gas fuelling, in our case through a gas inlet valve at the top of the machine, by several sources calculated by EDGE2D/EIRENE. These include neutrals recycled at the Be main-chamber wall and W divertor targets. In a dense but still not semi-detached plasma and hot SOL with plasma temperatures at the divertor in excess of 100eV, the majority of these neutrals are ionised in the SOL/divertor, and only about 1-2% of the total recycling flux, actually reach the core plasma[2][12][13]. We model pellet fuelling with NGPS[14] and HPI2[15], which describe the ablation and deposition of spherical pellets,. In order to control the plasma density, neutrals are also removed by a model of the divertor cryo-pump in EDGE2D.

One of the main aims of our simulations has been to keep the divertor power loads at the targets below their design limit of $10MW/m^2$. When needed, we achieved this by introducing Ne into the system through a gas inlet valve located at the outer divertor target.

The EDGE2D version we used could only handle one hydrogenic species, hence we model a pure D divertor plasma instead of DT. At the separatrix we split the neutral particle source, and D ion density from EDGE2D to JETTO into a 50/50 mix of DT. Conversely, the total DT plasma particle flux crossing from JETTO is converted into D when transferred to EDGE2D.

We developed a version[2] of the JETTO Bohm-gyro-Bohm transport model tuned to GLF23 to include a collisionality dependent particle pinch to reproduce the density peaking seen in GLF23. The impurities, Be sputtered from the main chamber wall and Ne seeding, were treated with SANCO assuming they have the same anomalous transport as the main ion species. We used NCLASS to calculate the neoclassical transport for each particle species.

Although we have evolved the core equilibrium in our simulations with ESCO, the internal fixed-boundary equilibrium solver in JETTO, for technical reason we had to keep the EDGE2D grid fixed. Therefore, in our current ramp-up and ramp-down simulations we adjusted the pitch of the magnetic field in the SOL to track the plasma current evolution.

The auxiliary heating foreseen for ITER is radio frequency (RF) heating and neutral beam (NB) injection. We have used PENCIL to calculate the NB power deposition profiles in DT plasmas. Due to the limitations of PENCIL, we had to use ASCOT for He plasmas.

At 5.3T the Ion Cyclotron Resonance Heating (ICRH) scheme will be He^3 minority in DT and H plasmas, to provide maximum ion heating. In He, a minority H ICRH heating scheme will be the preferred option. In our simulations we have, for simplicity, assumed an ad-hoc Gaussian ICRH deposition profile centred on-axis with equal distribution of the power to ions and electrons. For the Electron Cyclotron Resonance Heating (ECRH) we have assumed an ad-hoc Gaussian power deposition centred on normalised minor radius 0.2.

As there currently is no first-principle model that can accurately predict confinement transitions, we have applied the Martin L-H threshold scaling[16]. It was obtained for hydrogen plasmas and it has been observed in AUG, DIII-D, and JET[5][6][7] that for He plasmas the L-H transition threshold is lower by a factor of 0.7 than for D plasmas and we have used this in our simulations of He L-H transitions.

With EPED1[17] we have determined the edge transport barrier (ETB) width, which we have assumed to be fixed in H-mode. However, we let the level of residual anomalous transport within ETB depend on the excess of heat flux through the separatrix, P_{Loss}, with respect to power threshold P_{LH} so that for

$$P_{loss} - P_{LH} > 0$$

$$\chi, D_{ETB} = \chi, D_{anomolous} e^{-(P_{loss}-P_{LH})/(P_{LH}\cdot \Delta LH)} + \chi, D_{Ncoclassical},$$

where ΔLH determines the rate of decay of the anomalous transport with the height over the power threshold. In line with experimental observations on JET we use ΔLH=0.1[18].

During the L-H transition the pressure in the ETB builds up and the ballooning stability parameter α rises. When it reaches a prescribed value, α_{crit}, we trigger the continuous ELM model and an ad hoc increase of transport in the ETB maintains $\alpha = \alpha_{crit}$ in the ELMy H-mode.

Finally we have also used the Kadomtsev model to calculate the sawtooth reconnection. A sawtooth crash is triggered when the safety factor is below unity at the magnetic axis but only after a set minimum time has passed since the last crash.

3. JINTRAC Simulations of the Non-active Phase of ITER

We have focussed our non-active studies on achieving sufficient L-mode densities in H ($4.3\text{x}10^{19}\text{m}^{-3}$) and He ($2.7\text{x}10^{19}\text{m}^{-3}$) to allow for safe commissioning of the NB at any beam voltage and obtaining ELMy H-mode in He as H H-modes are unlikely at heating powers below 100MW at full field. Predictions for 7.5MA/2.65T He baseline H-mode show that the ELMs may produce energy loads above the $50\text{MJ}\cdot\text{m}^{-2}\cdot\text{s}^{-1/2}$ melting limit for W and hence provide highly relevant cases for the commissioning of the ELM control system to prove that ITER can effectively mitigate ELMs before entering the active phase[1].

3.1.Hydrogen L-mode Simulations to Achieve the NB Shine-through Density Limit

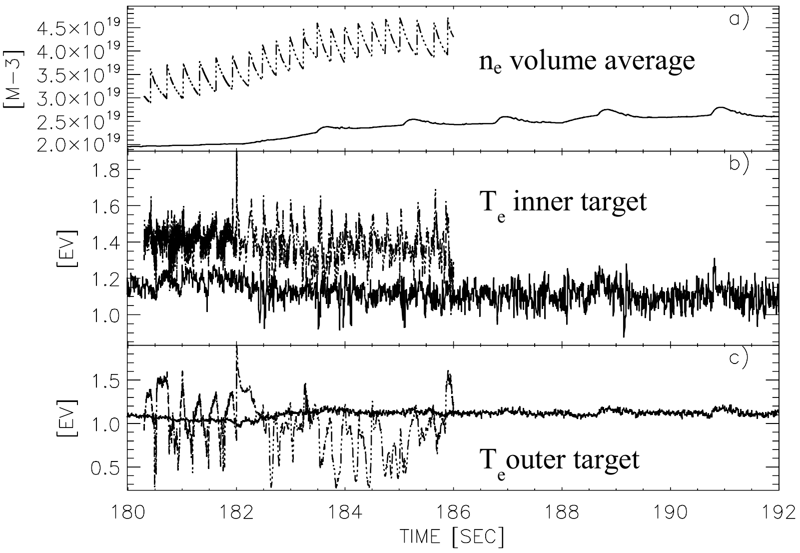

FIG. 1. Fuelling of ITER 15MA/5.3T H baseline plasma with gas fuelling $2.5\text{x}10^{22}$/s and 40MW of ECRH (solid); and pellet fuelling, $53.3\text{x}10^{20}$ particles/pellet at 3.3-4.0Hz, with gas fuelling $5.0\text{x}10^{20}$/s and 20MW of ECRH (chain). The pellet causes oscillations in the target temperatures rendering the outer target momentarily detached (T_e<1eV).

Our simulations of 10MA and 15MA hydrogen baseline plasmas at 5.3T predict that gas fuelling alone will not be sufficient to reach the NB shine-through density limit, $4.3\text{x}10^{19}\text{m}^{-3}$, even when we applied 40MW of RF power. Indeed, we only reached line-average densities of ~$2.8\text{-}3.1\text{x}10^{19}\text{m}^{-3}$ for a gas rate between $2.5\text{-}3.0\text{x}10^{22}\text{s}^{-1}$(FIG. 1.), for both currents, before the core density saturated and the divertor cooled off sufficiently to risk triggering a MARFE.

For more efficient core fuelling, we lowered the gas rate to $5.0\text{x}10^{20}\text{s}^{-1}$ and injected pellets (90mm^3/ $53.3\text{x}10^{20}$ particles) into the plasma. When we applied a pellet frequency of 3.3Hz and increased it to 4Hz after 4.5s, we achieved for 15MA/5.3T a line-average density of ~$4.6\text{x}10^{19}\text{m}^{-3}$ using only 20MW of ECRH (FIG. 1.). The inner target temperature stayed above 1eV whereas the outer target temperature temporarily detached with the intermittent particle flux from the injected pellet. We removed Ne seeding as it was not needed to suppress the target power loads and as Be content was negligible (Zeff≈1),we also ran this case without Be to further speed up the simulations.

3.2.He Current Ramp-up Simulations and Entry to ELMy H-mode

To simulate the current and density ramp-up in an ITER helium discharge to 7.5MA/2.65T, we started from a steady-state 3MA/2.65T, 20MW ECRH, helium plasma with a volume-average density of $1.0\text{x}10^{19}\text{m}^{-3}$ and applied current ramp rate of 200kA/s. The density ramp rate is very sensitive to the prescribed level of gas puff. If the gas puff level is too high ($>6\text{x}10^{21}$ 1/s), it can cause detachment of the divertor, whereas if it is too low ($<1\text{x}10^{21}$ 1/s), it cannot sustain a steady density ramp. We used numerical feedback to adjust the gas puff to model the density ramp at fixed Greenwald fraction of 50%.

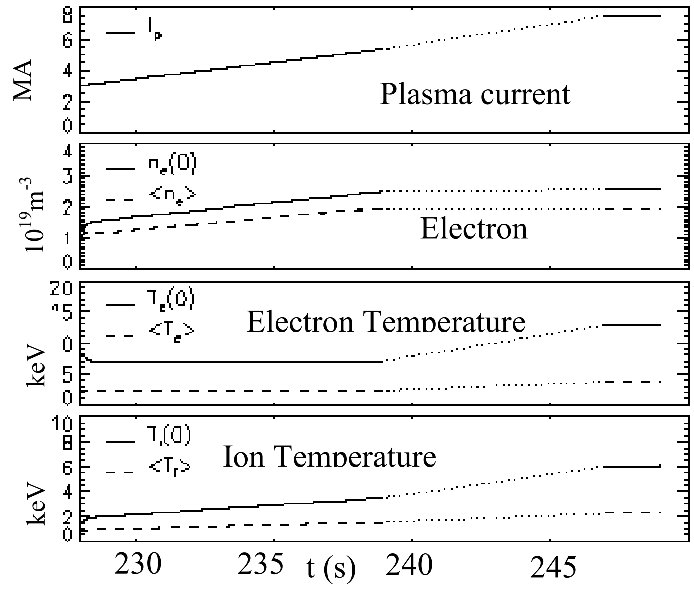

FIG. 2. Current ramp-up from X-point formation at 3MA to 5.5MA of an ITER baseline He plasma at 2.65T, 20MW ECRH. The first part of the solid (on-axis) and dashed(volume-average) lines shows the simulated ramp, the second part shows the steady state target L-mode prior to NB injection. The dotted line shows the missing part of the simulation, which could not be completed as the inner divertor approached detachment.

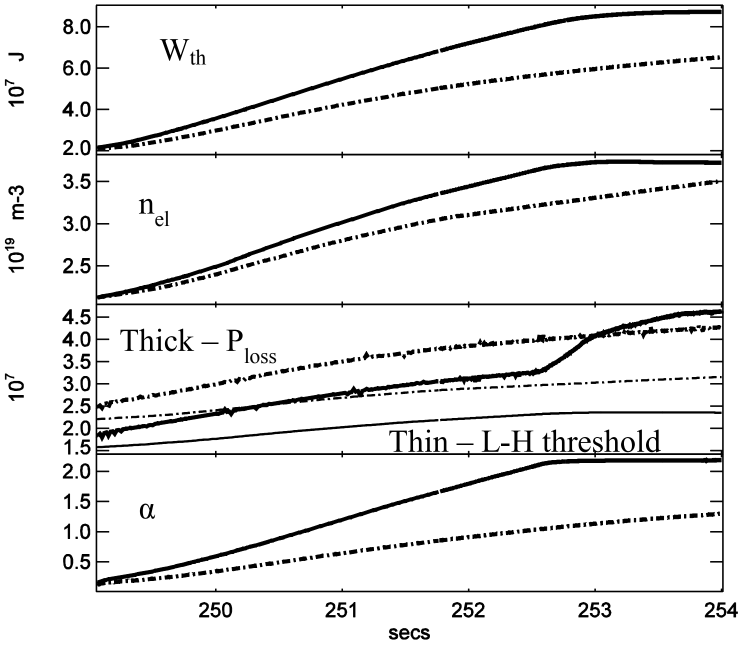

FIG. 3. L-H transition in 7.5MA/2.65T He ITER baseline plasma with 33MW NB and 20MW ICRH. With an optimistic L-H power threshold (solid) the He plasma reaches ELMy H-mode (ballooning parameter $\alpha=\alpha_{crit}=2.1$) in ~3.5s after the NB has been turned on. As we have applied the continuous ELM model in JINTRAC, the pedestal pressure gets clamped at $\alpha=\alpha_{crit}$ and the thermal energy content (W_{th}) and line-average density (n_{el}) saturate. The case with a realistic L-H threshold (chain) is still far from ELMy H-mode ($\alpha\approx1.4$) at the end of the run.

After 10s the density and the volume-average electron and ion temperature have reached the target values we achieved in steady-state simulations at 7.5MA/2.65T (FIG. 2.). However, the plasma current has reached only 5.5MA and the simulation should be continued at a constant density in order to achieve the target plasma current. Unfortunately, at this density the inner divertor was close to detachment, and we could not complete the run due to numerical instabilities.

In steady-state He baseline L-mode at 7.5MA/2.65T, we could reach ~$2.1\text{x}10^{19}\text{m}^{-3}$ line-average density at a He gas rate of $7.0\text{x}10^{21}$/s before the divertor became unstable. This density is lower than what would be considered safe for operating the H beams in He ($2.8\text{x}10^{19}\text{m}^{-3}$). Nevertheless, the density rise in the ELM-free phase is fast enough to lower NB shine-through power, as calculated by ASCOT, to acceptable levels within a few (~1.5) seconds in our simulated scenarios and we do not expect the vessel wall to sustain any damage during L-H transition.

For comparison we simulated two cases of L-H transition in He, one optimistic with the Martin L-H power threshold scaled in accordance to the hydrogen mass dependence, $P_{LH} \propto 1/A_{eff}$ (with $A_{eff}=4$ for He), and another, more realistic, with the Martin threshold multiplied by a factor 1.4 as experimentally observed. As expected the lower L-H threshold in the optimistic case allows for a faster transition into ELMy H-mode (FIG. 3.), with the ballooning parameter $\alpha=\alpha_{crit}=2.1$ in ~3.5s after the NB has been turned on. After 5s the case with the realistic threshold is still well within the ELM-free phase of the transition ($\alpha \approx 1.4 < \alpha_{crit}=2.1$).

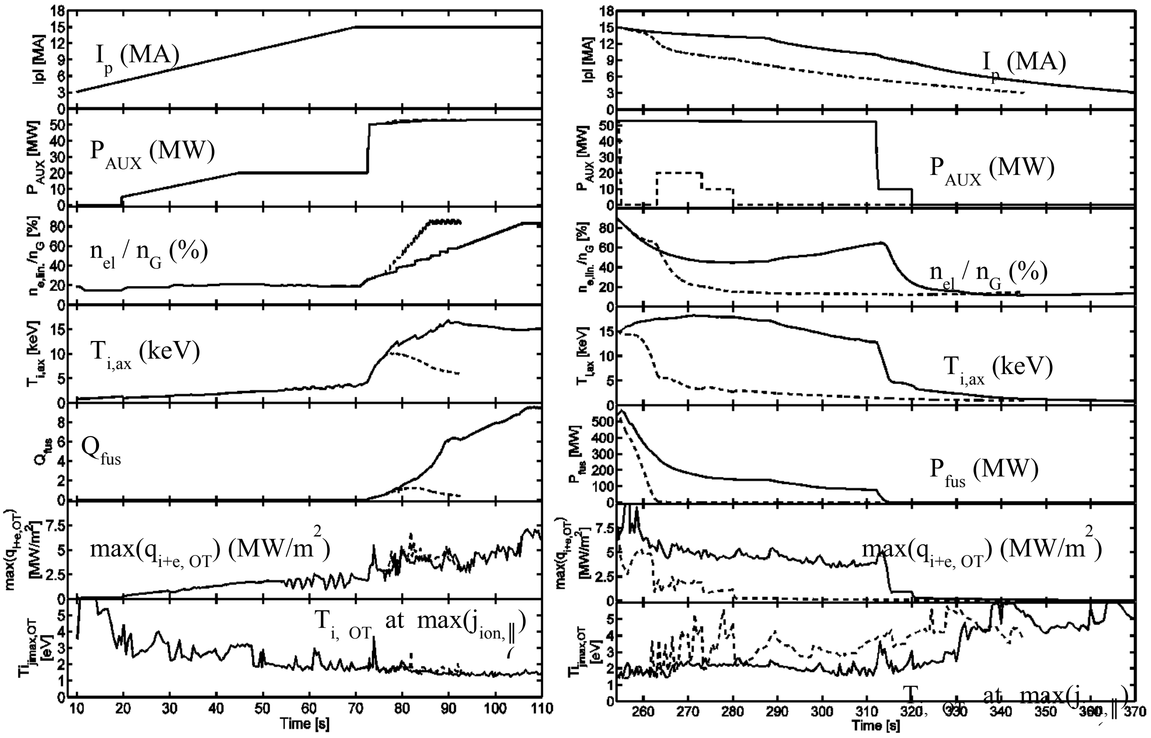

FIG. 4. Current-ramp up (left) for DT ITER baseline scenario with L-H transition at 15MA with 33MW NB +20MW ICRH. Slow (solid) and fast (dashed) density ramp after the transition. Current ramp-down (right) in ITER DT with H-L transition at 15MA (dashed) and ~10MA (solid).

4. JINTRAC Simulations of the Full ITER DT Plasma Evolution

In our simulations we start from an early X-point formation at 3MA/5.3T at 10s and use the auxiliary heating to reduce the flux consumption. We applied a current ramp-up rate of 200kA/s until 15MA is reached at 70s (FIG. 4. left).

For the density rise in ITER baseline DT L-modes, our results show that at a given input power, the core density increases with the gas rate and then saturates[2][3][19]. If we further increase the gas rate, the density build-up in the SOL, due to poor neutral penetration and insufficient power fluxes, will finally lead to a MARFE. Our JINTRAC simulations indicate that in the current ramp-up a Greenwald density fraction less than 35% can be expected with gas fuelling only at 20MW of RF heating (FIG. 4. Left).

Aligned with previous core-only predictions[8], our core+SOL/divertor modelling results suggest that DT plasmas on ITER will require fusion reactions to produce sufficient α heating in addition to the applied auxiliary heating in order to access ELMy H-mode conditions for currents ≥7.5MA at 5.3T[19]. Thus, during the L-H transition fuelling will have to be kept sufficiently low to allow the ion temperature to rise on-axis, which in turn boosts the build-up of fusion power needed to reach an ELMy H-mode. We then had to fine-tune the particle source from gas and pellets to avoid full divertor detachment while providing enough fuelling to reach Q=10. For instance, in our simulation of a 15MA/5.3T ITER ELMy H-mode plasma with a separatrix density ~$5.5\times10^{19}m^{-3}$, pellets bigger than 5.5×10^{21} atoms seriously disturbed the divertor and rendered the plasma unstable[19].

In our simulations the current ramp-down from 15MA/5.3T Q=10 burning plasma takes 185-200s depending on the plasma current at the H-L transition (FIG. 4. right). The transition takes ~5s, which is sufficiently long for the ITER vertical control systems to keep the plasma stable. In the initial phase of the H-L transition Ne seeding is required to keep the divertor power loads acceptable and the target temperatures below 5eV to avoid W sputtering and contamination. After that, the seeding has to be carefully reduced to allow for enough Ne to be pumped out not to cool the ensuing L-mode divertor plasma so much as to destabilise it.

5. Summary and Conclusions

In this paper we presented coupled core-SOL/divertor transport simulations with JINTRAC of the non-active and active phases of ITER baseline plasmas, including the first core-SOL/divertor simulations of He plasmas and of the current ramp-up/down phases. We have shown that pellet injection will likely the most effective way of reaching sufficient density in L-mode at 20MW of auxiliary power to safely operate the NB in H and DT. Gas fuelling alone may suffice in He and DT, especially at lower currents and/or higher input power, or if operating NB below the NB shine-through density limit for 1-2 seconds, after which the density has increased sufficiently for the NB shine-through power to be tolerable. This possibility is particularly important for He, in which injection of H pellets may seriously dilute the plasma and increase not only the NB shine-through density limit but also raise the L-H power threshold making it impossible to reach H-mode.

The above implies that commissioning of the ITER NB should be possible in H, at least at 15MA/5.3T and in He at 7.5MA/2.65T. Potentially ITER may commission its ELM mitigation systems in the non-active phase. Our simulations, so far, suggest that a 7.5MA/2.65T He ELMy H-mode at 53MW is likely if using an optimistic L-H threshold that follows the hydrogenic mass scaling but omits evidence in He from AUG, DIII-D and JET.

According to our results, the L-H transition in DT for currents ≥7.5MA at 5.3T will partly rely on the fusion power to supplement the auxiliary power in order to enter ELMy H-mode. Hence we had to moderate the particle fuelling during the ELM-free phase to allow the ion temperature to raise on-axis and boost the fusion reactions. Once in ELMy H-mode, pellet fuelling can provide a Greenwald fraction of 85% and Q=10 at 15MA/5.3T. However, the pellet size would have to be adjusted depending on how close the plasma is to detachment.

In our JINTRAC simulations of H-L transition at 10MA and 15MA during current-ramp down, the transition is sufficiently slow (~5s) for the ITER vertical control systems to keep the plasma from touching the vessel walls. In both H-mode and H-L transition, our simulations suggest that the SOL plasma is extremely sensitive to the Ne content. If this feature from our simulations is physical, Ne seeding might have to be closely monitored and controlled by a real-time system in order to keep the rapidly evolving plasma stable throughout the H-L transition. We are currently working on implementing such a system in JINTRAC to aid us with our future simulations.

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