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GLOBAL SIMULATIONS OF THE EXIT PHASE FROM THE FLAT-TOP OF AN ITER 15MA BASELINE SCENARIO

Fully predictive JINTRAC simulations with consistent treatment of D and T in the whole plasma

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Abstract

To design a safe termination scenario for a burning ITER plasma is a challenge that requires extensive core plasma and divertor modelling. The presented work consists of coupled core/edge/SOL/divertor simulations, performed with the JINTRAC code, studying the Q=10 flat-top phase and exit phase of the ITER 15MA/5.3T DT scenario. The modelling utilizes the recently implemented option to treat deuterium and tritium separately in the SOL/divertor enabling a consistent treatment of deuterium and tritium in the whole plasma volume which is a unique capability of JINTRAC. In addition, these are the first JINTRAC simulations of this scenario to use a first-principle transport model, self consistently model the ECRH power deposition and to include tungsten, keeping track of tungsten sputtering and accumulation. The flat-top simulations demonstrate the possibility of sustaining a steady state fusion Q of 10 using pure deuterium gas puff together with DT mixed pellets which is preferential as it allows a more effective use of tritium. Simulations of the exit phase is set up sequentially starting with a density decay at full current and auxiliary power that demonstrate the possibility to reduce the density safely within a few seconds. Following the density decay, a subsequent auxiliary power ramp down in H-mode is performed with a late H-L transition at low auxiliary power which is preferred for radial stability control. The final ramp-down phase consists of a current ramp-down in L-mode to 10MA.

1. INTRODUCTION

Integrated modelling is an important tool to self-consistently study the complex set of interactions occurring during all phases of the plasma discharge. To sustain optimal performance during the flat-top phase of the discharge as well as to safely exit from burning conditions, effects such as heating, fuelling, impurity radiation and accumulation are essential. The plasma also needs to stay within operational limits including limiting heat loads on divertor targets. The simulations in this work are performed with the integrated modelling tool JINTRAC [1], unique in its capability to self-consistently model the core/edge and scrape-off-layer (SOL)/divertor region in a single framework. The scenario studied is the ITER 15MA/5.3T DT scenario including the flat-top, fusion Q=10 phase in H-mode and the subsequent termination of the discharge. The path to a Q=10 plasma at full current is presented in [2] and an overview of the whole scenario is presented in [3].

For the sustainment of a fusion Q of 10 in flat-top, pure deuterium gas puff is used together with DT mixed pellets resulting in a deuterium rich plasma edge and close to a 50/50 mix of deuterium and tritium in the core for optimum fusion performance. The exit phase consists of the ramp-down of density at full auxiliary power and current followed by an auxiliary power ramp-down, an H-L transition, and finally, a current ramp-down in L-mode to 10MA. This ramp-down scenario differs from most previous simulations such as [4,5] where the density is assumed to linearly drop with the current. With the inclusion of the particle transport and a consistent treatment of core/edge/SOL/divertor interactions these simulations have the capability to study how fast the density decreases when the pellet fuelling is changed. Knowing the characteristic time of density decay for a given ITER fuelling system while maintaining H-mode and divertor heat load and density control will be important for safe emergency termination scenarios and designing ramp-down simulations with magnetic control including shape control, vertical stabilization, and force limits on the coils systems. The result of the density decay rate study can also be used to set the rate for a simultaneous density, current decay scenario.

Compared to previous JINTRAC simulations of this scenario, presented in [4,5] several improvements have been made to the modelling set-up including the additions of the EC code GRAY to simulate the EC deposition and current drive self-consistently, the first-principle transport model EDWM for anomalous core transport, the inclusion of tungsten in the plasma and, deuterium and tritium are now for the first time treated separately in the whole plasma volume [6]. The divertor heat load has been re-modelled to include contributions not only from the ion-, and electron particle fluxes, heat fluxes and recombination processes[1], but now, at runtime, with additional contributions from neutral heat loading, reflected heat and, kinetic energy, enabling improved monitoring and control. The scenario envisaged here relies on the divertor staying in a partially detached state for density control purposes, meaning a total divertor heat load below $10MW/m^2$ and strike point electron and ion temperature above 1eV. Accurate calculation and runtime control is therefore one essential aspect of this work.

2. MODELLING SETUP

The modelling in this work is performed with the JINTRAC code, which combines JETTO/SANCO for the integrated core/edge modelling and EDGE2D/EIRENE for the plasma and neutrals in the SOL/divertor including gas puff and pumping and sputtering and recycling from the divertor and first wall. The simulations utilize the recently implemented option of treating deuterium and tritium separately in EDGE2D resulting in a fully consistent treatment of deuterium and tritium in the whole plasma volume. For computational reasons, a partial coupling scheme is used allowing JETTO to advance for a maximum of 3ms without advancing EDGE2D followed by a 1ms coupled phase. A correction is used to compensate for the non-conservation of particle flux during the uncoupled phase by temporarily changing the particle source and approximate a fully coupled run.

The fuelling for the Q=10 ITER baseline scenario is expected to need a combination of gas puff and pellets [4] due to the high densities and temperatures required. In this paper the fuelling scheme consists of deuterium gas puff together with DT mixed pellets where the pellet frequency is adapted by a feedback scheme to keep a specified Greenwald density fraction throughout the simulation. The pellets are launched from the high field side upper launcher with velocity 300m/s. Sizes used are 0.2cm radius pellets in the high-density flat-top phase and a reduced 0.14cm radius in the low-density phase of the simulations, to reduce the density fluctuations during the pellet cycle, with a composition of 45/55 mixed DT in H-mode and pure D in L-mode. The HPI2 code is used to model the pellet ablation and particle deposition. Deuterium gas is puffed from the upper SOL at a rate between $0.5*10^{22}/s$ and $3*10^{22}/s$ where a higher rate helps to cool down the divertor target plates limiting the heat load to targets. The main technique used to avoid prolonged maximum heat loads above the maximum limit of $10MW/m^2$ is neon seeding. Neon is injected from an inlet valve in the private region under feedback control on the maximum heat load to target. Neon seeding with a maximum rate of $2.5 * 10^{20}/s$ is activated when the maximum heat load exceeds $8MW/m^2$ which subsequently radiates and cools down the target plates reducing the heat load. Excessive radiation of neon in the SOL needs to be avoided though to avoid a full detachment of the plasma. A semi-detached plasma is important for density control in ITER. In addition, for numerical reasons, important molecular reactions needed to properly simulate detachment are not included in JINTRAC and therefore the plasma needs to remain partially detached. In addition to neon, impurities included are helium and tungsten with reaction cross sections determined by the ADAS database. Zero redeposition of sputtered tungsten is used to study the worst possible case.

The heating scheme used consists of the originally designed heating scheme [7] of 33MW NBI and 20MW EC in the flat-top phase of the simulation. The NBI is modelled with the PENCIL code and for self-consistent modelling of the EC power deposition and current drive the beam-tracing code GRAY [8] is used. The 20MW is divided equally between the top, mid and bottom equatorial launcher in O-mode using 170GHz. The poloidal angles are set to optimize the electron heating in the region of $\rho_t = 0.1 - 0.3$, to avoid tungsten accumulation, while minimizing the negative driven current from the top equatorial launcher. The resulting heat and current deposition profiles at full power in the flat-top and at the end of the exit phase are shown in *FIG 1* together with the evolution of the auxiliary power and current during the exit phase. A gradual reduction of the auxiliary power is made during the exit phase for two main reasons. First, a gradual reduction of the auxiliary power and consequently also the fusion power has been shown to limit the drop in poloidal beta which is beneficial for vertical stability control reducing the risk of disruption [9]. Secondly, a slower variation of the plasma stored energy helps avoid tungsten accumulation and excessive heat loads during the exit phase [10]. The NBI power is

[1] which has been used previously in post-processing

here linearly reduced to zero over 10s and, over the same time scale, the EC power is reduced with 10MW EC power kept between the mid and bottom equatorial launchers to help avoid full detachment [4]. An H to L transition is triggered when $P_{comp} < P_{L-H}$ where the L to H power threshold, P_{L-H}, is set according to the Martin scaling [11], including a 20% reduction for DT plasmas compared to D plasmas, and $P_{comp} = P_{aux} + P_{\alpha} + P_{ohm} - P_{rad} - dW_{tot}/dt$ where W_{tot} is the total stored plasma energy. The total current is prescribed as 15MA in flat-top and then linearly ramped down at a rate of 5MA over 30s (~0.16MA/s), to stay within the range of controlled plasma current ramp-down [12], to 10MA during the exit phase. A total current boundary condition is used for the predictive current profile calculation where the total current satisfies the current diffusion equation with contributions from an inductive current from the central solenoid together with contributions from the non-inductive current from auxiliary heating, a bootstrap current and an ohmic current. The magnetic equilibrium is calculated every 100ms with the equilibrium solver ESCO inside a prescribed, fixed last closed flux surface boundary. For the region inside the outer radii where the safety factor crosses the $q = 1$ surface, a continuous sawtooth model is used to include a time averaged effect of sawteeth.

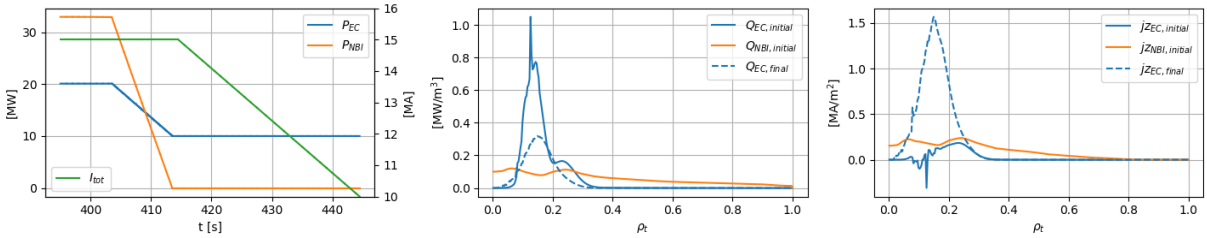

FIG 1 Evolution of the auxiliary power and total current starting at the end of the flat top phase at 395s (left). Heating (mid) and current (right) deposition for the auxiliary power at the first and final time of the exit phase.

For the transport in the plasma core, the neoclassical transport is modelled by NCLASS and the anomalous transport is modelled with EDWM. A 10% Bohm coefficient is added in H-mode for numerical stability and, to model the increase in transport in L-mode, the Bohm/gyro-Bohm L-mode model is used together with the EDWM model. In addition to the improvement in its predictive capability compared to previously used Bohm/gyro-Bohm model, the choice of EDWM is motivated by its resilience simulating inverted profiles occurring in ITER edge fuelling dominated plasma [13] and its computational speed. The presence of ELM control schemes is assumed so the effect of ELMs is also chosen to be time averaged by using a continuous ELM model. The pedestal width and maximum achievable pedestal pressure are imposed limiting the edge pressure gradients to a specified α_{crit} set to 1.9 [14]. The effect of discrete ELMs on the Q=10 flat-top phase of this scenario is presented in [3]. In the SOL, perpendicular heat and particle transport is described with radially dependent transport coefficients. The near SOL is matched to the values at the separatrix with a gradual transition to prescribed values in the far SOL. Details and sensitivity studies to SOL transport coefficients are available in [15,16]. Parallel transport in the SOL is calculated from the Braginskij model [17]. Cross-field drifts are not included.

3. RESULT

3.1. Flat-top with Fusion Q =10

The flat-top phase of the simulation, summarized in *FIG. 2*, is set up with a Greenwald density fraction of 85% resulting in a pellet frequency of 8Hz using the chosen fuelling scheme. *FIG. 2* demonstrates that it is possible to obtain a Q=10 plasma with close to 50/50 mix of DT in the plasma core together with a deuterium rich edge. The ion content in the core and edge are kept steady when the pellet is slightly tritium rich together with the pure deuterium gas puff. The resulting total fuelling rate of $2 * 10^{22}$/s for D and $0.9 * 10^{22}$/s for T is consistent with previous JINTRAC simulations of this scenario [4] and balances well the flux to the pump. The helium level in the core saturates at 1.9% with a source rate from fusion reactions of $2 * 10^{20}$/s which matches the time averaged helium pump rate. Even without any redeposition of tungsten the tungsten sputtering values remain very low and there is no accumulation in the core. As shown in [3], when discrete ELMs are used, the sputtering levels are significantly increased. The neon content is tied to the heat load on the divertor targets. After 4s the level of neon saturates at 0.3% and the average neon pumped out is equal to the average of the injected and recycled neon resulting in a radiation level of 7MW in the core during steady state (total core radiation including bremsstrahlung and synchrotron radiation is 25MW). This reasonable amount of neon will be important during the low-density, current ramp-down phase to avoid excessive cooling of the divertor targets which can result in full detachment. The final time trace in *FIG. 2* consist of the confinement factor H98Y (radiation corrected)

which is 1 throughout the flat-top simulations so the calculated transport is consistent with the ITER scaling law. Not shown in *FIG. 2* is the electron temperature at the inner most point of the divertor. Both inner and outer target remain steady and above the 1eV limit for avoiding detachment. In addition, the divertor region where recombination rate is higher than the ionisation rate is limited to the private region below the target plates. In a fully detached plasma this region would spread above the target plates.

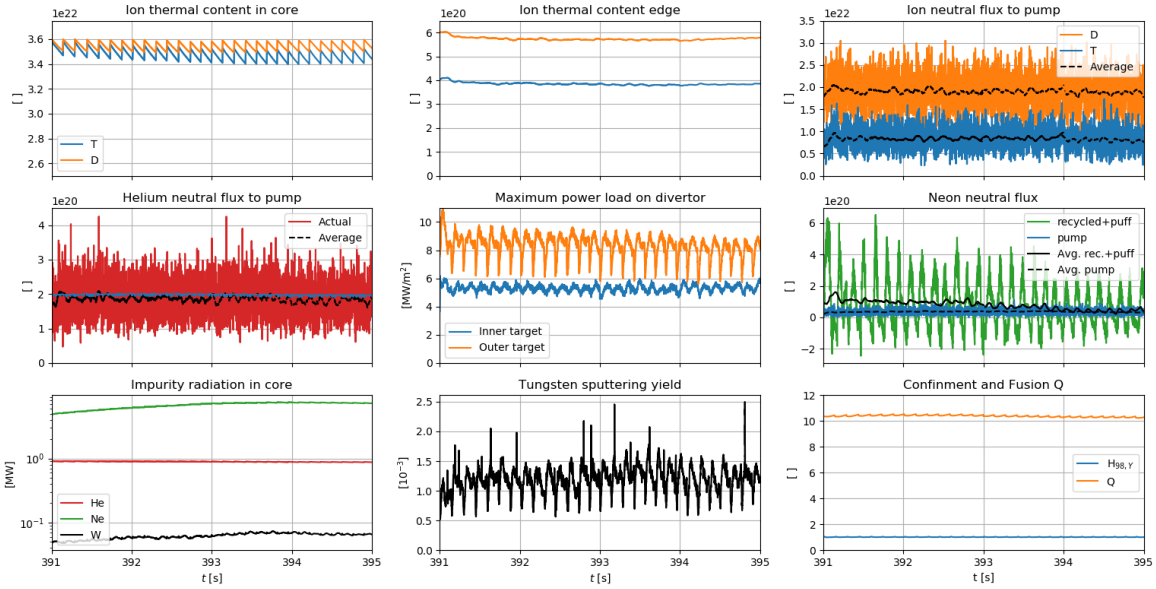

FIG. 2 Time traces illustrating the steady state phase of the simulation for a 45/55 DT pellet and pure D gas puff. The helium neutral flux to pump is overlaid by the helium reaction rate in blue. The impurity line radiation in the core is shown on a logarithmic scale.

Final profiles in the flat-top phase for deuterium, tritium, helium, neon and tungsten are presented in *FIG 3*. The density peaking is marginally higher for tritium than deuterium in part due to the 45/55 DT mix in the pellets which penetrates further into the core than the deuterium gas puff and in part due to difference in transport between D and T. The pure deuterium gas puff also results in a deuterium rich edge. Ion temperature is 14.8keV on axis with a fusion Q of 10.3 for the duration of the flat-top phase. Also in *FIG 3* is the contribution to the heating and current density at the end of the flat-top with resulting safety factor. As expected, the dominant contribution to the heating power is from the alpha heating and the total current is dominated by the inductive current. The safety factor crosses the $q = 1$ surface around $\rho_t = 0.3$.

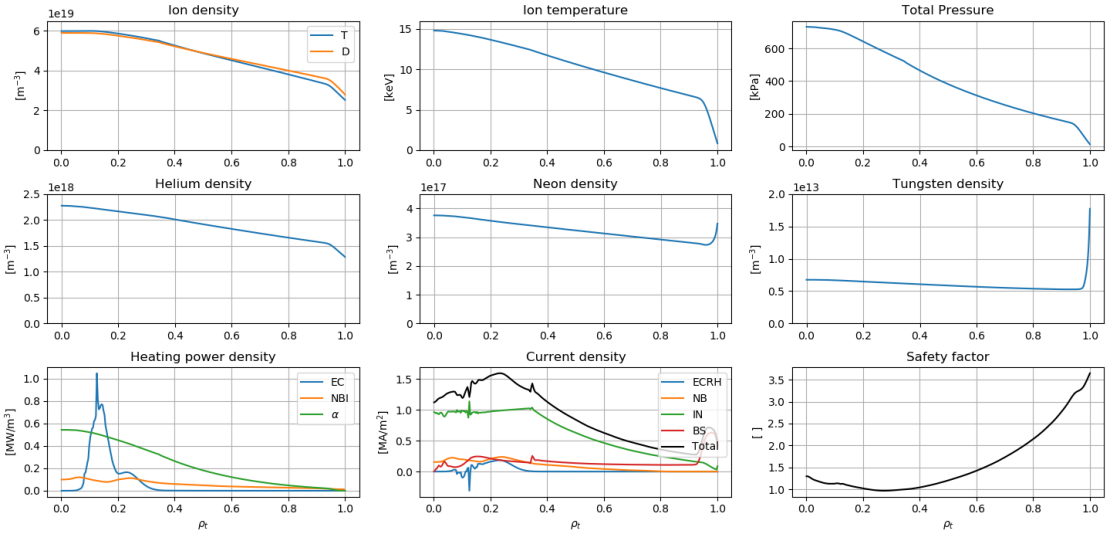

FIG 3 Core profiles at the end of the flat-top phase.

A 2D plot of the deuterium density and the ratio of tritium to deuterium density is shown in *FIG 4*. We observe that deuterium is dominant in the far SOL as well as in the private region below the target plate. To clarify the difference between deuterium and tritium in the SOL, the density profile along the outer midplane is also shown in *FIG 4*.

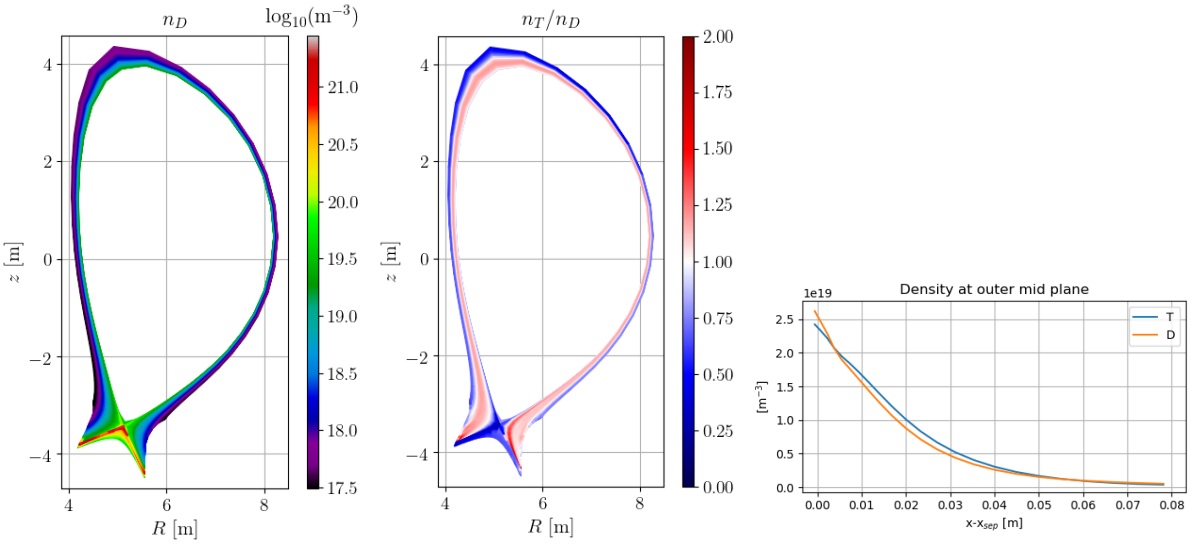

FIG 4 2D profiles of the deuterium ion density and the ratio of tritium to deuterium density in the SOL/divertor region at the end of the flat-top phase at 395s as well as the deuterium and tritium density profiles along the outer mid plane.

3.2. Exit phase

Starting from the end of the flat-top phase at 395s, the exit phase starts with a density decay at full auxiliary power and current, keeping the plasma in H-mode. During this phase the density is reduced from 85% Greenwald density fraction to 45% which reduces the fusion Q to ~5. For the initial density decay phase two cases are considered with summary time traces depicted in *FIG 5*. In the first case the pellets are instantaneously switched off and in the second consists of a linear reduction of 5% per second of the Greenwald density fraction which corresponds to an almost linear decrease of the pellet frequency over 5s. As the density reduces there is an initial increase in fusion Q, due to increase of the ion temperature, and a momentary increase in the heat load to target. This triggers the neon seeding and there is a subsequent increase in neon in the edge and core. With the continued reduction of density, the ion temperature reduces, and the heat load is once again below the limit triggering the neon seeding and the neon content is then steadily pumped out reducing the content in the core and edge. There is also an increase in tungsten sputtering and the tungsten content in the core increases though from very low levels. When the density decays over the slightly longer timescale in the second case, the maximum heat load is kept under the limit of $10 MW/m^2$, except short spikes coinciding with the pellets. During the density decrease at full NBI power the NBI shine-through is increasing from levels of 0.05MW at flat-top to 0.1MW and 0.12MW for the first and second case respectively, which is well within acceptable levels. Worth noting, as seen in *FIG 5* the trends are very similar in the two cases and none of them result in any lasting issues in terms of radiation from tungsten in the core, excessive cool down of the target risking full detachment or long exposure to too high heat loads. To limit the increase in heat load to target during the initial density decay at high fusion Q the remaining of the exit phase is continued from the end of the slower density decay phase.

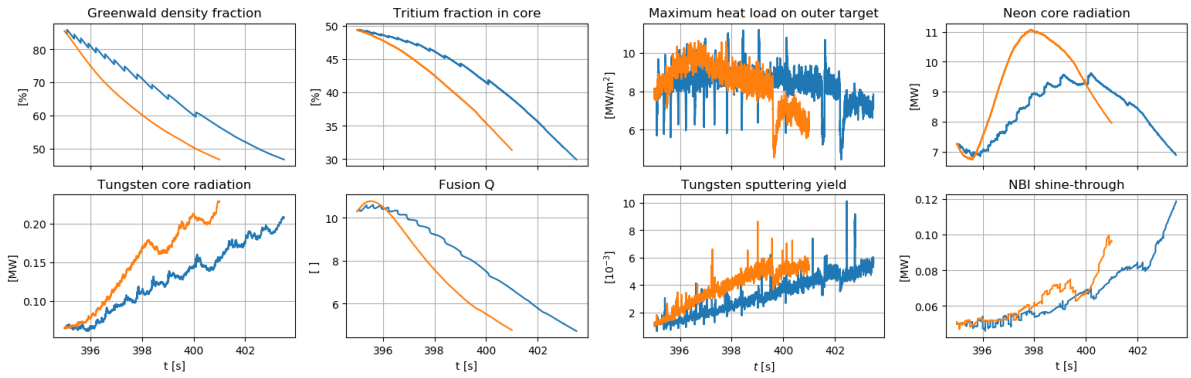

FIG 5 Time evolution during the density decay phase at full auxiliary power and current. Linear reduction of 5%/s of Greenwald density fraction (blue) and pellet switch off (orange).

2s into the slower density decay phase, which is the point of highest maximum heat load to target in this case, the heat load distribution as well as the temperatures along the target plates are shown in *FIG 6*. At the radial point of maximum heat load the electron and ion temperature are equal at 3.2eV and 1.4eV at the IT and OT respectively. This is below the 5eV level estimate for issues with excessive tungsten sputtering. Also shown in *FIG 6* is the 2D profile of the total impurity radiation in the SOL/divertor region at this time which is dominated by the neon radiation in the divertor region. As mentioned above, this amount of neon causes no issues related to detachment and will gradually reduce during the remaining exit phase. The ionisation rate remains above the recombination rate above the target plates.

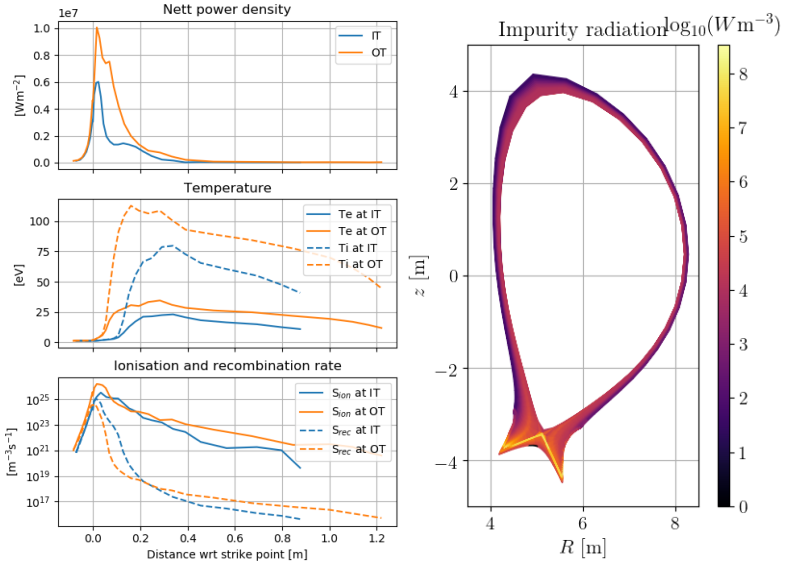

FIG 6 (left) Profiles along the inner and outer target at 397s, 2s into the density decay at full current and auxiliary power. Ionisation, recombination balance is shown on a log scale with absolute values of recombination rate. (right) 2D profiles of the total impurity radiation in the SOL/divertor region.

The entire exit phase, including density decay, is summarized in *FIG 7*. Following the 8s density decay is a 10s auxiliary power ramp-down. Pellet fuelling is used to keep the Greenwald density fraction at 40% to maintain the validity of the Martin scaling for the H-L power threshold. An increase in the gas puff rate at the start of the auxiliary power ramp down reduces the maximum heat load to target to $\sim 3MW/m^2$ at both inner and outer target for the remaining of the H-mode phase and reduced further in L-mode. With the reduction of the pellet frequency during the density decay, the tritium content in the core reduced at a higher rate than the deuterium which is slowed down due to the deuterium gas puff. The ratio of 50/50 DT mix in the core is increased to ~80/20 by the start of the auxiliary power ramp down. Regardless of the loss of tritium during the density decay phase, the fusion power and remaining auxiliary power are high enough to keep the plasma in H-mode throughout the auxiliary power descent as intended. At the end, when the NBI power is down to zero and the EC power is down to 10MW $P_{comp} \approx P_{L-H}$. During this time the plasma is dithering between H- and L-mode for ~0.4s before it transitions to L-mode and remains there throughout the rest of the exit phase. Profiles of the ion pressure and the ion heat and particle diffusivity is shown in *FIG 8* before and after the H-L transition illustrating the effect of the increase in transport at the edge in L-mode. For the heat diffusivity the main difference between the H- and L-mode phase shown is from the change in Bohm transport while the deuterium particle diffusivity also has difference in anomalous transport from EDWM. There is a small increase in tungsten content during the H-L transition though no accumulation occurs, and the neon is pumped out reducing the neon content throughout the remainder of the simulation.

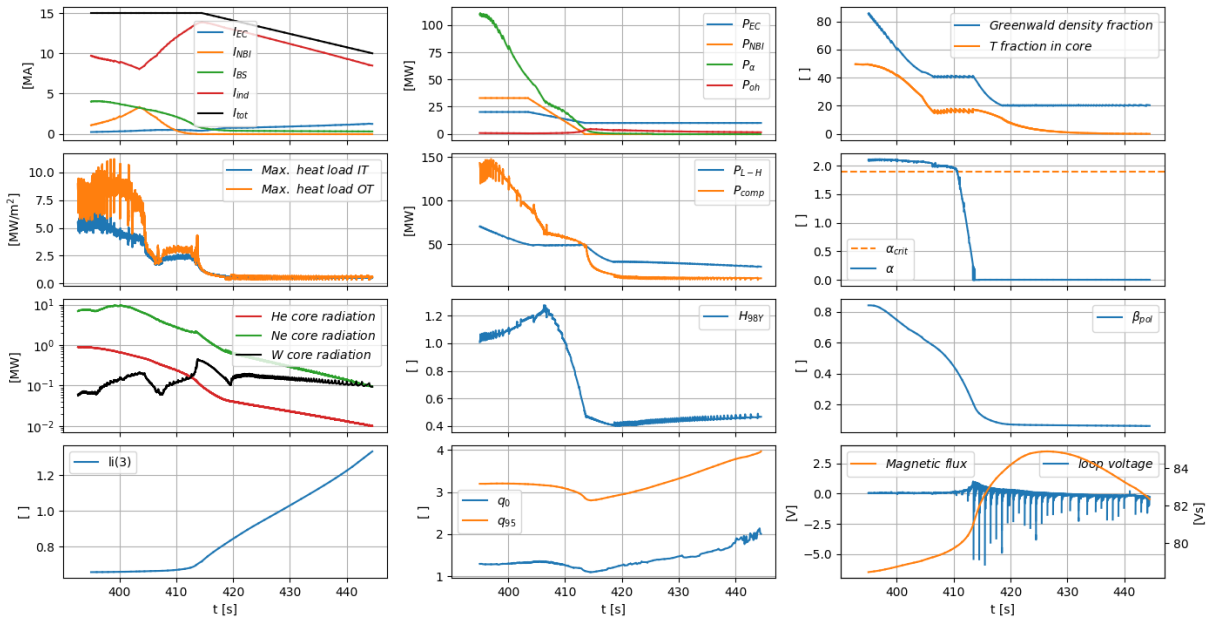

FIG 7 Time traces summarizing the exit phase.

In the final step of the exit phase the total current is linearly reduced from 15MA to 10MA over 30s at a fixed density and auxiliary power. Following [4] and keeping some EC power throughout the ramp down the issue with divertor detachment is avoided. As shown in bottom left of *FIG 7*, the plasma internal inductance increases steadily as the current is decreased. To ensure vertical stability in this phase vertical stability control including plasma shaping is used in the experiment. As the plasma boundary is fixed in these simulations this is not included in the modelling presented in this work. The increase in internal inductance and reduction in poloidal beta both known to reduce vertical stability margin [18] show similar trends of previous ITER ramp down simulations [9]. Finally, the change in magnetic flux consumption is shown at the last closed flux surface and the loop voltage is the total corresponding to that in the central solenoid in addition to the PF coils and the voltage induced by the plasma. The spikes in loop voltage coincide with the magnetic equilibrium updates in ESCO.

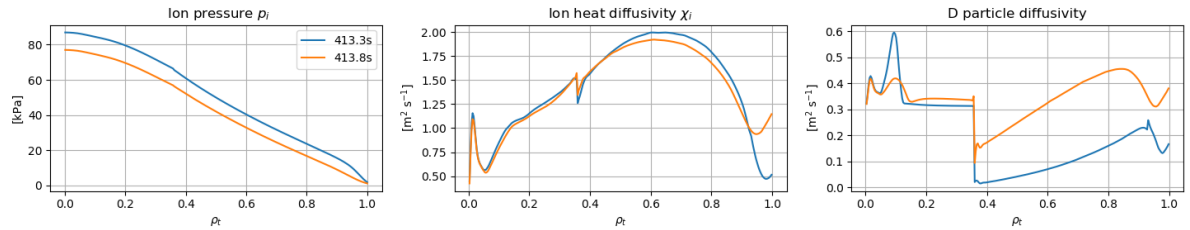

FIG 8 Profiles before and after the H-L transition.

4. CONCLUSION

The presented work consists of the details of the sustainment of the flat-top Q=10 phase and the stepwise approach for the safe termination of plasma for ITER 15MA baseline scenario. The flat-top simulations demonstrate the possibility of sustaining a fusion Q of 10 using DT pellets and pure deuterium gas puff, which is preferential as it allows a more effective use of tritium, while staying within operational limits and keeping track of tungsten sputtering and accumulation as well as neon seeding. Using this fuelling scheme requires that the pellet mix is slightly tritium rich to keep 50/50 mix of deuterium and tritium in the core. The maximum heat load to target is kept just below the operational limit of $10 MW/m^2$ with neon seeding under feedback from the private region. The amount of neon is saturated during the flat-top phase at a level that does not cause any detachment during the exit phase and there is no tungsten accumulation occurring. The sequential setup for the exit phase consists of a gradual reduction of density at full auxiliary power and current followed by a ramp down of the auxiliary power, a late H-L transition and finally a current ramp down in L-mode. The density decay phase shows the promising result that the density can be reduced safely rather quickly compared to what was previously expected. In these simulations the density is reduced from the flat-top value of 85% Greenwald

density to 45% over 8s without lasting issues for heat load or radiation. The reduction of the pellet frequency during the density decay significantly reduces the fraction of tritium in the core though the fusion power and remaining auxiliary power in the power ramp down phase is enough to keep the plasma in H-mode. An H-L transition occurs at the end of the auxiliary power ramp down which is preferential for radial stability control. Finally, the total current is ramped down from 15MA to 10MA in L-mode using a total current boundary condition.

ACKNOWLEDGEMENTS

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