

Core-SOL fully integrated simulations characterizing the plasma response to gas-puff fuelling in ITER

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Introduction

In a fusion power plant, the control of fuel density and composition in terms of deuterium (D) and tritium (T) relative concentration is of paramount importance. For this reason, experiments aiming at studying and controlling burning plasmas in a reactor-relevant regime, such as ITER, need to develop their own density and fuel mix control systems to guarantee the stationarity of the fusion power output. To design such a control system, one needs to characterise the plasma response to external fuelling of plasmas in regimes not explored experimentally so far, featuring, for example a scrape-off layer (SOL) highly opaque to neutral penetration. A possible approach when experimental data are not available is to try and characterize the plasma response by means of high-fidelity integrated scenario modelling. To characterise the response to gas-puff fuelling of ITER plasmas and inform the initial development of the density control system [1, 2], a series of fully integrated core-SOL simulations has been performed with the COCONUT suite of codes integrating the JETTO core transport code and the EDGE2D/EIRENE codes modelling the transport in the SOL and validated on existing machines [3]. These high-fidelity simulations of gas fuelling will be used to benchmark simpler control-oriented models applied to design the density control functions of the ITER plasma control system.

The scenarios analysed in the preliminary study presented in the remaining of this paper are 5 MA/2.65 T and 7.5 MA/2.65 T hydrogen L-mode plasmas with 10 MW of ECRH. The analysis focusses on ITER start of research operations (SRO) scenarios, because these are the earliest operation for which these simulations can be validated empirically. Steps in gas puff rate were applied to model the plasma density response and provide the ITER team with a dataset starting from which synthetic diagnostics could be developed and an initial tuning of the density control system could be performed. The results obtained are also compared to those from older fully integrated core-SOL simulations.

Simulations set-up

All the simulations presented in the following sections were done with the JETTO/SANCO core transport code and the EDGE2D/EIRENE SOL transport code equipped with the EDWM [4] transport model for the anomalous transport and NCLASS [5] for the neo-classical transport. The plasma composition included H, He, Ne and W. H was puffed from the top of the vacuum vessel and, when introduced, Ne was puffed from the outer divertor leg. A 50% prompt redeposition was assumed for W. The target plasmas were heated with 10 MW of ECRH in X-mode from the equatorial launcher and the ECRH deposition was computed self-consistently with the GRAY code [6].

Results at 5 MA/2.65 T

In the simulations at 5 MA/2.65 T, the line average density was initially set $\sim 1.2 \times 10^{19} \text{ m}^{-3}$ (corresponding to a Greenwald fraction $f_G=40\%$). However, at this density, the divertor turn out to be sufficiently detached for the SOL to be completely opaque to gas puffing. This result is in line with previous simulations of 5MA/5.3T D-T L-mode plasmas where the density, for gas fuelling only, saturated at $n_e \sim 1.2 \times 10^{19} \text{ m}^{-3}$ for a gas fuelling rate of $5 \times 10^{21} \text{ s}^{-1}$ and an

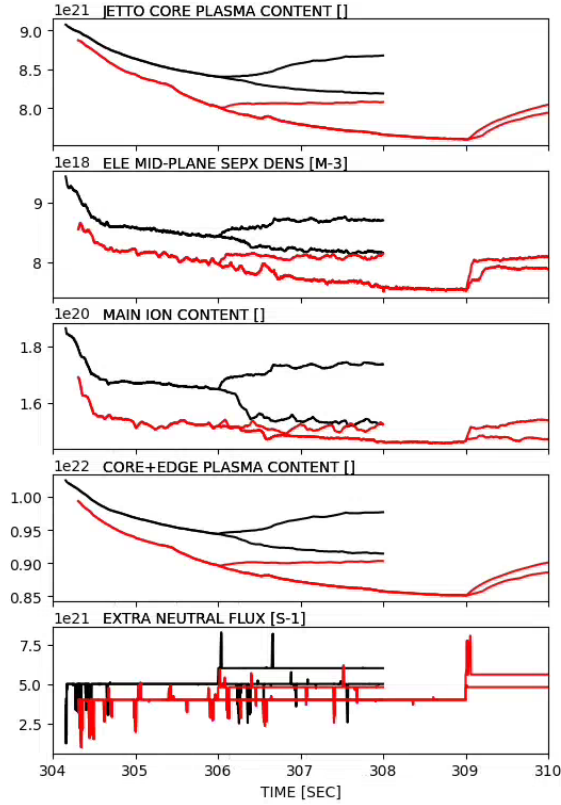


Figure 1: 5MA/2.65T H L-mode plasma density response simulations with reduced initial density ($f_G=30\%$), starting from two different baseline fuelling rates. From top to bottom core plasma main ion content, density at separatrix, SOL main ion content, total (core and SOL) main ion content and gas fuelling rate.

was a 7.5 MA/2.65 T L-mode H plasma with 10 MW of ECRH. These simulations started with a JETTO 5 s stand-alone phase where the volume-average density was held constant by setting the recycling factor at the separatrix equal to 1. After this phase, lasting a few confinement times, when the relaxation of the kinetic profiles has completed, we coupled JETTO/SANCO to EDGE2D/EIRENE for 100 ms with a prescribed gas puff of $5 \times 10^{21} \text{ s}^{-1}$. This phase is intended to allow the SOL to relax and adapt to the new level of fuelling. Subsequently, we continued the simulation either keeping the fuelling constant or by applying steps of various amplitude to the fuelling rate. In particular, we increased the fuelling rate by 0.8, 2.0, 10.0 and $12.0 \times 10^{21} \text{ s}^{-1}$ respectively.

The response of the plasma density is shown in figure 2. It can be seen that, during the stand-alone phase the particle source calculated by FRANTIC adjusts itself around the value of $2.2 \times 10^{22} \text{ s}^{-1}$ in order to maintain the plasma volume-average density at $2.7\text{--}2.8 \times 10^{19} \text{ m}^{-3}$, corresponding to $f_G \sim 50\%$. When a fuelling rate of $5 \times 10^{21} \text{ s}^{-1}$ is applied in the fully integrated modelling phase, the plasma volume average density starts to decrease and keeps decreasing at a very similar rate even when the fuelling rate is increased by 0.8 and $2.0 \times 10^{21} \text{ s}^{-1}$ after the first 100 ms of simulations. This indicates that: a) such a fuelling rate is not sufficient to sustain the density of the target plasma considered and b) the target plasma is not sensitive to increases of

auxiliary heating power of 5 MW of ECRH, and at $n_e \sim 1.8 \times 10^{19} \text{ m}^{-3}$ for a gas fuelling rate of $7.0 \times 10^{21} \text{ s}^{-1}$ and an auxiliary heating power of 10 MW of ECRH [7].

In light of this result, it was decided to lower the starting line average density to $\sim 9.5 \times 10^{18} \text{ m}^{-3}$ (corresponding to a Greenwald fraction $f_G=30\%$). In this second set of simulations, after reaching the lower target density of $9.5 \times 10^{18} \text{ m}^{-3}$, the base gas rate was increased by 20% and 40%. After 1 s, a clear density response was visible, indicating that the density had not yet saturated. A summary of the results is given in figure 1, where we show the waveforms of the mid-plane separatrix density, the particle content for different region of the plasma and the applied gas fuelling rate for the simulations performed.

These results were considered sufficient for ITER to start the design of the density control system and investigate the potential risk of onset of locked modes due to the magnetic field ripple at such low densities. Further modelling is planned to accommodate ITER request once the analysis of these preliminary results is completed.

Results at 7.5 MA/2.65 T

A second series of COCONUT simulations was performed to characterise the response of ITER plasmas to steps in the fuelling rate.

The target plasma considered in this study

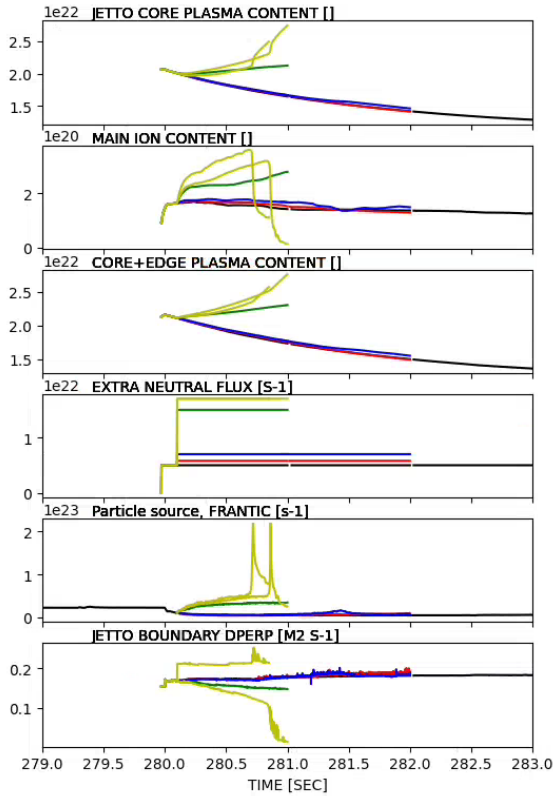


Figure 2: From top to bottom: core, SOL and core plus SOL main ion content, total fuelling rate, total core particle source and particle diffusivity at the separatrix for a series of COCONUT simulations of a 7.5 MA/2.65 T ITER L-mode hydrogen plasma with 10 MW of ECRH heating and initial volume average plasma electron density $\sim 3 \cdot 10^{19} \text{ m}^{-3}$. The different colours correspond to different fuelling rate waveforms in the fully coupled simulation phase, note that the run at the highest total fuelling rate was repeated with two different particle edge diffusivities. In the case with the higher diffusivity the density runs away and the simulation crashes earlier than in the one at lower diffusivity.

separatrix density. Therefore, to see whether this unphysical decrease of the particle edge diffusivity could have caused the crash of the run, we ran the same case but forced a higher diffusivity at the edge with respect to the cases at lower fuelling rate ($D_{\text{edge}} \sim 0.2 \text{ m}^2/\text{s}$ as opposed to $D_{\text{edge}} < 0.15 \text{ m}^2/\text{s}$). This second case is also shown in figure 1. It can be seen that the effect of the increased particle transport at the edge is to accelerate the edge density increase in such a way that the effects of over fuelling the plasma are felt earlier and the run crashes even before the lower diffusivity one. This is likely due to the fact that, in these simulations, the level of transport in the plasma edge was extended a short distance in the SOL. Since a full edge

the fuelling rate $< 2.0 \times 10^{21} \text{ s}^{-1}$. When the fuelling rate is increased by $10.0 \times 10^{21} \text{ s}^{-1}$ the density decrease is halted and even reversed as the particle source in the main plasma reaches a value close to the one of the stand-alone phase. This indicates that a gas rate of $1.5 \times 10^{22} \text{ s}^{-1}$ is adequate to sustain the density of the target plasma once the transmissivity of the SOL is taken into account in the modelling. Eventually, if the gas rate is further increased by an extra $2.0 \times 10^{21} \text{ s}^{-1}$, a sudden increase of the density at the separatrix is observed, leading to a similar increase of the plasma volume average density and, at the same time a collapse of the temperature in the SOL. This is interpreted as the plasma being overfuelled, the SOL becoming completely opaque to the gas puff and the divertor becoming detached, a situation that COCONUT cannot model. It is interesting to note that, after the initial increase of the density in the SOL and at the separatrix both quantities suddenly drop indicating that the gas puff is not fuelling the plasma, but cooling the SOL and causing the thermal collapse of the edge. This indicates that the SOL is extremely sensitive to the fuelling rate and even a small deviation from the level required to sustain the target density can lead to the onset of detachment and the overfueling of the SOL. To better characterise the plasma overfueling observed in the simulations employing the largest gas-puff rate ($1.7 \times 10^{22} \text{ s}^{-1}$), we note that the parametric dependencies of the transport model leads to a reduction in particle diffusivity at the separatrix as the density increases. Experimentally, the observed trend is opposite, and an increased particle diffusivity and lower particle confinement time is observed at higher

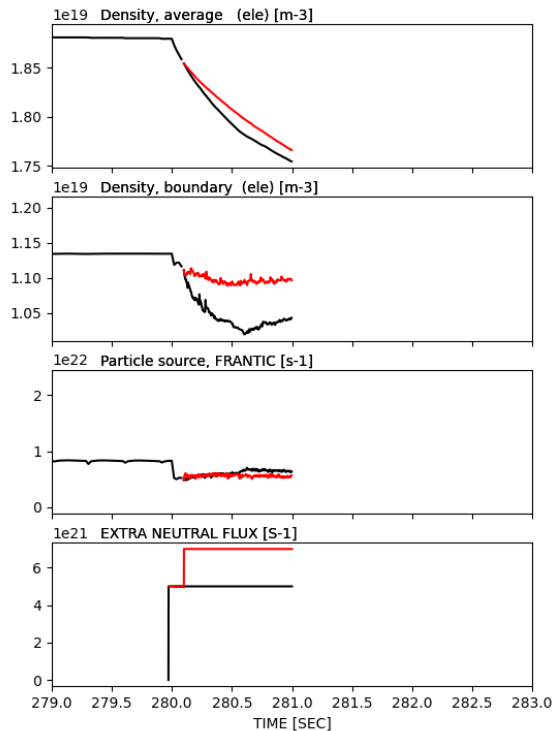


Figure 3: from top to bottom: volume average core electron density, electron density at the separatrix, total core particle source and total fuelling rate for a COCONUT simulation of a 7.5 MA/2.65 T ITER L-mode hydrogen plasma with 10 MW of ECRH heating and initial volume average plasma electron density $\sim 2 \times 10^{19} \text{ m}^{-3}$. The different colours correspond to different fuelling rates in the fully coupled simulation phase.

density corresponding $f_G \sim 30\%$ - 40% gas puff rates in the order of $1.0\text{-}1.5 \times 10^{22} \text{ s}^{-1}$ are necessary and at this density the plasma is sensitive to small variations of the fuelling rate which can result in the plasma being underfuelled with consequent secular decrease of the density or overfuelled with consequent thermal collapse of the SOL. These findings will be used by the ITER team as a starting point to design an effective density control system and suggest that the gains will have to be finely tuned to remain in the window where gas puff fuelling can be effective. They also confirm that pellets will be necessary to fuel the plasma in conditions where gas puff cannot be used.

References

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diffusivity scan to assess the effect of this parameter was out of the scope of this study, it is not clear what level of transport will be necessary to prevent the density build-up at the separatrix and whether this will be compatible with the expected plasma performance.

Finally, we ran a simulation with a lower target plasma volume-average density ($\sim 2 \times 10^{19} \text{ m}^{-3}$, corresponding to $f_G \sim 40\%$) both with fixed fuelling rate of $0.5 \times 10^{22} \text{ s}^{-1}$ and increasing the fuelling rate by $2.0 \times 10^{21} \text{ s}^{-1}$ after 100 ms of coupled simulation. As shown in figure 3, also at this lower target density, the plasma average density is decreasing after the initial JETTO/SANCO stand-alone phase indicating that fuelling rates similar to the higher density case will be necessary and that the plasma response and sensitivity to steps in fuelling rate will be weakly dependent on the target density. These conclusions, however, are preliminary and more simulations are necessary and are planned to characterise the plasma response at different target densities.

Conclusions

In this paper it has been shown that at 5 MA/2.65 T ITER H plasmas in L-mode are insensitive to variation in gas puff for $f_G > 40\%$. For $f_G \sim 30\%$ a clear plasma response was visible within 1 s when the gas fuelling rate was increased by 20% and 40%. Moreover, at 7.5 MA/2.65 T to sustain a