Integrated modelling of fuelling and density control in ITER

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Introduction

The fuelling and the control of the plasma density in ITER present many challenges and uncertainties. The high density and temperature at the separatrix will almost certainly make the scrape-off layer (SOL) opaque to the neutral penetration and the fuelling by means of gas puff less efficient than in present-day experiments. Therefore, depending on the transport characteristics of the SOL and the pedestal, other methods like pellet injection will probably be needed to reach the density required during the different phases of the discharge. In addition, the power flowing through the SOL will have to be reduced in order to avoid damaging the divertor plates but, at the same time be high enough to maintain partial attachment and avoid the onset of thermal instabilities like MARFEs. To model this problem comprehensively and self-consistently, it is necessary to take an integrated approach including the description of the core plasma, the SOL and the interaction with the first wall and the divertor plates. In this paper we present fully integrated core-SOL simulations of fuelling and density control in ITER D-T plasmas at different current and fields and levels of additional power. Simulations are carried on from the L-mode phase preceding the injection of the neutral beams, through the L-H transition, during the burn phase and during the current and density ramp-down. The sensitivity to parameters that are little known like, for example, the level of transport in the SOL is also explored. The simulations were performed with the JINTRAC suite of codes developed at JET [1], which allows to run JETTO/SANCO (for main ion and impurity core transport), EDGE2D (for main ion and impurity SOL transport) and EIRENE (neutral transport) in a coupled fashion.

L-mode simulations

Initial simulations of the ITER L-mode phase prior to the injection of neutral beam power were presented in [2]. The analysis was extended to a number of ITER L-mode scenarios at full field (i. e. 5.3 T) but different current, auxiliary power and fuelling schemes. In particular we simulated ITER L-mode plasmas at 5 MA / 5.3 T, 7.5 MA / 5.3 T, 10 MA / 5.3 T and 15 MA / 5.3 T. The crucial point in these simulations was to assess how one could reach the minimum density required to safely operate the neutral beam injectors ($\sim 2.5\cdot 10^{19}$ m^{-3} in an ITER D-T plasma) and avoid the shine-through. It should be noted that the maximum gas puff rate achievable in these simulations was limited by the fact that, beyond a certain limit, we observed a drop of the temperature at the divertor plates and the onset of a numerical instability in the code, which could indicate the appearance of a MARFE and the full detachment of the divertor. The results of the simulations are summarized in figure 1, where we show the maximum volume average density achievable in different scenarios and compare it with the NBI shine-through limit. From figure 1 it can be seen that, in ITER, it will be difficult to reach a volume average density above the NBI shine-through limit by means of gas puff only. Indeed, to apply the high gas puff rate needed to reach a volume average density above $2.5\cdot 10^{19}$ m^{-3}, additional RF power in excess of 30 MW would be required to avoid the detachment of the divertor. This level of additional power could induce an L-H transition and therefore might not be compatible with an L-mode scenario.

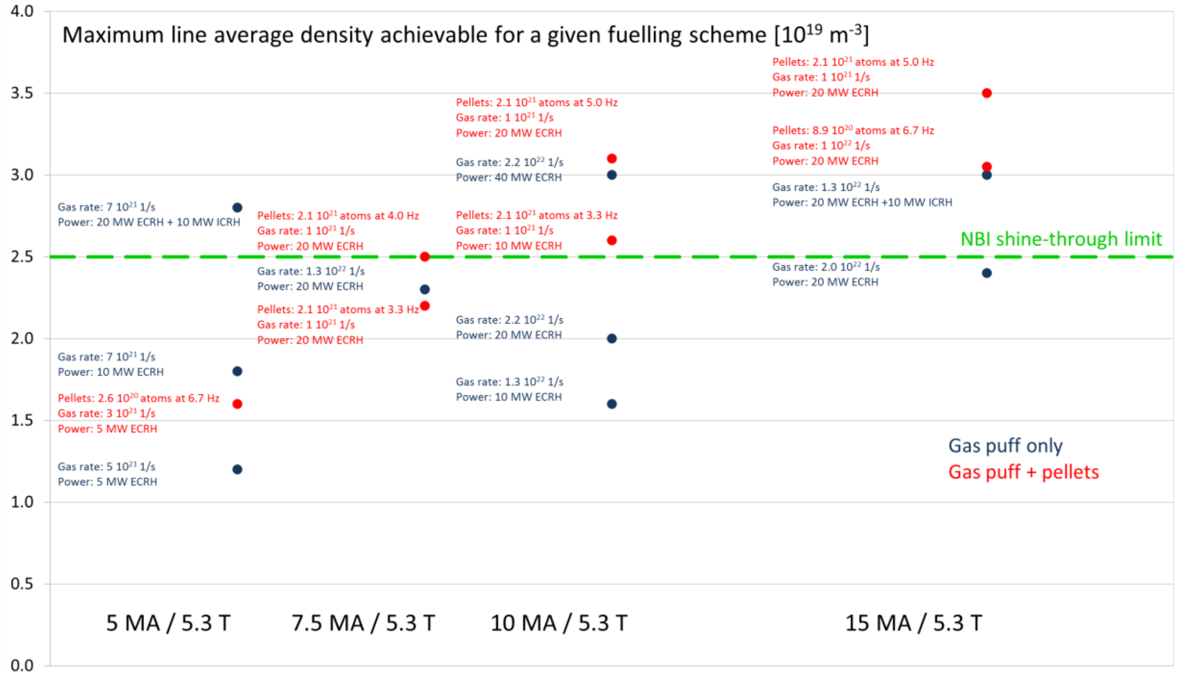

Figure 1: maximum volume average densities achievable in an ITER L-mode plasma at full field and different currents according to the simulations considered in the paper. The heating and fuelling schemes are specified next to each simulation point. Blue points indicate simulations obtained with gas puff only and red points indicate simulations obtained with gas puff and pellets. Gas is pure D, core plasma and pellets are 50-50 D-T.

From the simulations performed, it appears that a more effective way to increase the plasma volume average density above the shine-through limit is pellet injection. Figure 1 shows that a combination of pellet injection and gas puff can bring the plasma to a density where the application of the NBI is safe. However, our simulations indicate that one should avoid injecting too big pellets or using too high injection frequencies in order not to overload the SOL with fuel and cause the detachment of the divertor. Relatively small pellets are desirable also because they minimize the perturbation of the SOL parameters and improve the stability of the divertor. It should be noted that our simulations are very sensitive to the level of perpendicular transport assumed in the SOL. In particular, the results presented in this section were obtained with D=0.3 m^2/s and $\chi_{i,e}$=1 m^2/s in the SOL. Reducing these values to 0.07 m^2/s and 0.25 m^2/s respectively, resulted in a higher density at the separatrix and indicates that, in these conditions, pellets might not be required to fuel the plasma to a density above the shine-through limit [2].

L-H transition simulations

The L mode simulations at $I_p \geq 7.5$ MA presented in the previous section were used as starting points to simulate the L-H transition at different currents. 33 MW of NBI heating power were applied in addition to the RF power and an H-mode was triggered in the simulation when the power across the separatrix exceeded the L-H transition threshold according to the scaling described in [3]. The simulations show that in all cases, because of the additional power due to the α-particle heating, it is possible to make the transition from an L-Mode to an ELMy H-mode where the power crossing the separatrix is well above the L-H threshold and the pressure gradient in the edge transport barrier (ETB) is limited by peeling-ballooning stability. However, the fuelling during the phase prior to the ELMy H-mode had to be carefully tuned in order not to increase the density and decrease the ion temperature too

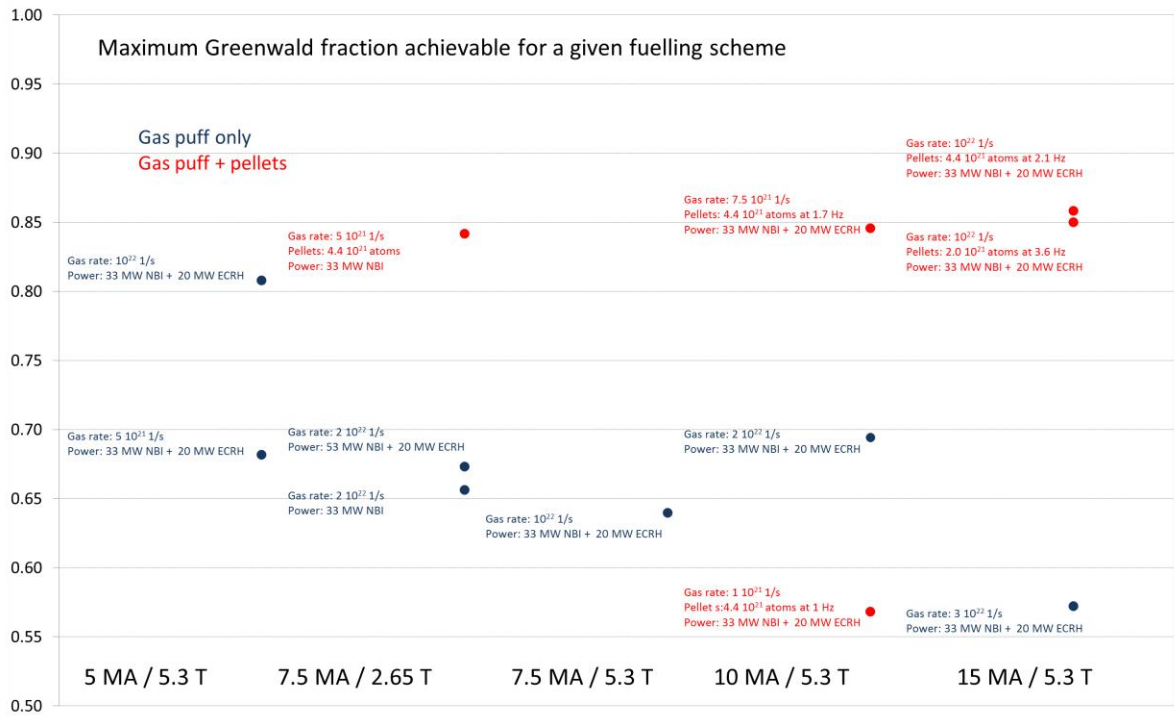

Figure 2: maximum Greenwald fraction achievable in an ITER ELMy H-mode plasma at different fields and currents according to the simulations considered in the paper. The heating and fuelling schemes are specified next to each simulation point. Blue points indicate simulations obtained with gas puff only and red points indicate simulations obtained with gas puff and pellets.

fast and allow the α-particle heating to reach the level required to keep the plasma in H-mode. In particular, we saw that a purely gas fuelled transition from an L-mode to an H-mode plasma could take from 8 s to 25 s depending on the modelling assumption. The use of pellets could be envisaged during the transition before the ETB is completely developed but, just as an excessive gas puff it has the potential to over-fuel the plasma and degrade the H-mode confinement.

H-mode simulations

In this set of simulations we assessed the maximum density achievable by gas puff only in an ITER H-mode plasma and explored fuelling schemes that could lead to a Greenwald fraction f_G~0.85, which is the level required at 15 MA to obtain Q=10. We performed simulations at 5 MA / 5.3 T, 7.5 MA / 2.65 T, 7.5 MA / 5.3 T, 10 MA / 5.3 T and 15 MA / 5.3 T. A further constraint imposed on these simulations was that the power density reaching the divertor plates should not exceed 10 MW/m^2, in order not to damage the ITER divertor. Although this constraint can be relatively easily fulfilled at $I_p \leq 10$ MA, it becomes more stringent above this level because of the additional power crossing the separatrix generated by the fusion reactions. In this situation our simulations show that a residual level of gas puff in the order of 10^{22} 1/s and Ne seeding in the order of a few 10^{19} 1/s can limit the power density at the divertor plate to less than 10 MW/m^2. The results are summarized in figure 2, where we show the Greenwald fraction achievable at different currents and fields for different fuelling and heating schemes. It can be seen that $f_G \geq 0.85$ is achievable only with a combination of gas puff and pellet injection. As discussed in the previous section, such a fuelling scheme can only be applied once the α-particle heating has reached the maximum level attainable after the L-H transition is achieved with gas puff only. In addition, our simulations show that a target plasma average density can be controlled with pellets of different size as long as the total pellet particle throughput $f_p \cdot N_p$ (where f_p is the pellet frequency and N_p is the pellet particle inventory) is constant. However, our simulations show that there is an upper limit to N_p depending on how close the divertor is to full detachment. Indeed, for a 15 MA ITER ELMy H-mode plasma with a density at the separatrix in the order of $5.5 \cdot 10^{19}$ m^{-3}, pellets bigger than $5.5 \cdot 10^{21}$ atoms could push the divertor into full detachment. To conclude this section it should be noted that the simulations presented in this analysis assumed a level of radiation in the SOL compatible with Z_{eff}~1.6. In a purer plasma (Z_{eff}~1.0) the level of radiation in the SOL and the recombination sink at the divertor would be lower and the density at the separatrix would be higher. Our simulations show that, for this extreme case, f_G~0.85 could be achievable by means of gas puff only, without the need of pellet injection.

Current ramp-down simulations

To conclude the simulation of the fuelling of an ITER discharge we simulated the current ramp down. The results of the simulations show that in order to reduce the density quickly enough to ramp down I_p at an acceptable f_G and without incurring in a density limit, we need to stop the pellet injection and reduce the gas puff to the minimum level compatible with a temperature at the target plates below 5 eV, to avoid tungsten sputtering. Initially, some Ne seeding is required to mitigate the power flux on the divertor plates. The beneficial effect of Ne seeding could become deleterious after the H-L transition has taken place because, if the Ne is not removed quickly enough, it can cool the divertor too much and cause its detachment. To avoid this problem one could envisage a feedback scheme controlling the Ne injection rate or applying some additional RF heating power during the ramp down or delaying the H-L transition until I_p<10 MA to allow for Ne to be pumped away.

Conclusions

In this paper we presented the main results of a series of integrated core/SOL simulations of the fuelling of the various phases of an ITER D-T plasma. Our main conclusions are that pellets will likely be needed in the L-mode phase prior to NBI injection to reach the minimum density required to avoid significant beam shine-through. During the L-H transition the fuelling will have to be carefully controlled to obtain a fast enough density ramp-up and, at the same time, keep the plasma in a good confinement H-mode to allow the α-heating to become dominant. After this phase pellets will be required again to achieve and sustain f_G~0.85, which is the value required to reach Q=10 at I_p=15 MA and B_T=5.3 T. At the same time some level of D and Ne fuelling will be necessary to protect the divertor and to keep the power density on the divertor plates below 10 MW/m^2. During the current ramp-down almost all fuelling will have to be switched off to ramp down the density and avoid a density limit disruption. Some Ne seeding will probably be needed to protect the divertor, but it will have to be carefully controlled (or used in combination with some additional heating) to avoid thermal instabilities that could compromise the final phase of the discharge.

Acknowledgments

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