# Coupled core/SOL modelling of fuelling requirements during the current ramp-up of ITER L-mode plasmas

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An initial assessment of fuelling of ITER L-mode plasmas indicated that it could be difficult to reach sufficient density for unrestricted use of neutral beam injection (NBI; 16.5 MW per injector; ion energy 1 MeV) by gas puff alone [1]. That assessment was carried out with the integrated Core/SOL suite of codes JINTRAC [2] by performing a gas rate scan, incrementally increasing the gas rate until the divertor plasma detached. The highest core line average density ($n_{eav}$) obtained for 15 MA / 5.3 T plasmas with 20 MW of Electron Cyclotron Heating (ECRH) marginally exceeded the density required for unrestricted use of NBI heating with acceptable shine-through loads on ITER's first wall $n_{eNBI} \sim$ 2.5-3.0 $10^{19}$ $m^{-3}$. For lower plasma currents the maximum density achieved by gas puffing was found to be lower than $n_{eNBI}$, which means that NBI modulation or operation at lower NBI energy would be required for acceptable shine-through loads. In this paper we therefore concentrate on the fuelling of lower current ITER H-modes as one option presently foreseen is to access the H-mode in the Q = 10 scenario in the ramp-up phase at a current of 10 MA which will require the use of NBI injection. Regarding SOL modelling assumptions, we have used the optimized EDGE2D/EIRENE parameter settings obtained from a dedicated benchmark between SOLPS and EDGE2D [2]. The perpendicular transport coefficients in the SOL are described by a tanh-fit decay from the core values to the asymptotic values of $\chi_{i,e}$=1.0$m^2$/s, $D_\perp$=0.3$m^2$/s in the far SOL. In the core, the plasma was modelling with JETTO with anomalous transport being described by the empirical Bohm/gryo-Bohm (BgB) model transport found to describe L-mode plasmas satisfactorily [3]. The ECRH power deposition was described by a Gaussian profile with its maximum at normalised $\rho_{tor}$ = 0.2, $\Delta\rho_{tor}$ = 0.26 and total of 10 MW.

We have carried out a series of L-mode simulations with different gas puffing rates from 1.0 $10^{21}$ $s^{-1}$ to 1.3 $10^{22}$ $s^{-1}$; at the highest fuelling rate the divertor plasma was found to detach with electron temperatures, $T_e$ < 1 eV for in a region 50 cm wide upwards of the separatrix strike point corresponding to 5 cm from the separatrix

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mapped to the outer midplane. Applying higher gas puffing rates leads to density instabilities associated with oscillatory behaviour of plasma detachment in the simulations. In order to ensure that the confined plasma has reached steady state conditions the simulations were carried out for 10s of real plasma time until the core density (and temperature) profiles reached stationary conditions. The maximum plasma density achieved in these gas fuelled simulations for 10 MA plasmas in ITER is 1.8 $10^{19}$ $m^{-3}$, which is noticeably lower than $n_{eNBI}$.

As the plasma density achievable by gas fuelling is limited by divertor detachment, an additional heating scan was carried out by increasing the power to 20 and 40 MW with the highest fuelling rate explored at 10 MW (1.3 $10^{22}$ $s^{-1}$). This leads to an increase of the $n_{eav}$ to 2.0 $10^{19}$ $m^{-3}$ and 2.6 $10^{19}$ $m^{-3}$, respectively (Fig. 1). The increase of the main plasma density is caused by the increase of the separatrix density which is possible due to the re-attachment of the divertor plasma as the power entering the SOL increases. It is important to note that, as described in [1], neutral penetration into the confined plasma is very inefficient so that there is a direct relation between the separatrix density $n_{sep}$ and the main plasma density $n_{eav}$ which depends on core plasma physics and not edge neutral ionization. These results show that 40 MW of additional heating are required to achieve a density by gas fuelling which is marginally sufficient for unrestricted heating with NBI. Although this level of RF heating is in principle possible in ITER (20 MW ECRH and 20 MW of ICRH are available), additional heating at that power level is already in excess of that required for the plasma to enter the H-mode in these conditions ($P_{L\text{-}H}$ = 25 MW), from the scaling in [4]. Access of H-mode with RF heating only can pose complications due to the change of coupling efficiency of the ICRH heating due to changes in the edge plasma parameters due to the L-H transition itself.

A more robust alternative for ITER is to achieve higher density in L-mode by pellet fuelling so that the H-mode transition can be triggered by the application of NBI. The pellets in our modelling are assumed to have a 50-50 DT mixed and they enter the plasma by the high field side with an injection velocity of 300 m/s. The deposition of the pellet mass in the plasma is modelled with the neutral gas and plasma shield (NGPS) model [5]. To evaluate the impact of pellet size on the core density profile and on the divertor parameters a scan of the pellet size has been carried out at a constant fuelling rate of ~ 1.5 $10^{21}$ $s^{-1}$ by adjusting the pellet size to 2.5 $10^{20}$, 8.4 $10^{20}$, 1.4 $10^{21}$ and 3.0 $10^{21}$ DT particles per pellet. In addition, gas puffing with a rate of 5.0 $10^{21}$ $s^{-1}$ was applied together with a power of 10 MW by ECRH. Fig. 2 shows the result of this scan demonstrating final density achieved in the plasma is independent of the pellet size. It is important to note that because the modelled plasma is in L-mode with low edge temperatures the ablation of the pellet occurs relatively deep in the plasma (peak of pellet ablation at normalized toroidal $\rho_{toroidal} = 0.75$). On the contrary, the perturbation caused by the pellets to the divertor plasmas increases strongly with pellets size so that for the largest pellet in the scan the divertor plasma is fully detached after the injection of the pellet.

Due to a lack of a solid physics basis for SOL transport that can be extrapolated to ITER, we have performed a scan of SOL transport assumptions to determine how the L-mode fuelling results depend on them. Simulations with EDGE2D/EIRENE stand-alone of JET L-mode plasmas in the high recycling regime required transport coefficients, $\chi_{i,e}$=0.5m$^2$/s, $D_\perp$=0.15m$^2$/s, in order to match the density and temperature profiles at the outer mid plane separatrix and at the outer divertor target [6,7]. Based on this and on the observations from other tokamaks, the SOL transport coefficients were varied within a wide range of assumptions including : a) a tanh decay of the core values towards the far SOL asymptotic values $\chi_{i,e}$=1.0m$^2$/s, $D_\perp$=0.3m$^2$/s, b) constant transport coefficients in the SOL with the following coefficients: $\chi_{i,e}$=1.0m$^2$/s - $D_\perp$=0.3m$^2$/s; $\chi_{i,e}$=0.5m$^2$/s - $D_\perp$=0.15m$^2$/s; and $\chi_{i,e}$=0.25m$^2$/s - $D_\perp$=0.07m$^2$/s. In all the simulations pellets of a size 8.4 $10^{20}$ particles where injected with a frequency of 3.3 Hz (2.8 $10^{21}$ $s^{-1}$ pellet fuelling rate) in addition to gas puffing with a rate of 5.0 $10^{21}$ $s^{-1}$. As shown in Fig. 3, higher SOL transport leads to a decrease of $n_{eav}$ through the reduction in separatrix density for a given fuelling rate. This is in agreement with previous simulations performed with gas fuelling only and is reproduced in the density of the plasma achieved before pellet injection starts in Fig. 3 (a gas fuelling rate of $10^{22}$ $s^{-1}$ was applied before the start of pellet fuelling in these simulations). As shown in Fig. 4, the use of pellet fuelling breaks the link between separatrix density and line average density found in gas puffing by the direct deposition of particles in the plasma leading to higher densities being reached with pellets than with gas puffing. Here it should be noted that decreasing SOL transport increases the peak divertor heat flux and thus the separatrix density that can be achieved before the divertor detaches and thus allows a higher density to be reached by gas puffing or pellet fuelling. For gas puffing $n_{eav}$ can only reach or exceed $n_{eNBI}$ for the case with lowest SOL transport while for pellet fuelling this value is reached/exceeded for wider range of SOL transport assumptions. The density that can be reached by pellet fuelling can be further increased by reducing gas fuelling (from 5.0 $10^{21}s^{-1}$ to 1.0 $10^{21}s^{-1}$) and increasing pellet fuelling (8.4 $10^{20}$ to 2.0 $10^{21}$ particles per pellet injected with frequency of 3.3 Hz). This allows $n_{eav}$ to reaching $n_{eNBI}$ even for the most pessimistic SOL transport assumption (see Fig. 5).

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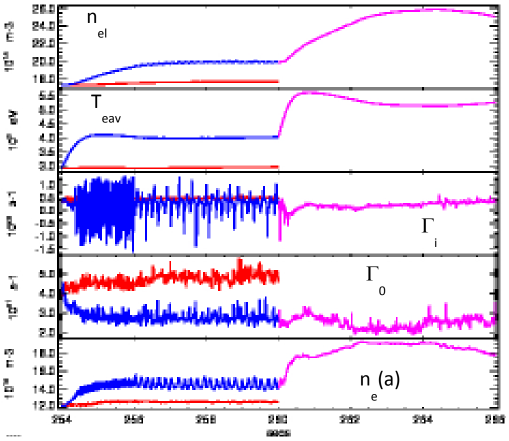

Figure 1: a) Line average core density; b) average electron temperature; c) main ion flux; d) neutral main ion flux and electron density at the separatrix time traces of the simulations with 1.3 $10^{22}$ $s^{-1}$ gas rate and different input ECRH power of ECRH: 10 MW; 20 MW; 40 MW

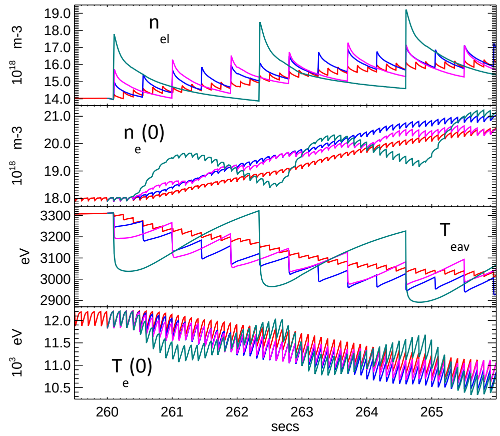


Figure 2: a) Line average core density; b) core axis electron density; c) average electron temperature; d) axis electron temperature time traces of the simulations with 5.0 $10^{21}$ $s^{-1}$ gas rate and different pellet size and frequency: 2.5 $10^{20}$ part. 6.7 Hz, 8.4 $10^{20}$ part. 2.2 Hz; 1.4 $10^{21}$ part. 1.1 Hz; 2.3.0 $10^{21}$ part. 0.44 Hz.

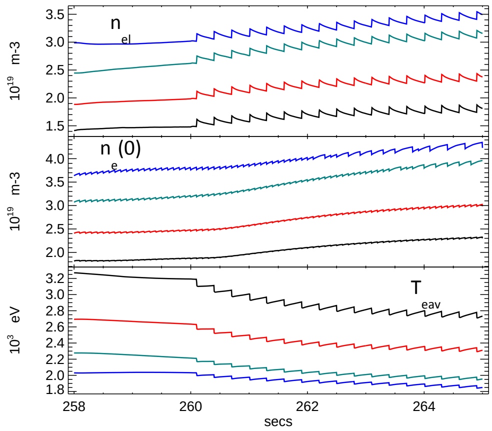


Figure 3: a) Line average core density; b) core axis electron density; c) average electron temperature; time traces of the simulations with 5.0e21 p/s gas rate, 1.5 mm pellet size 10/3 Hz pellet frequency and different SOL perpendicular transport coefficients: Tanh decay to $\chi_{i,e}$ = 1.0 $m^2/s$, $D_\perp$ = 0.3 $m^2/s$; constant $\chi_{i,e}$ = 1.0 $m^2/s$, $D_\perp$ = 0.3 $m^2/s$; $\chi_{i,e}$ = 0.5 $m^2/s$, $D_\perp$ = 0.15 $m^2/s$; $\chi_{i,e}$ = 0.25 $m^2/s$, $D_\perp$ = 0.07 $m^2/s$

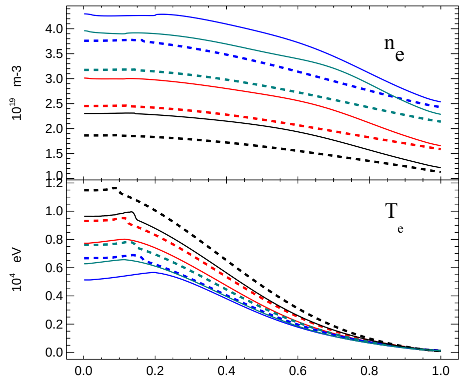

Figure 4: a) core density; b) core electron temperature profiles of the simulations with 5.0e21 p/s gas rate, 1.5 mm pellet size 10/3 Hz pellet frequency (continuous line); gas puff only of 1.0e22 p/s (dashed line) and different SOL perpendicular transport coefficients: Tanh decay to $\chi_{i,e}$ = 1.0 $m^2/s$, $D_\perp$ = 0.3 $m^2/s$; constant $\chi_{i,e}$ = 1.0 $m^2/s$, $D_\perp$ = 0.3 $m^2/s$; $\chi_{i,e}$ = 0.5 $m^2/s$, $D_\perp$ = 0.15 $m^2/s$; $\chi_{i,e}$ = 0.25 $m^2/s$. $D_\perp$ = 0.07 $m^2/s$

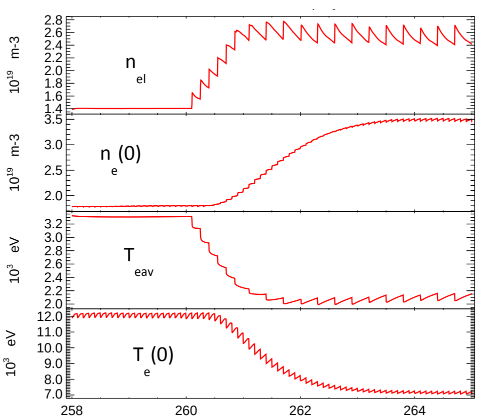

Figure 5: a) Line average core density; b) core axis electron density; c) average electron temperature; d) axis electron temperature time traces for the simulations with 1.0 $10^{21}$ $s^{-1}$ gas puffing rate and pellet injection with 2.0 $10^{21}$ particles per pellet injected with frequency of 3.3 Hz rate. SOL perpendicular transport coefficients described by tanh decay to $\chi_{i,e}$ = 1.0 $m^2/s$, $D_\perp$ = 0.3 $m^2/s$ in far SOL.