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Analysis of fuelling requirements in ITER H-modes with SOLPS-EPED1 derived scalings

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Abstract

Fuelling requirements for ITER are analysed in relation to pellet fuelling and ELM pacing, and a divertor power load control consistent with the ITER pumping and fuel throughput capabilities. The plasma parameters at the separatrix and the particle sources are derived from scalings based on SOLPS simulations. Effective transport coefficients in the H-mode pedestal are derived from EPED1 + SOLPS scalings for the pedestal height and width. 1.5D transport is simulated in the ASTRA framework. The operating window for ITER DT plasmas with the required fusion performance and level of ELM, and divertor power load control compatible with ITER fuelling and pumping capabilities, is determined. It is shown that the flexibility of the ITER fuelling systems, comprising pellet and gas injection systems, enables operation with $Q = 10$, which was found to be marginal in previous studies following a similar approach but with different assumptions. The present assessment shows that a reduction of $\langle n_e \rangle$ by a factor ~2 (from 9 to 5×10^{19} m^{-3}) in 15 MA H-mode plasmas leads to a reduction in the required pellet fuelling rate by a factor of four. Results of the analysis of the fuelling requirements for a range of ITER scenarios are found to be similar to those obtained with the JINTRAC code that included 2D modelling of the edge plasma.

Keywords: ITER, integrated control, fuelling, ELM pacing, divertor detachment, numerical simulations

(Some figures may appear in colour only in the online journal)

1. Introduction

The interplay between gas puffing, pellet fuelling and edge localized mode (ELM) pacing taking into account the loss of particles due to ELMs, and the specifications for the fuelling and pumping systems (including tritium re-processing), was originally studied for ITER in [1]. This study showed that it is not trivial to meet all ITER operational requirements for high

Q operation with the specifications for the fuelling and limitations on the pumping systems, in particular due to the required tritium throughput. However, in those simulations, transport at the pedestal was not considered (i.e. the pedestal plasma was specified) and the ITER operating window was characterized as a function of the required core fuelling, regardless of the pellet deposition profile, boundary density, core and pedestal transport. The ITER operating window was originally analysed for a controlled ELM energy loss size of δW_{ELM} ~ 1 MJ and for the range of pellet speeds 500–1000 m s^{-1} for the baseline 15 MA ITER scenario. This approach was later

applied to the ITER case with an updated limit for the tolerable controlled ELM energy loss size of $\delta W_{ELM} \sim 0.6$ MJ [2].

The ITER core fuelling requirements evaluated with this approach depend on the boundary conditions, the transport model and the particle deposition profile. In fact, the particle deposition profile from pellet injection depends on the pellet size and speed, and on the pedestal plasma parameters [3]. The dependence of the fuelling requirements on the pellet deposition profile for $\delta W_{ELM} \sim 1$ MJ was discussed in [4] but the effect of the boundary conditions on the results obtained was not studied there. The first attempt to analyse the particle balance along the lines of [1], but calculated self-consistently with boundary conditions from SOLPS modelling, was carried out in [5] for ITER using the ICPS transport model (plus additional assumptions concerning the pellet deposition profiles), and assuming that ITER $Q = 10$ operation would take place with a carbon fibre composite divertor.

The analysis presented in this paper, includes, for the first time, a self-consistent model of all effects required to assess the ITER fuelling requirements with a tungsten divertor, including the specification of the separatrix density for acceptable power load control, pellet pacing requirements for ELM control and modelling of the transport in the edge transport barrier. For the separatrix parameters and penetration of the gas from the edge, we use the SOLPS parameterisation derived for ITER operating with a tungsten divertor. The pedestal transport coefficients are fitted to provide the pedestal height and width predicted by EPED1 + SOPLS modelling [6] and the particle deposition profile from pellet injection is calculated consistently using the model [3].

In section 2, we describe the modelling approach, tools and assumptions. In section 3, we describe the results of our simulations for DT H-mode plasmas, and their extrapolation to ohmic and L-mode plasmas, and we determine the operating window for the ITER fuelling systems compatible with divertor power load and ELM control. In section 4, we summarize the results of our analysis.

2. Transport model and ITER design specifications

There are several design specifications and physics limitations that determine the boundaries of the ITER operating window with respect to fuelling and pumping. The average fuel throughput for ITER plasmas with 400 s burn duration is limited by the capabilities of the tritium re-processing system at the level of

$$G_{DT} \leqslant G_{DT,max} = 200 \, \text{Pa} \, \text{m}^3 \, \text{s}^{-1}, \tag{1}$$

while the maximum pumping speed is determined by the cryopumping systems design

$$S_{eng} \leqslant 75 \, \text{m}^3 \, \text{s}^{-1}. \tag{2}$$

The gas throughput and the associated neutral density at the divertor are found to affect the state of plasma detachment, which in turn determines the divertor power load. Total divertor detachment is found to occur in ITER modelling when the normalised average neutral pressure in the divertor private

flux region (μ) is sufficiently high so that $\mu = 0.67 p_n/P_{SOL}^{0.39}$ (Pa, MW) = 1 [7], where p_n is the modelled neutral pressure and P_{SOL} is the edge power flow. The divertor neutral pressure can be controlled by pumping (S_{eng}) [7]; for a given fuelling rate G_{DT}, $p_n = 4.79 \, (G_{DT}/S_{eng})^{0.83}/P_{SOL}^{0.13}$. Thus, following [7] the normalised neutral pressure can be parameterized as:

$$\mu = (G_{DT}/(4.39 S_{eng}))^{0.83}(P_{SOL}/100 \, \text{MW})^{-0.52} \leqslant 1. \tag{3}$$

Total divertor detachment is usually associated with strong neutral decompression and deteriorated H-mode confinement in the present experiments and, thus, for high energy confinement ITER operation the assumed limit is $\mu \leqslant 1$.

The choice of μ for ITER divertor operation (under the limit of 1) is determined by the control of the peak divertor power load [7]:

$$q_{pk}(\mu, P_{SOL}, n_{imp}) \leqslant 10 \, \text{MW} \, \text{m}^{-2}. \tag{4}$$

Thus, for a given P_{SOL}, μ can be decreased when impurity puffing is applied as the peak power load decreases with increasing impurity concentration, $q_{pk} \sim \left(n_{imp}/n_e\right)^{-\alpha}$, $\alpha \sim 0.2$–0.3.

The energy losses associated with the uncontrolled ELMs predicted for H-mode operation at full magnetic field/full current $B/I_p = 5.3/15$ (T MA^{-1}) in ITER can reduce the life of the divertor under that required for acceptable availability for experimental exploitation. One of the techniques proposed for ELM control in ITER is ELM pacing by pellet injection [8]. Injection of pellets, required to decrease the ELM energy loss to an acceptable level,

$$\delta W_{ELM} \leqslant 0.6 \, \text{MJ}, \tag{5}$$

creates a particle flux, G_{LFS}, which also contributes to the throughput [1].

Thus, the net particle throughput in ITER discharges includes the particle outflux from the confined plasma, due to the transport processes, G_{SOL}, the particle outflux associated with the ELMs, G_{ELM}, the particle flux required for ELM control by pellet pacing, G_{LFS}, the gas fuelling, G_{aux}, used for control of divertor detachment and power loads (for example, gas puffing G_{div}), and the gas injection for ICRH coupling, G_{IC}, if necessary:

$$G_{DT} = G_{SOL} + G_{ELM} + G_{LFS} + G_{aux} + G_{IC}. \tag{6}$$

Note that G_{aux} and G_{IC} may not be required if all other particle fluxes are sufficient to maintain the divertor parameters within the limits in equations (3) and (4), and provide the required ICRH coupling. From equation (3) it follows that operation at lower normalized neutral pressure, μ, and lower pumping speed, S_{eng}, is less demanding regarding the required particle throughput and fuelling. Thus, the amount of G_{aux} that is required for detachment control can be decreased by either decreasing the pumping speed or increasing impurity seeding while maintaining the divertor power load at acceptable levels, $q_{pk} \leqslant 10$ MW m^{-2}. This provides some flexibility in meeting the specification for the maximum average particle throughput in ITER in equation (1). It should be noted, however, that both impurity seeding and the reduction of the pumping have implications for the contamination of the main

plasma by extrinsic impurities and by helium ash accumulation, respectively, and both impact the fusion performance of ITER and, thus, the flexibility provided for ITER by these approaches is restricted for high Q operation.

The design of the ITER pellet injection system (PIS) incorporates flexibility in pellet size, speed, injection location and fuel mix. The pellet size (V_{pel}) can be chosen to be 90/50/33/17 mm^3, with the possibility of changing it during the discharge by $\pm 20\%$ from any of these pre-set values. The maximum pellet injection speed for which pellets are expected to arrive intact in the plasma is $v_{inj} = 300$ m s^{-1} (the maximum pellet injection speed $v_{inj,max} = 500$ m s^{-1} is expected to cause pellets to break into fragments due to the curvature of the ITER pellet injection tracks). At $v_{inj} = 300$ m s^{-1} only 10% of the average pellet mass is expected to be lost in the guide tube. The pellets can be injected from the high field side (HFS) for core fuelling, and from the low field side (LFS) for ELM pacing. It is important to note that although the HFS fuelling pellets are utilized to fuel the core plasma and thus control the plasma density, they are also found to trigger ELMs and this reduces the ELM pacing requirements by LFS pellet injection [9]. This reduction provides some flexibility to optimize the divertor power load control within the total throughput design limits, as follows from equation (6). The pellets delivered to the ITER plasma can be either pure D pellets or DT ones, either being provided by two feeding lines with the capacity of each line of 120 Pa m^3 s^{-1} delivering $G_{pel} = G_{HFS} + G_{LFS} \leqslant G_{pel,max} = 0.9 \times 240 = 216$ Pa m^3 s^{-1} to the plasma, when losses in the pellet injection tracks are accounted for. The isotopic DT composition in the pellets can be varied in one of the lines to a maximum of 90% T (foreseen to be used for HFS pellet fuelling), while the second line provides pellet injectors with pure D pellets (foreseen to be used for HFS pellet fuelling and LFS ELM pacing).

Parameterisation of the results of the SOLPS modelling [7] provides the boundary conditions for the electron and ion separatrix temperatures, $T_{ie,s}$, electron, DT ions and helium ash separatrix densities, $n_{e,s}$, $n_{DT,s}$, $n_{He,s}$, and the ionisation source from the edge neutrals into the confined plasma, G_{sep}, which are consistent with the power and particle fluxes to the SOL, P_{SOL} and G_{SOL}, as well as with the gas puffing level, G_{aux}, required to keep plasma in the partially detached divertor condition that provides acceptable divertor power loads. The particle outflux from the core plasma, G_{SOL}, depends on the pedestal width, the values of the plasma density at the pedestal top and separatrix, the pedestal transport coefficients, diffusivity D and pinch velocity V_p. To maintain the required density at the pedestal it is necessary to compensate this outflux, G_{SOL}, and that driven by the controlled ELMs, G_{ELM}, by HFS pellet injection providing the required core plasma fuelling, G_{HFS}, while taking into account fuelling of the plasma by neutrals penetrating from the edge to the core, G_{sep}, and the core fuelling provided by the neutral beam injection (NBI), G_{NBI}.

$$G_{SOL} + G_{ELM} = S_a(D \nabla n - V_p n) = G_{sep} + G_{HFS} + G_{NBI}, \tag{7}$$

where S_a is the plasma surface area, and the particle source from neutrals that have penetrated the core plasma from the SOL, G_{sep}, is obtained from the SOLPS parameterisation [7].

Note that in equations (6) and (7) we assume for simplicity that all the particles delivered to the plasma by pellets injected from the LFS for ELM control drift out of the core plasma and do not contribute to core plasma fuelling.

To simulate the heat and particle transport in the plasma core with ASTRA [10] we use the scaling-based model with prescribed profiles of the heat diffusivities, $\chi_e = \chi_i = \chi_{eff} = C_D(1 + 3x^2)$, where the factor C_D is fitted to provide the energy confinement time corresponding to the empirical scalings, $\tau_E = \tau_{scaling}$ derived for ohmic [11], L- and H-mode [12] operation. For particle diffusivity we take the empirical relation $D = 0.2\chi_{eff}$, derived from JET experiments for ITER-like conditions [13]. We have performed sensitivity studies for the particle pinch velocity using the expression $V_p = C_v Dr/r_s^2$ and varying C_v in the range $C_v = 0$–0.5. $C_v = 0$ is the reference value (i.e. purely diffusive profiles) and we assume the same anomalous particle transport coefficients for all species including He.

The transport coefficients in the H-mode pedestal region are specified to fit the pedestal plasma pressure, p_{ped} and width, Δ_{ped} obtained from EPED1 modelling, including SOLPS-derived boundary conditions [6]:

$$p_{ped} = 4.34 \, B^{0.84} I_p/a \text{ (kPa,T, MA,m)}, \tag{8}$$

$$\Delta_{ped}/\psi_s = 0.05 p_{ped}^{0.5}/I_p \text{ (kPa, MA)}. \tag{9}$$

Here, B is the toroidal magnetic field, I_p the plasma current, a the minor radius and ψ_s the separatrix value of the poloidal magnetic flux (i.e. Δ_{ped}/ψ_s provides the pedestal width in normalised magnetic flux units). The heat diffusivity, χ_{eff}, in the pedestal region of width Δ_{ped} is fitted to provide the plasma pressure at the pedestal top, p_{ped}. The boundary conditions T_s, n_s, $n_{He,s}$ are derived from SOLPS scalings [7] consistent with the power and particle fluxes to the SOL.

Following [1] we derive the frequency required for ELM control through the empirical scaling for the ELM energy loss with small pellets [14]:

$$f_{pel} = 0.2 \, P_{SOL}/\delta W_{ELM}, \tag{10}$$

with f_{pel} sufficient to keep the controlled ELM energy loss $\delta W_{ELM} \leqslant 0.6$ MW. For small ELMs in ITER, similar to findings in present experiments, we assume that the ELM energy loss from the core plasma is fully convective. Thus, the total core plasma outflux associated with the controlled ELMs can be expressed as

$$G_{ELM} = f_{pel} N_{ped} \delta W_{ELM}/W_{ped} = 0.2 N_{ped} P_{SOL}/1.5 V p_{ped}, \tag{11}$$

where $N_{ped} = V n_{ped}$ and $W_{ped} = 1.5 V p_{ped}$ are the pedestal particle and energy content, and V is the total plasma volume.

The frequency of the fuelling pellets, f_{HFS}, is chosen in our modelling to provide the required core plasma density:

$$G_{HFS} = G_{SOL} + G_{ELM} - G_{sep} - G_{NBI} = f_{HFS} \delta N_{HFS,pel}, \tag{12}$$

where $\delta N_{pel} = V_{pel} 6 \times 10^{19}$ mm^{-3} is the number of particles in a pellet of volume V_{pel} (mm^3).

Finally, the particle flux provided by the LFS pellet for ELM pacing is determined by the additional pellets required

to achieve the necessary controlled ELM frequency (f_{pel}) once the HFS pellets have been subtracted:

$$G_{LFS} = (f_{pel} - f_{HFS})\delta N_{LFS,pel}. \tag{13}$$

The goal of our study is to determine the operating window for a range of ITER DT plasmas. That is, the range of plasma parameters that can be achieved in a controlled way taking into account all the operational constraints regarding stationary divertor power fluxes, ELM energy loss as well as the limits imposed by the design from the ITER PIS, gas injection system (GIS) and pumping systems.

3. Operating window

Based on the considerations described in section 2, it is possible to assess the window for ITER plasma operation where divertor power load and ELM control can be provided simultaneously with the required operating density. We consider first the full-field/full-current operation $B/I_p = 5.3/15$ (T MA^{-1}) in H-mode for the range of the plasma densities discussed in [6]. For this case equations (8) and (9) give the following values for the top of the pedestal pressure and width:

$$p_{ped} \sim 130\,\text{kPa} = 0.13\,\text{MJ m}^{-3},\ \Delta_{ped}/\psi_a \sim\ 0.038.$$

For the plasma volume at full bore, $V = 816$ m^3 and the controlled ELM energy loss of $\delta W_{ELM} \sim 0.6$ MJ, this yields

$$W_{ped} = 1.5Vp_{ped} = 160\,\text{MJ},\ \delta W_{ELM}/W_{ped} = 0.0038,$$

which corresponds to small convective ELMs, as discussed in section 2.

For baseline operation at $Q \sim 10$, $n_{ped} \sim 10^{20}$ m^{-3}, $P_{SOL} \sim 100$ MW, $f_{pel} = 0.2\,P_{SOL}/\delta W_{ELM} \sim 35$ Hz, the plasma particle outflux caused by the ELMs is sizeable:

$$G_{ELM} = f_{pel}N_{ped}\delta W_{ELM}/W_{ped} = 0.2n_{ped}P_{SOL}/1.5/p_{ped} \sim 20\,\text{Pa m}^3\,\text{s}^{-1}. \tag{14}$$

In order to maintain the pedestal density above the separatrix density, the minimum fuelling provided by pellet injection must be larger than the ELM-caused outflux, i.e. $G_{HFS} > G_{ELM}$.

For the minimum pellet size of $\delta N_{pel} = 2 \times 10^{21}$ ($V_{pel} = 33$ mm^3), which is required for ELM triggering for LFS and HFS injection [9], the total pellet particle flux required for ELM control is $\delta N_{pel}f_{pel} = G_{HFS} + G_{LFS} \sim 120$ Pa m^3 s^{-1}, which is a significant fraction of the maximum fuel throughput in ITER (see equation (1)). For $Q = 10$ operation in ITER G_{sep} and G_{NBI} are very small (low penetration of neutrals in the core plasma and very low fuelling rate of the 1 MeV ITER NBI system). Therefore, from equation (7), $G_{SOL} \approx G_{HFS} - G_{ELM}$ in these conditions. Analysis of the total particle flux balance in ITER from equation (6), and taking into account that the maximum fuel throughput is $G_{DT} \leqslant 200$ Pa m^3 s^{-1}, shows that gas puffing can be applied in ITER up to a level of:

$$G_{aux} + G_{IC} \leqslant G_{DT} - G_{HFS} - G_{LFS} \sim 80\,\text{Pa m}^3\,\text{s}^{-1}, \tag{15}$$

enabling the independent control of the divertor power loads from the core plasma density. In practice, the additional

fuelling for divertor power load control can be provided by gas puffing, $G_{aux} = G_{puf}$, or by injection of very small pellets from the LFS ($V_{pel} < 33$ mm^3), which neither fuels the plasma nor triggers ELMs. In this respect, it should be noted that the latency of the PIS, which has an injection length of $L_{tube} \sim$ 15 *m*, $\Delta t_{PIS} \sim L_{tube}/v_{inj,max} \sim 15/500 \sim 0.03$ s, is much shorter than the latency of GIS, $\Delta t_{GIS} \sim 1$ s. Thus using small pellets injected from the LFS could be advantageous if fast control of the divertor power load/divertor detachment is required.

Once the ELM control requirements are fixed, the required plasma density and corresponding plasma outflux determines the frequency of the HFS fuelling pellets following equation (2). Use of larger size fuelling pellets (50, 90 mm^3) reduces the HFS pellet injection frequency for a given total fuelling flux as $f_{HFS} \sim 1/V_{HFS,pel}$. This frequency decrease has to be compensated by more frequent LFS pellet injection in order to keep the required frequency for ELM control, $f_{pel,ELM}$, i.e. $f_{LFS} = f_{pel,ELM} - f_{HFS}$. The use of larger size pellets for HFS fuelling leads to an increase in the total fuelling flux that the PIS (LFS+HFS) provides and thus reduces the room to control divertor power loads independently by gas puffing. Therefore, core plasma fuelling by HFS pellets having the smallest size that is sufficient to provide ELM triggering appears to be optimal for the independent control of divertor power loads from core plasma fuelling. For fuelling by pellets, and for the particle outflux by ELMs, we used so-called 'continuous' or time-averaged models with radial profiles of particle sources and sinks calculated by the model in [3].

The gain in control flexibility by varying the HFS pellet size for a particular operational point in ITER is, of course, dependent on the magnitude of G_{HFS} versus G_{LFS}, which is required to achieve this operational point. In addition, the larger HFS pellets penetrate deeper into the plasma and can fuel the plasma core with a higher efficiency (see figure 1). Thus the optimum pellet size for HFS fuelling (above the minimum for ELM triggering) that minimizes fuel throughput would be set by the balance of the better fuelling efficiency of larger HFS pellets versus the need for additional LFS pellets for ELM control due to the reduced frequency of HFS pellet injection. This optimization requires detailed models of the particle losses following pellet injection and is beyond the scope of this paper.

Using the results above, and taking into account the divertor detachment parametrization in equation (3), we can determine the ITER operating window for 15 MA/5.3 T H-mode operation with $P_{aux} = 50$ MW (33 MW of NBI and 17 MW of ECRH) for which divertor plasma detachment/divertor power loads, the required pumping speed, and the HFS and LFS injection pellet size (sufficiently large for ELM pacing) are chosen to have values away from engineering design and physics limits: $\mu = 0.7$ (away from full divertor detachment), $S_{eng} = 50$ m^3 s^{-1} (2/3 of the maximum), and $V_{HFS} = V_{LFS} = 33$ mm^3 (1/3 of the maximum). The DT mix of the fuelling systems is adjusted so as to provide $n_D = n_T$ in the plasma core. The resulting H-mode operating window for ITER 15 MA/5.3 T DT plasmas for a density range $\langle n_e \rangle = 4.4$–$9.8 \times 10^{19}$ m^{-3} is shown in figure 2. In these simulations, we assume a moderate fraction of neon, $n_{Ne}/n_{es} = 0.5\%$, to provide divertor radiation
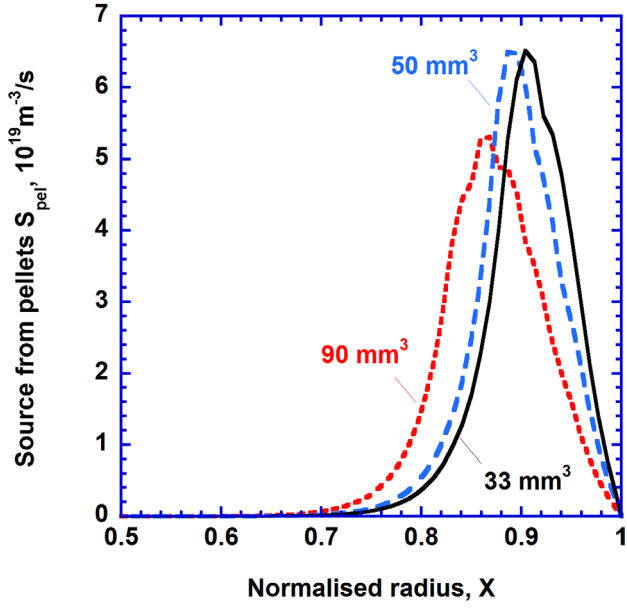
Figure 1. Fuelling profile of HFS pellets of different sizes predicted by [3] for an ITER baseline scenario plasma, $Q = 10$, $I_p = 15$ MA.
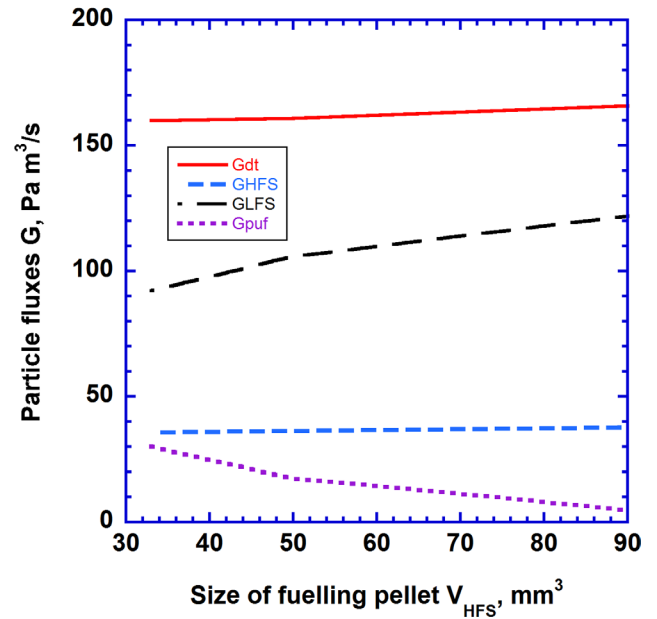

Figure 2. ITER 15MA/5.3 T, $P_{aux} = 50$ MW H-mode operation at $\mu = 0.7$, $S_{eng} = 50$ m^3 s^{-1}, and the same size of HFS and LFS pellets $V_{HFS} = V_{LFS} = 33$ mm^3.

Figure 3. ITER 15MA/5.3 T, $P_{aux} = 50$ MW $Q = 10$ H-mode operation at $\mu = 0.7$, $S_{eng} = 50$ m^3 s^{-1} and $V_{LFS} = 33$ mm^3 for different sizes of HFS pellets.

for power load control. With this assumption, the resulting separatrix densities from SOLPS scalings [7] are in the range $n_{es} \sim 3.8$–5.9×10^{19} m^{-3}. At low densities $\langle n_e \rangle < 5.5 \times 10^{19}$ m^{-3}, for which $Q < 5$, the core plasma particle outflux by the pellet-triggered controlled ELMs dominates because the ratio of separatrix to pedestal density is close to 1 and the plasma outflux between ELMs is negligible. The ELM particle outflux in these conditions is balanced by fuelling with HFS pellets, but its magnitude is small because the pedestal plasma density is low, $G_{HFS} \sim 5$–10 Pa m^3 s^{-1}. Note that the plasma parameters predicted for the low density range with controlled ELMs and low HFS pellet injection fuelling rate predicted by using the SOLPS parameterization here, for similar core transport assumptions, are similar (within $\sim 10\%$) to the parameters simulated with JINTRAC (which includes a full integrated model of the core and SOL plasma) with pure gas fuelling alone [15].

This is in agreement with the comparison of JINTRAC and ASTRA-SOLPS results described in [15] and consistent with the low fuelling source from the edge neutrals, $G_{sep} < 2$ Pa m^3 s^{-1} in these conditions. On the other hand, increasing the plasma density towards the $Q \sim 10$ operating conditions requires a substantial increase in the HFS pellet fuelling rate up to a level of ~40 Pa m^3 s^{-1}. This is caused by the increased particle outflux by ELMs due to the increased P_{SOL} (from 5 to 21 Pa m^3 s^{-1}) at higher Q and the reduced ratio of separatrix to pedestal density that increases the plasma outflux between ELMs [6].

Our simulations show that for the chosen parameters for the degree of divertor detachment, pumping speed and pellet size, away from engineering and physics limits, plasma operation can be achieved that satisfies the requirements regarding divertor power load control and total particle throughput. This is also the case for the largest HFS fuelling pellets at $Q \sim 10$ with volume $V_{HFS} = 90$ mm^3, as shown in figure 3.
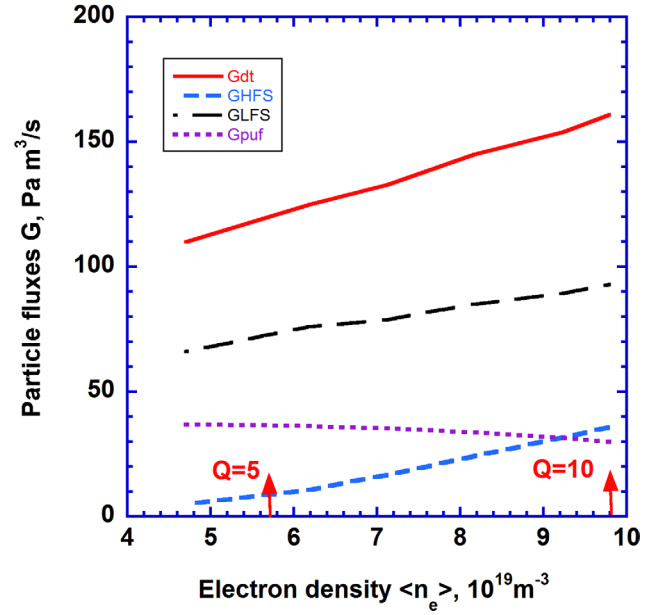
In our simulations above we have assumed auxiliary heating by NBI and by ECH (i.e. $G_{IC} = 0$). If ICRH heating requires significant gas puffing, in addition, to provide the necessary coupling of the RF waves to the plasma ($G_{IC} > 0$) then, for a given total G_{DT}, the range of fuelling rates that can be applied for divertor power load control G_{aux} could be more restricted.

If the moderate values of S_{eng} and μ used above are replaced by a higher pumping speed, $S_{eng} \sim 60$ m^3 s^{-1}, and operation closer to detachment, $\mu \sim 0.8$ the total average fuel throughputs required to achieve the range of densities typical for $Q = 10$ operation can exceed the ITER design limit, as also found in [5]. This can be
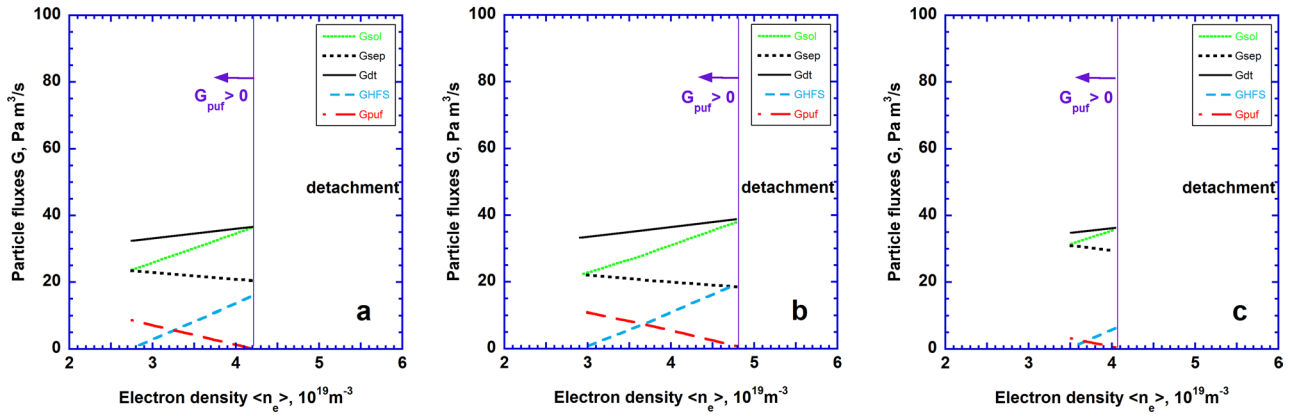
Figure 4. Extrapolation of SOLPS scalings [7] to ohmic operation at $I_p = 15$ MA with $P_{SOL} \sim 10$ MW, $\mu = 0.85$ and $S_{eng} = 70$ m^3 s^{-1}. Case (*a*) corresponds to a high separatrix density with low neon seeding ($n_{Ne}/n_{es} = 0.2\%$); case (*b*) corresponds to a case with the same assumptions as (*a*) but with anomalous pinch, $C_v = 0.5$; case (*c*) corresponds to a low separatrix density ($n_{Ne}/n_{es} = 0.3\%$) with anomalous pinch, $C_v = 0.5$.

partially mitigated by the decrease of neon seeding to increase the separatrix density for the same n_{ped} and, thus, decrease the plasma outflux between ELMs G_{SOL} ($G_{SOL} \sim D(n_{ped} - n_s)/\Delta_{ped}$). It should be noted, however, that because the particle flux caused by ELMs is larger than the outflux between ELMs ($G_{ELM} > G_{SOL}$), this approach is of limited application. Obviously, the results obtained depend on the assumptions used for particle transport modelling. For instance, the presence of a sizeable inward pinch in the plasma core and, more importantly, in the H-mode pedestal modify quantitatively our evaluation of the required fuel throughput to achieve a given plasma core density.

In this respect, the operating window for ohmic and L-mode plasmas in ITER is more sensitive than H-mode plasmas to the value of the separatrix density, and to the details of the edge particle transport modelling assumptions due to the absence of controlled ELMs and their associated outflux. We have evaluated the operating window for 15 MA/5.3 T ohmic and L-mode plasmas by applying a similar methodology as for H-mode plasmas, albeit with larger uncertainties. In first place, the results used for the scalings of the separatrix conditions from SOLPS [7] correspond to typical H-mode plasma conditions in ITER with $P_{SOL} \geqslant 40$ MW. In addition, the anomalous edge plasma transport is much larger in ohmic and L-mode plasmas than in H-modes so that the SOL power decay length is smaller in H-modes than in ohmic and L-mode plasmas ($\lambda_q^H < \lambda_q^{OH}, \lambda_q^L$). Both the lower P_{SOL}, and the larger λ_q, in ohmic and L-mode plasmas reduce the separatrix density required to achieve a given level of plasma detachment μ compared to H-mode plasmas and thus the achievable core plasma density. This effect has been included quantitatively in our studies by extrapolating the SOLPS scalings [7] to lower P_{SOL} and by decreasing the value of P_{SOL} used in these scalings by $\lambda_q^H/\lambda_q^x = (\chi_{edge}^H/\chi_{edge}^x)^{0.5}$, where x = ohmic or L-mode, to account for the lower parallel power flux in the SOL in ohmic and L-mode plasmas for a given value of P_{SOL} compared to H-mode, which decreases the density required to achieve a given degree of detachment.

The results of our modelling studies for 15 MA/5.3 T ohmic ($P_{SOL} = 10$ MW) and L-mode ($P_{SOL} = 20$ MW) plasmas with

the extrapolated boundary conditions from the SOLPS scalings following the approach described above and assuming $\mu = 0.8$–0.85 (no effect of detachment degree on ohmic and L-mode confinement is expected) and $S_{eng} = 50$–75 m^3 s^{-1} are shown in figures 4 and 5. For the ohmic and L-mode plasmas, a much better penetration of the neutrals from the edge is obtained than in H-mode and thus $G_{sep} \sim 10$–20 Pa m^3 s^{-1}. However, pellet fuelling is still required to achieve plasma densities above 2.5–3.5×10^{19} m^{-3} because of the much larger edge anomalous transport level in ohmic and L-mode compared to H-mode due to the absence of a transport barrier, as found in [16], where JINTRAC full modelling of the core and edge plasma is performed. Operation in these conditions is far from the ITER average particle throughput limit, but is close to the point in which divertor detachment control is lost, also in agreement with findings in [16]. In fact, independent control of detachment from core fuelling becomes impossible when $G_{aux} \rightarrow 0$. Puffing of impurities, which might be used to reduce the NBI shine-through loads at low plasma densities by the increased impurity concentration, reduces the required separatrix density for a given level of plasma detachment. This improves neutral penetration from the edge but ultimately reduces the operating window over which divertor conditions can be independently controlled from core fuelling, as shown in figures 4(*b*), (*c*) and 5(*a*), (*b*). This effect is more severe at low power, i.e. for ohmic plasmas in which $P_{SOL,OH} < 10$ MW. On the other hand the presence of an inwards particle pinch in the core plasma can increase the operating window density range by about 20% for ohmic plasma conditions (figures 4(*a*) and (*b*)). Similarly, increasing the pumping speed from 50 to the maximum of 75 m^3 s^{-1} in L-mode conditions is found to increase the operating window density range by 35% (figures 5(*b*) and (*c*)).

4. Discussion and conclusions

Our analysis of the integrated control of the divertor power loads, core plasma fuelling and ELM control reveals that the ITER baseline H-mode operation with $Q = 10$ and $P_{aux} = 50$ MW
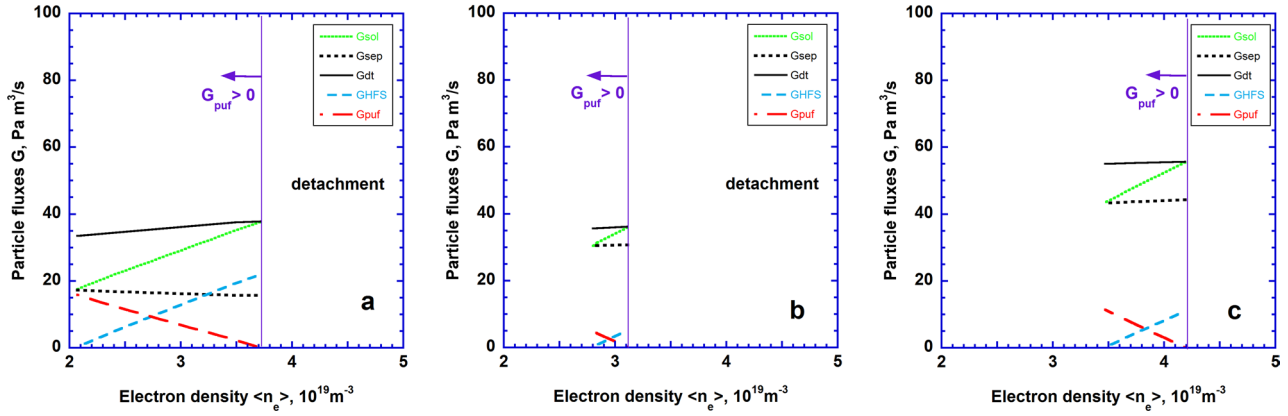
Figure 5. Extrapolation of SOLPS scalings [7] to L-mode operation at $I_p = 15$ MA with $P_{SOL} \sim 20$ MW and $\mu = 0.8$. Case (*a*) corresponds to a high separatrix density with low neon seeding ($n_{Ne}/n_{es} = 0.5\%$) and pumping speed $S_{eng} = 50$ m^3 s^{-1}; case (*b*) corresponds to a low separatrix density with higher neon seeding ($n_{Ne}/n_{es} = 1\%$) and pumping speed $S_{eng} = 50$ m^3 s^{-1}; case (*c*) corresponds to a low separatrix density with higher neon seeding ($n_{Ne}/n_{es} = 1\%$), and with the highest pumping speed, $S_{eng} = 75$ m^3 s^{-1}.

with high edge power flux $P_{SOL} \sim 100$ MW can be achieved with LFS pellets of a size sufficient for ELM triggering of $V_{LFS} = 33$ mm^3, and HFS pellets over the whole size range of $V_{HFS} = 33/50/90$ mm^3 within physical limits and design requirements of the ITER systems, $\mu \leqslant 1$, $q_{pk} \leqslant 10$ MW m^{-2}, $\delta W_{ELM} \leqslant 0.6$ MJ, $G_{DT} \leqslant 200$ Pa m^3 s^{-1}.

To have flexibility for integrated and simultaneous control of all the required parameters, the operational point in terms of degree of detachment and pumping speed should be chosen sufficiently far from their limits; otherwise simultaneous control is not possible in some conditions as already identified in [5]. The 15 MA/5.3 T, $P_{aux} = 50$ MW operating window for ITER H-mode plasmas that fulfils the physical limits and system design requirements is wider if the smallest pellets sufficient for ELM triggering are used for both fuelling and ELM pacing, $V_{LFS} = V_{HFS} = 33$ mm^3, whereas the largest fuelling pellets, $V_{HFS} = 90$ mm^3, provide better fuelling efficiency but a smaller operating window due to the required increase in LFS pellet injection frequency for ELM control. This conclusion is sensitive to assumptions regarding the increase of fuelling efficiency with increasing pellet size in ITER, which is subject to uncertainties such as the quantification of pellet particles, which are expelled by the ELMs triggered by the pellets. Similarly, the evaluated operating window can be modified by the RF heating method applied if ICRH heating requires significant additional gas puffing to ensure appropriate coupling of the antenna to the plasma.

Since the smaller size LFS pellets, $V_{pel} \sim 17$ mm^3, considered in the ITER design are not expected to trigger ELMs, injection of such pellets can be used for divertor power load control, at least during confinement transients where a fast response is required, which is unlikely to be achieved by gas puffing in ITER due to the large dimensions of the device and the long length of gas fuelling lines. For this goal it is not required that fully intact pellets reach the plasma and, therefore, the pellet injection velocity can be increased to the design limit of 500 m s^{-1}, which decreases the latency of the PIS to $\Delta t_{PIS} \sim 0.03$ s (for comparison, the latency of GIS is expected to be, $\Delta t_{GIS} \sim 1$ s in ITER).

In our analysis we use several assumptions, based on experimental data and results of other ITER modelling studies, which can affect the boundaries of the ITER H-mode operating window obtained. In particular, the minimum pellet size sufficient for ELM triggering has been determined for fixed pedestal parameters in ITER corresponding to $Q \sim 10$ operation [9]. To predict the required pellet size for ELM triggering further non-linear MHD simulations, along the lines of [9], for a range of ITER plasma conditions, are required to determine how the minimum pellet size for ELM triggering changes with pedestal plasma conditions in ITER. We also assume a simplified model for LFS injected pellets in which they do not contribute at all to core plasma fuelling. Some residual fuelling from the LFS injected pellets will take place in ITER and, if sizeable, this could extend the operating window as well. Our simulations were performed with models that replace the transients caused by ELMs and pellets. However, fuelling by pellets, and the particle outflux due to the convective losses by ELMs, are strongly dynamical processes and their precise evolution can, in principle, affect the fuelling efficiency of pellets and thus modify the operating window that we have identified. Regarding ELMs we do not expect a large difference between our results and those that could be obtained by including the ELM energy losses. Considering ELMs decreases the power flux to the SOL between ELMs by ~20% (see equation (14)), this only affects very moderately the achievable density in H-mode conditions as we also choose our operational point far from the detachment limit, $\mu = 1$. In addition, the resulting ELMs by pellet pacing are small $\delta N_{pel}/N_{ped} \sim 2.5$–6%, $\delta W_{ELM} \sim$ 0.6 MJ with moderate frequencies, $f_{ELM} \sim 30$ Hz and for similar conditions (1 MJ, $f_{ELM} \sim 50$ Hz) the oscillation of the detachment divertor conditions are rather moderate for ITER, as shown in [17]. Regarding pellets the effect on the divertor plasma detachment state can potentially be more significant, particularly for large 90 mm^3 pellets, as the injection of the pellet can lead to a transient increase in the separatrix density and thus increase the level of detachment at the divertor to unacceptable levels. However, whether this actually will happen in ITER or not also depends on the effect of pellet injection on edge particle and energy transport. It is known

from present experiments [18] that pellet injection can affect plasma transport. Depending on the relative size of the transiently increased energy transport (increased edge power flux decreasing divertor detachment level) to the particle transport (increased edge particle flux leading to increased separatrix density and increasing detachment level) following pellet injection, the size of the fuelling pellets will have to be optimized for efficient fuelling of ITER plasmas while avoiding unacceptable transient levels of divertor detachment. This issue is the topic of ongoing ITER modelling studies and experiments in present tokamaks.

Finally we assume that the pedestal pressure remains at the level predicted by EPED1 + SOLPS for all H-mode conditions and is not affected by ELM control. While it is required that ELM control in ITER does not significantly decrease the pedestal pressure and thus energy confinement, a decrease in the time-averaged pedestal pressure, under the maximum value predicted by EPED1 + SOLPS, associated with ELM control is unavoidable and this can modify the operating window.

The evaluation of the ohmic and L-mode 15 MA/5.3 T plasmas in ITER shows a relatively limited operational window, similar to results from more sophisticated integrated core + SOL plasma JINTRAC modelling studies [15, 16]. Strictly speaking an evaluation of the fuelling requirements for L-mode plasmas and plasma dynamics in the L–H transition is beyond the parametric range of the SOLPS simulations [5] that we have used as boundary conditions in our simulations. However, with the prescription used to renormalize the SOLPS results to L-mode operation the analysis of the fuelling requirements for L-mode plasmas are found to be in good agreement with predictions of fully consistent coupled core-edge simulations [15] for L-mode plasmas, which assume similar levels of SOL transport as those obtained by our renormalization procedure above. In particular, our modelling studies of the L-mode phase with $P_{sol} \sim 20$ MW predicts saturation of the core density at the level $\langle n_e \rangle \sim 2.2 \times 10^{19}$ m^{-3} at $G_{DT} \sim 30$ Pa m^3 s^{-1} in the absence of pellet fuelling (see figure 5(*a*)), which is close to the results discussed in section 3 of [15]. In our simulations we significantly extend the plasma density we can achieve by replacing gas puffing by the much more efficient HFS pellet fuelling, keeping the same pumping rate, G_{DT}, thus providing detachment control. This significant increase in the achievable plasma density when gas puffing is replaced by pellet fuelling in the L-mode is also in excellent agreement with fully consistent coupled core-edge simulations in [16] (see figure 5 of [16]). It is also important to note that the electron density that can be achieved in the L-mode phase with 20 MW of the ECRH heating with pellet fuelling is beyond 3×10^{19} m^{-3} (figure 5), which is the minimum value required for unrestricted NBI operation with acceptable shine-through power fluxes on the

first wall in ITER [19]. This makes it possible to inject an additional 33 MW of the NBI power in these L-mode plasmas, thus providing sufficient power for the plasma to undergo the L–H transition. As shown in [15] (see figure 8(*b*) of [15]) such transition does not cause an increase in the detachment state of the plasma and leads to a density increase of up to 4.2×10^{19} m^{-3}, when only gas puffing is used. This is also in excellent agreement with our predictions for the minimum density for 15 MA H-mode plasmas without pellet fuelling (see figure 2). To further refine our initial ohmic and L-mode, further SOLPS simulations at low SOL power with appropriate SOL transport values for ohmic and L-mode plasmas in ITER would be required to more precisely assess the ITER operational window at 15 MA in these conditions, and to compare in detail with the full integrated modelling results in [15, 16].

Acknowledgments

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