Optimisation of ITER Operational Space for Long-pulse Scenarios

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1. Background and Objectives

Long-pulse operation $\Delta t_{burn} \sim 1000$ s with $Q \geq 5$ [1] is foreseen in the ITER baseline to demonstrate high neutron fluence scenarios which can be of use for the qualification of nuclear technology and for the TBM. The main plasma regime foreseen for long-pulse $Q \geq 5$ operation is the hybrid scenario, which requires plasma confinement above the H-mode scaling but is expected to be less demanding than the baseline steady state scenario [2]. In this study we address the viability of achieving ITER's long-pulse scenario goal in plasma regimes with H-mode confinement level by characterizing the current-density (I_p-n) operational space (OS) and the achievable Q of ITER plasma with long pulse burning phases ($\Delta t_{FT} > 800$ s) for plasmas with H = 1. In this study we take into account specific properties of the edge density profiles in ITER high performance plasma for which gas fuelling is very inefficient to increase the pedestal and core density.

2. Consistent predictions of pedestal and boundary parameters in ITER

Plasma performance depends strongly on the boundary conditions for "stiff" models of core transport [3]. The EPED1 code [4] has been widely used in the integrated modelling of the ITER scenarios, especially for the long-pulse operation based on the hybrid scenario [5-7]. In these integrated modelling studies the temperature and density at the plasma separatrix (boundary conditions for the edge plasma) are usually given by $T_s = 75$ eV, $n_{ped}/n_s = 4$. For this specific choice of boundary conditions the EPED1 model predicts for ITER H-mode plasmas a degradation of the pedestal pressure, P_{ped} with the reduction of the density, n_{ped}. The standard boundary conditions for EPED1 are not unreasonable for the baseline ITER inductive 15 MA scenario with $P_{fus} = 500$ MW, Q = 10 which requires a high pedestal density, $n_{ped} \sim n_G = 12\ 10^{19} m^{-3}$, for flat core plasma density profiles. However, simulations of the SOL and divertor with SOLPS [8] predict that the neutral penetration into the core plasma is almost negligible for high current H-mode operation in ITER. This causes the link between n_s and the pedestal density n_{ped} which applies to present experiments to be broken in ITER. In ITER n_s is controlled by gas fuelling and it must be adjusted to allow appropriate divertor power control (highly radiating/semi-detached divertor operation) while n_{ped} is controlled by pellet fuelling. This leads to the separatrix density and temperature to be typically at the level: $n_s \sim 3\ 10^{19} m^{-3}$, $T_s \sim 0.2 - 0.3$ keV for a range of pedestal densities. For such boundary conditions the EPED1 model predicts no degradation of the pedestal pressure for $n_{ped} < n_G$ (Fig. 1). This calls for a reconsideration of the integrated simulations of ITER high Q scenarios based on the application of the EPED1 model with standard boundary conditions and, in particular, of those for low core plasma densities to determine their potential as regimes alternative to the hybrid plasma for long pulse high Q operation in ITER.

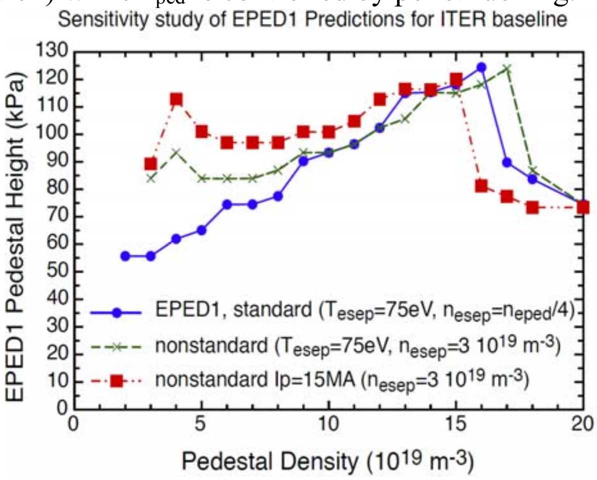

Figure.1 Pedestal height predicted by EPED1 for 12 MA plasma with standard boundary conditions and SOLPS boundary conditions for 15 MA, and 12 MA H-mode plasmas with toroidal field of 5.3T.

3. Operational space for long pulse high Q scenarios in ITER with H ~ 1.

An assessment of the Operational Space (OS) in terms of plasma current-plasma density for long-pulse operation in ITER DT plasmas has been carried out for a range I_p= 11-15 MA, n/n_G = 0.5-1 in plasma current and density respectively. Different transport models have been considered (CDBM [9], GLF23 [10], Bohm/GyroBohm (BgB) [11], MMM7.1 [12], MMM95 [13], Weiland [12], Coppi-Tang [14], Scaling-Based [15]) for the study presented here. All these models provide a similar set of plasma parameters for the baseline ITER inductive DT operational point with I_p = 15 MA, P_{fus} = 500 MW, Q = 10, high density $n/n_G \sim 1$ and burn duration $\Delta t_{burn} \sim 400$ s.

For the simulations in this study we assume the same plasma heating and current drive (H&CD) with 33 MW of the Neutral Bean Injection (NBI) and 15-20 MW of the Electron Cyclotron (H&CD) located at r/a ~ 0.4 of the minor radius. For the NBI we consider one of the beams aimed at the innermost possible location and the one at the outermost location. Two approaches have been taken in the study: in the first approach we use various transport models to assess the fusion gain and burn phase achievable for a range of densities at I_p = 15 MA keeping a constant pedestal pressure which provides the baseline operational point in an original implementation of each model. The results shown in Fig.2 demonstrate that for the lowest density plasmas a fusion gain $Q \geq 5$ with burn lengths of ≥ 800 s can be achieved with the usual H-mode energy confinement enhancement $H_{y2,98} \sim 1$. In the second approach we use a pedestal pressure consistent with EPED1+SOLPS predictions and the same transport models as for the first approach and we perform a plasma density scan for a range

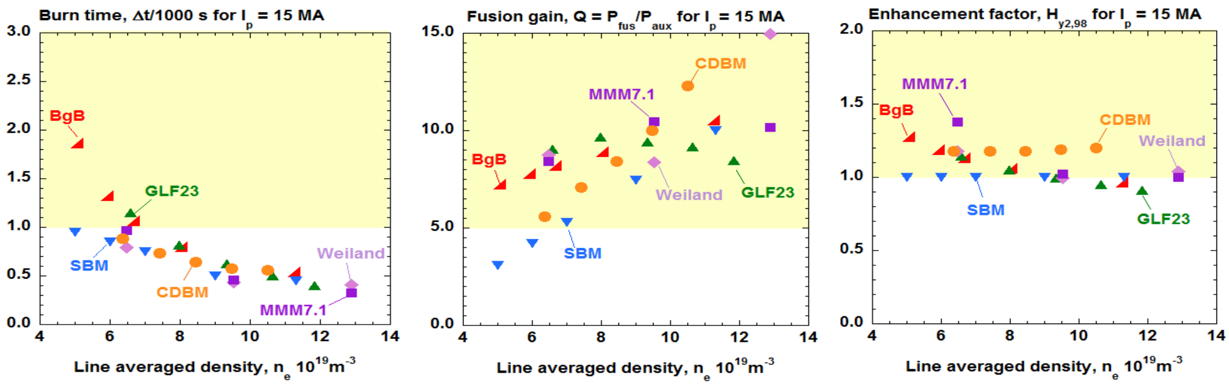

Figure 2. Length of burn phase, Δt_{burn}, fusion gain Q, and enhancement factor $H_{y2,98}=\tau_E/\tau_{y2,98}$ for 15 MA scenario modelled with a range of transport models with P_{ped}=const in the original implementations.

of plasma currents I_p = 11 - 15 MA. Typical cases of modelling predictions from this second approach with the BgB and GLF23 transport models are shown in Fig. 3 and Fig. 4. The results show that the lack of dependence of the pedestal pressure height on plasma density in ITER (from EPED1+SOLPS boundary conditions) allows the achievement of the long pulse Q ≥ 5 scenario for a H-mode in the range of I_p = 13 - 15 MA and H ~ 1 energy confinement.

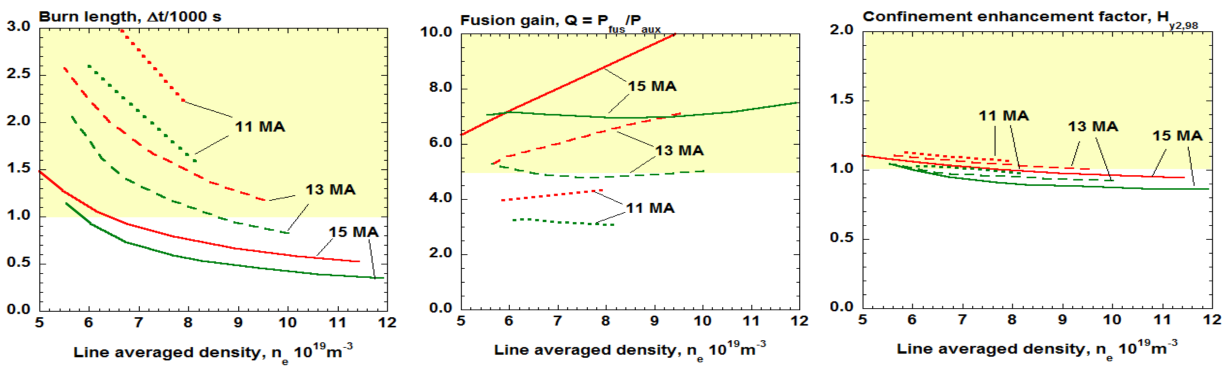

Figure 3. Length of burn, fusion gain, and H factor for BgB (red) and GLF23 (green) core transport model [10, 11] with pedestal pressure predicted by EPED1 with SOLPS boundary conditions (~75% of the P_{ped} in the original implementation for 15 MA case). The maximum average density considered is $n_e \sim n_{GW}$ for all plasma currents.

4. Summary and conclusions

The EPED1 model with boundary conditions from SOLPS predicts no degradation of pedestal pressure with decreasing density in ITER. Modelling of core transport with 1.5D transport models carried out with pedestal parameters predicted by EPED1+SOLPS indicate that there is a large operational space for long pulse plasma operation with high fusion gain Q ≥ 5. Reducing the plasma density to n_e~5-6 $10^{19}m^{-3}$ leads to an increased plasma temperature (similar pedestal pressure) which reduces the loop voltage increases the duration of the burn phase to Δt_{burn}~ 1000 s with Q ≥ 5 for I_p ≥ 13 MA at moderate normalised pressure, β_N ~ 2 in ITER.

These ITER plasmas require the same level of additional heating power as the reference Q = 10 inductive scenario at 15 MA (33 MW NBI and 17 - 20 MW EC heating and current drive power). However, unlike the ‘hybrid’ scenarios considered previously, these H-mode plasmas do not require specially shaped q profiles nor improved confinement in the core for the majority of the transport models considered in this study. In addition, the neutron fluence, $F = 0.8\ P_{fus}\Delta t_{burn}$ for these long-pulse scenarios is larger than that of the Q = 10 inductive scenario although the margin above the L-H threshold power is lower than for the reference Q = 10 inductive operation (Fig. 4). Thus, these medium density H-mode plasma scenarios with $I_p \geq 13$ MA present an attractive alternative to hybrid scenarios to achieve ITER’s long pulse $Q \geq 5$ and deserve further analysis and experimental demonstration in present tokamaks.

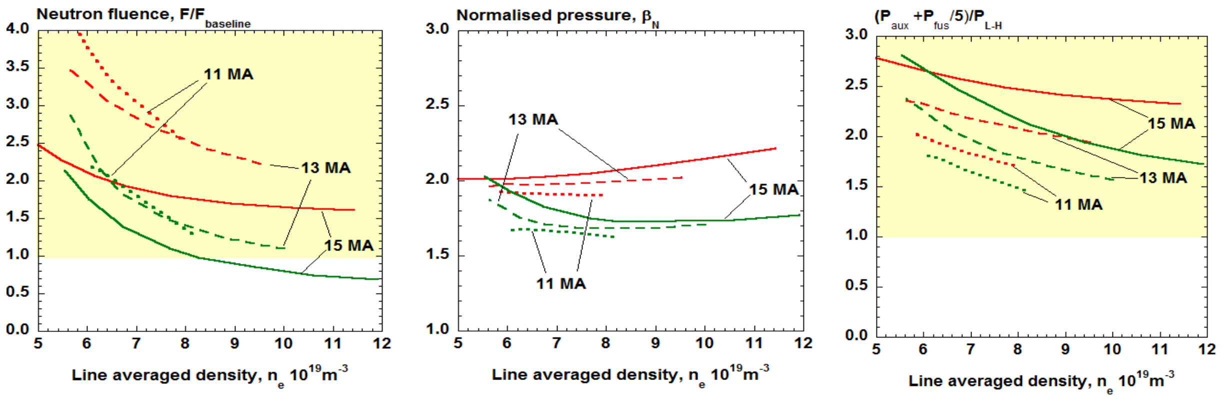

Figure 4. Normalized beta, neutron fluence, and ratio of heating power to the L-H threshold for BgB (red) and GLF23 (green) core transport model [10,11] with pedestal pressure, predicted by EPED1 with SOLPS boundary conditions. The maximum average density considered is $n_e \sim n_{GW}$ for all plasma currents.

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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