Assessment of Operational Space for Long-pulse Scenarios in ITER

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Introduction

Straightforward transport calculations suggest a certain chosen transport model for a chosen set of actuators, current, I_p density, n and input power, P_{aux}. To provide energy multiplication $Q = P_{fus}/P_{aux} \geq 5$ for long pulse (LP), $\Delta t = 1000$ s hybrid and steady-state (SS) operation [1] with configuration of heating and current drive systems (H&CD) designed for ITER [2] high pedestal pressure and improved core confinement are typically assumed [3]. It remains unclear whether the obtained operational points (OPs) are unique or optimal, what improvement of confinement is needed if any, how to provide operation within the design and physical limits. To clarify these issues we propose for ITER analyses the inversed transport task (ITT) approach. The ITT assumes that the set and configuration of the H&CD systems is already specified, $P_{aux} = \Sigma P_k$, (P_k: P_{NBI} = 33 MW, P_{EC} = 20 MW, P_{IC}=20 MW) and there is no synergism between them. Then, using CD efficiencies calculated by codes validated versus experiments [6] we define the confinement required for LP and SS operation and operational space (OS), i.e. the range of actuators, I_p, n, P_k where such operation is possible within the design and physical limits.

Inversed transport task approach

Magnetic flux available for the flat-top ITER reference scenario can be approximated as: $\Delta\Psi = \Psi_0 - (L_p+\mu_0 C_{Ejima}R)\, I_p = 240 - 14\, I_p$ [V, MA]. Duration of the current flat top is determined by inductive current and resistivity, η: $\Delta t = \Delta\Psi/\eta(T, Z_{eff})\,(I_p - I_{bs} - \Sigma\, I_{CD,k})$. Bootstrap and driven currents can be expressed as, $I_{bs} = \alpha_{bs}(T, I_p, q_{min})\, n/I_p$, [4], $I_{CD,k} = P_k\alpha_k(T,Z_{eff})/n$, [5]. Thus, for the inversed duration of flat-top we finally have:

$$\Delta t^{-1} = (\, I_p - \alpha_{bs}(T, q_{min})\, n/I_p\ - \Sigma\, P_k\alpha_k(T, Z_{eff})/n)\, \eta(T, Z_{eff})/\,(240 - 14\, I_p\,). \qquad (1)$$

Analytical approximations for the functions $\alpha_{bs}(T, q_{min})$, $\alpha_k(T, Z_{eff})$, $\eta(T, Z_{eff})$ for ITER design configuration are calculated by ASTRA 1.5D modeling with pedestal parameters within the peeling-ballooning limit calculated by KINX. Impurity density is assumed (2% of Be, 0.12% of Ar). Solving quadratic equation (1) we derive the densities, which provide required duration Δt at a certain temperature T: $n = n_{1,2}(T, I_p, P_k, Z_{eff}, \Delta t)$. All other plasma parameters, such as energy content, W, fusion power, P_{fus}, $Q = P_{fus}/\Sigma P_k$, power loss to divertor, P_{los}, required confinement enhancement, $H/H_{y2,98}$, L-H threshold, P_{los}/P_{L-H} [6], normalized beta, β_N , etc are calculated from this solution.

Operational space for inductive, hybrid and steady-state scenarios

The H-mode OS can be derived from the solution of equation (1) by fixing of appropriate targeting parameters. In figure 1 the OS is shown for fixed current and confinement, I_p= 15 MA, $H/H_{y2,98}$=1. The OS with variable n, Δt and $P_{aux}= \Sigma P_k$ is limited by $P_{los}/P_{L-H} \geq 1$, $P_{los} \leq$ 100 MW, $n/n_G \leq 1$, $Q \geq 5$. Ideal wall limit, $\beta_{N,ideal-wall}$ is not shown, because it is far beyond the obtained OS. The targeting OP for reference inductive scenario, Q = 10, P_{fus} = 500 MW appeared to be close to the Greenwald density, n/n_G = 0.91. For full available input power, P_{aux}= 73 MW the operational range with $Q \geq 5$ shrinks due to increased loss to divertor.

For SS operation there is an additional boundary for the OS, q_{min}> 1.5 caused by MHD stability of low-n kink-modes. The optimal configuration for this condition corresponds to the maximal difference in tilting of the NB injectors, i.e. 16.5 MW in the innermost on-axis and 16.5 MW in the outermost off-axis injector which we suggest further in our analysis. For LP operation the targeting parameters are duration of the current flat-top, Δt and $Q \geq 5$. Plasma parameters, n, β_N, $H/H_{y2,98}$, P_{los}/P_{L-H}, P_{fus}, (Figs. 2,5,6) required for LP operation with Q = 5 and Δt^{-1}= 0, q_{min}= 1.6 for SS, Δt = 1000 s, q_{min}= 1 for hybrid are derived from solution of eq.(1). The operational density for SS scenarios decreases for higher currents (Fig. 2). Thus, for SS operation it looks optimal to choose I_p = 9 MA to provide the widest range of possible density variations $0.85 < n/n_G < 1$ with $Q \geq 5$ (Fig. 3). We need this flexibility to reserve some power for NTM stabilization at q=2 keeping $Q \geq 5$.

Reference steady-state scenario

Parameters of chosen reference SS scenario from 1.5D ASTRA modelling without ITB similar to [7] are presented in table 1 and Fig. 4. We assume that P_{EC} = 4 MW needed for NTM stabilisation at q = 2 from the upper launcher (UL) and P_{EC} = 18 MW from equatorial launcher (EL) is available for current drive. Thus, for P_{aux} = 55 MW which is 10% higher than in Fig.3 the density required for Q =5 corresponds to the density $n/n_G \sim 0.9$. The consistent separatrix shape according to CORSICA calculation is within the PFC design limits.

Table 1. Reference SS scenario with Q =5, I_p= 9 MA, P_{EC}=22 MW, P_{NB}= 33 MW

$I_{bs}/I_{NB}/I_{EC}$,%	53/38/9	**$q_0/q_{min}/q_{95}$**	2.45/1.58/5.8	**Z_{eff}**	1.66
W_{th},/W_α/W_{NBI}, MJ	285/33/23	**$T_i(0)/\langle T_i\rangle$**	31/11.4	**$T_e(0)/\langle T_e\rangle$**	34/13.5
$P_{fus}/P_{rad}/P_{los}$, MW	274/26/84	**P_{los}/P_{L-H}**	1.65	**$HH_{y2,98}$**	1.66
$\beta_N/_{no-wall,1}/_{no-wall,2}$	2.94/2.57/3.1*	**n/n_G**	0.9	**l_i3**	0.75

*)For this configuration $\beta_{N,no\text{-}wall}(n=2) = 3.1$, $\beta_{N,ideal\text{-}wall}(n=1)=3.33$. Thus, RWM stabilization of n=1 mode will be not sufficient for $\beta_N > \beta_{N,no\text{-}wall}(n=2)$.

Discussion and conclusions

It is shown that the LP operation, Δt = 1000 s with Q = 5, can be possible for moderate confinement, H ~ 1, close to the L-H power threshold $P_{los}/P_{L\text{-}H}$ ~ 1-1.5, with n_e/n_G ~ 0.5 – 1, q_{95} ~ 3 - 3.7. Thus, the hybrid scenarios in ITER comfortable for TBM testing in general do not require confinement improvement typically assumed in the simulations with the traditional approach. The MHD stable SS operation with pedestal within the peeling-ballooning limit without low hybrid CD or ITB can be possible for I_p ~ 8.5- 9 MA with $P_{los}/P_{L\text{-}H}$ ~ 1.5 - 2, close to the Greenwald density, $n_e \sim n_G$, provided the energy confinement can reach $H/H_{y2,98}$ = 1.5 - 1.8. Operation with q_{min} > 1.5 requires maximal difference between axis of the on/off NB injectors and the outermost ECCD from the equatorial launcher. The results of our analysis with the ITT method can also be used for selection of the ITER relevant experiments for the R&D in support of the ITER and DEMO projects.

This report was prepared as an account of work by or for the ITER Organisation. The Members of the Organisation are the People's Republic of China, the European Atomic Energy Community, the Republic of India, Japan, the Republic of Korea, the Russian Federation, and the United States of America. The views and opinions expressed herein do not necessarily reflect those of the Members or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the ITER Joint Implementation Agreement.

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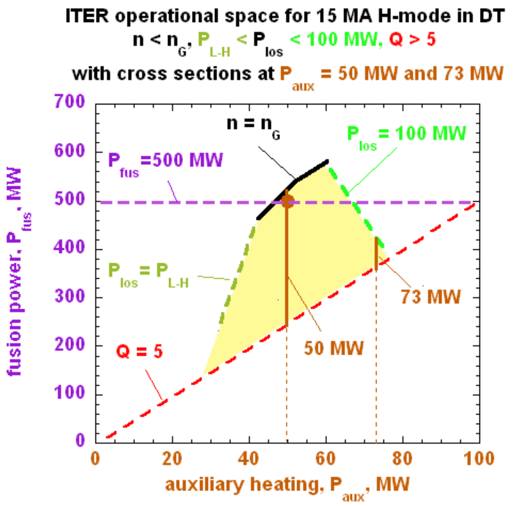

Figure 1. Inductive operational space for $H/H_{y2,98}$=1

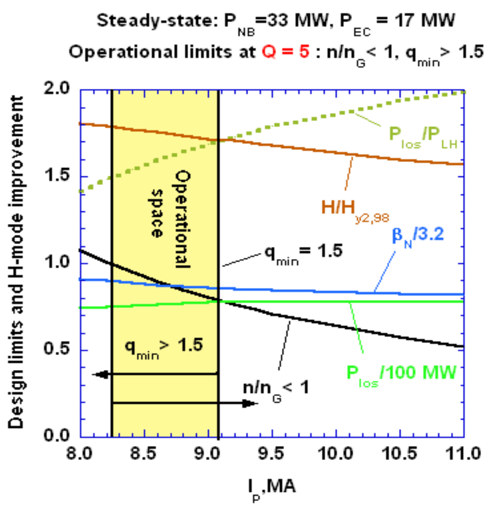

Figure 2. SS operational space for P_{aux}=50 MW, Q=5

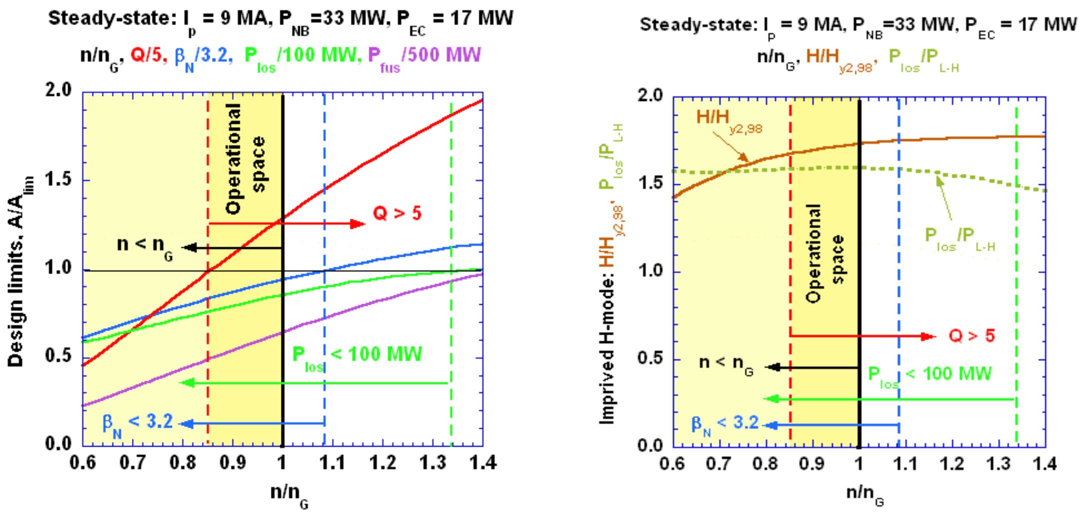

Figure 3. Steady-state operational space for I_p=9 MA, P_{aux}=50 MW. Operational limits: $n/n_G < 1$, $Q > 5$.

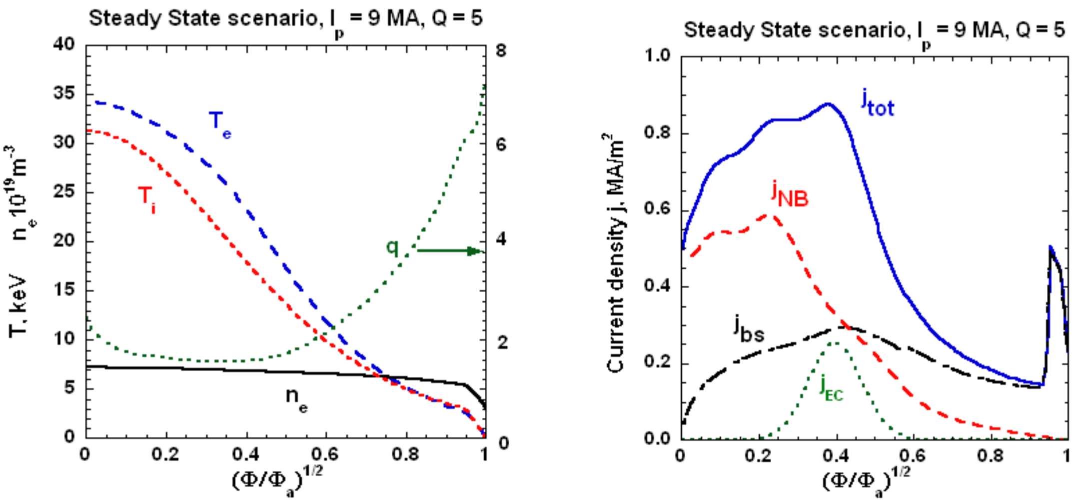

Figure 4. Profiles for the reference steady-state operation with I_p= 9 MA, P_{aux}=55 MW

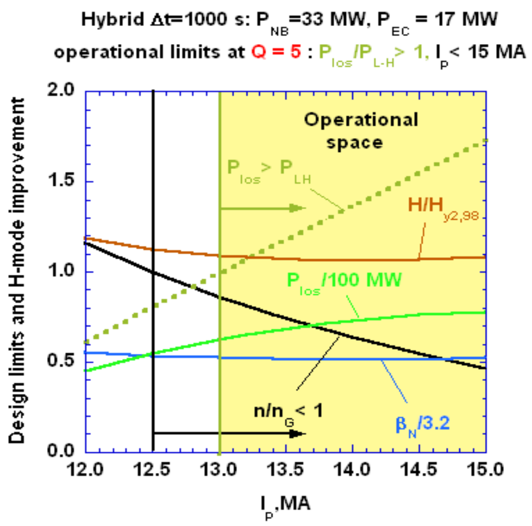

Figure 5. Hybrid operational space for P_{aux}=50 MW

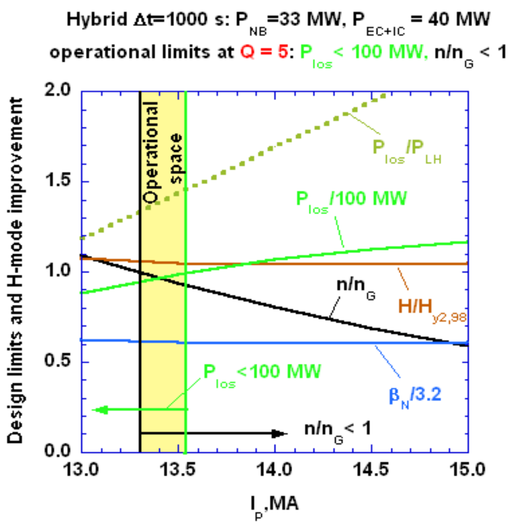

Figure 6. Hybrid operational space for P_{aux}=73 MW