Reassessment of Steady State Operation in ITER with NBI and EC Heating and Current Drive

A.R. Polevoi[1], S.Yu. Medvedev[2,5], G.T.A. Huijsmans[3], S.H. Kim[1], A. Loarte[1],
E. Fable[4], A.A. Ivanov[2], A.Y. Kuyanov[5].

[1]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France, [2]Keldysh Institute of Applied Mathematics, Miusskaya 4, 125047 Moscow, Russia, [3]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France, [4]Max-Planck Inst. für Plasmaphysik, Boltzmanstraße 2, D-85748 Garching, Germany, [5]NRC "Kurchatov Institute", Kurchatov sq. 1, 123098 Moscow, Russia

Introduction. Demonstration of Steady-State Operation (SSO) with the current fully driven non inductively with the fusion gain $Q = P_{fus}/P_{aux} \geq 5$ is one of the goals of the ITER project [1]. The parametric Operational Space (OS) for SSO in ITER has been reassessed by global analysis using inversed transport task approach [2] taking into account the baseline design of the Neutral Beam Injection (NBI) and EC H&CD systems with P_{NBI} = 33 MW, P_{EC} = 20 MW and their suggested upgrades, P_{NBI} = 49.5 MW, and P_{EC} = 30 MW. The analysis has been carried out for so called Type-II SS scenarios, i.e. the SSO with NBI and EC for heating and current drive H&CD w/o the LHCD, ICCD and ITBs [3]. The optimal Operational Points (OPs) have been chosen for detailed 1.5-D transport and further MHD stability analysis to demonstrate the Q = 5 SS goal in ITER, where the bootstrap current, I_{bs}, an externally driven current, I_{cd}, fully replace the inductive current, $f_{NI} = (I_{bs} + I_{cd})/I_p = 1$. The possibility of the MHD stability control in chosen SSO scenarios by variation of the NBI and ECH&CD is demonstrated. The feasibility of such scenarios from the point of view of theory, experiments and ITER design limits is discussed.

Global operational SS OS. To derive the SS OS the inversed transport task approach [2] is used. According to this approach the energy confinement required for ITER SSO with $f_{NI} = 1$, Q=5 is derived as a function of controllable plasma parameters, density, n, and plasma current, I_p, for a chosen set of the H&CD options. It uses known dependencies of plasma parameters on density and current, $I_{bs} = \alpha_{bs}(T,n_0/\langle n\rangle,q_{min})\ n/I_p$, $I_{CD,k} = P_k\alpha_k(T,Z_{eff})/n$, k = NB, EC, and plasma power balance, $1.5\ nT\ V = H\tau_{E,y2,98}(n,P_{sol},I_p)\ P_{sol}$, [4], with $P_{fus} \sim n^2\alpha_{fus}(T,Z_{eff})$, $Q = P_{fus}/\Sigma P_k$, $P_{sol} = \Sigma P_k(1 + Q) - P_{rad}(n,T,Z_{eff})$. Functions α_{bs}, α_k, α_{fus}, P_{rad} are derived from 1.5D transport simulations on the basis of the Automated System for Transport Analysis (ASTRA) [5], then for the chosen set: f_{NI}=1, Q=5, $n_0/\langle n\rangle$=1.3, q_{min}~1, Z_{eff} ~2, the inversed transport task is solved numerically for each set of H&CD options, P_k. The derived functions for confinement,

$H = H_{fQP}(I_p,f_{NI},Q,\Sigma P_k)$, and density, $n = n_{fQP}(I_p,f_{NI},Q,\Sigma P_k)$, are displayed in the figure 1 together with the normalized beta, $\beta_N = \beta\ aB/I_p[\%,mT/MA]$, P_{sol}, and maximum load on the divertor plates, $q_{pk}/10\ MW\ m^2$, extrapolated from the scaling [6] for 2 options of H&CD schemes. The operational points A1 (I_p=9 MA) for the baseline scheme P_{NBI} = 33 MW, P_{EC} = 20 MW, and A2 (I_p=10 MA) for an upgrade scheme, P_{NBI} = 49.5 MW, P_{EC} = 30 MW, are chosen for detailed 1.5D transport analyses and further MHD stability analysis. Note that for $I_p > 11$ MA, $q_{min} < 1$ and sawteeth become unstable at least in the frame of ideal MHD.

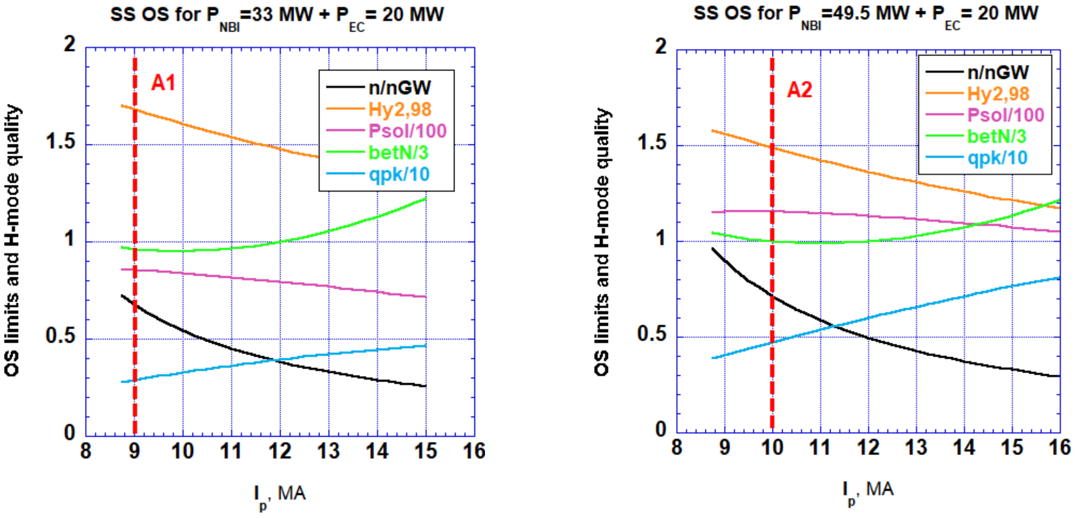

Figure 1. Steady-state operational space for P_{aux} =53 MW (left) and P_{aux} = 70 MW (right)

1.5D Transport simulations. The 1.5D transport simulations are carried out by ASTRA for the electron and helium densities, n_e, n_{He}, ion and electron temperatures, T_i, T_e, and current density, j, with the SOLPS boundary conditions with controllable divertor detachment [6] and EPED1+SOLPS pedestal [7], with the particle diffusivity and pinch velocity, $D=(\chi_i+\chi_e)/10$, V=0.3 Dx/a. The heat diffusivities, $\chi_i=\chi_e$, are fitted to provide the SSO, f_{NI}=1. The fuelling is fitted to provide the Q=5 SS OPs densities A1, A2, n~0.7 n_{GW}. The impurities are prescribed as n_{Be}/n_e = 2%, $n_{Ne}/n_e(a)$ ~ 0.6-0.7 (Z_{eff}~ 1.7). Following the ECR H&CD design we assume the sharing of the power between the Equatorial and Upper Launcher (EL,UL) as, P_{EL}/P_{UL} = 2, with the innermost UL fixed aiming, x_{ULEC} = 0.43, and with the EL ECRH&CD location steered in the range x_{ULEC} = 0.35-0.5 for plasma safety factor and pressure profile control, q(x), p(x). For the NBI H&CD we assume for the baseline one NBI of 16.5 MW with the innermost aiming Z_{in}=0.156 m, and one NBI of 16.5 MW with the outermost aiming Z_{out}=- 0.417 m. For the upgrade option we assumed the third NBI of 16.5 MW with varying aiming $Z_{out}< Z< Z_{in}$.

Control of MHD stability of SS operation. The MHD stability analysis is carried out using consistent 1D profiles and 2D equilibria simulated by ASTRA for chosen operational points.

The results of MHD analysis for the reference H&CD geometry with ECH&CD at x=0.43 for the cases A1, A2, carried out with the code KINX [8], are shown in the figure 2. The β_N is within the MHD stability limits meanwhile the modes with the toroidal numbers n =2 (A1) and n=3, 4 (A2) are just marginally stable.

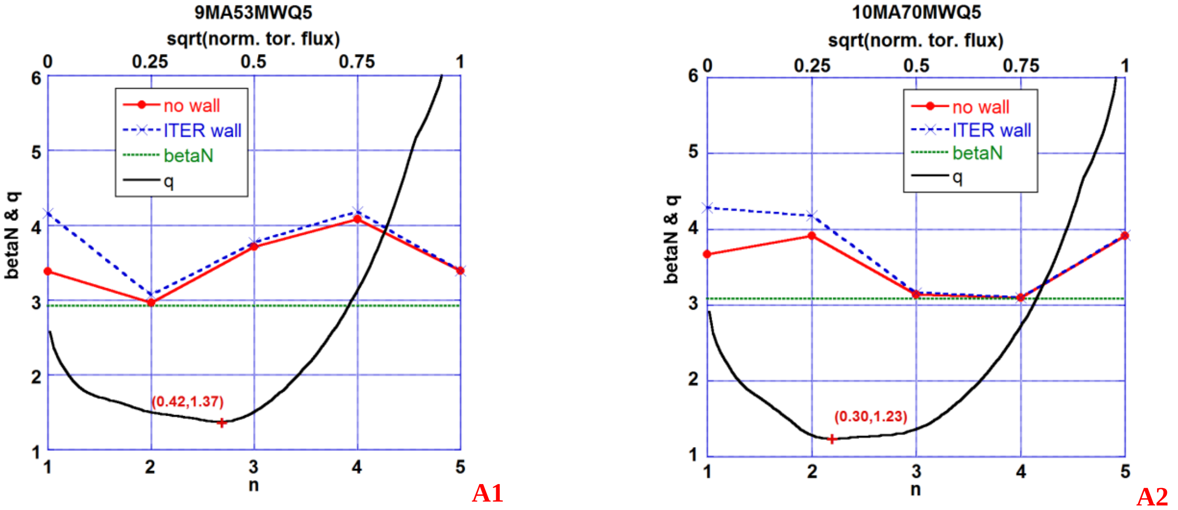

Figure 2. MHD stability analysis for OP (left) at OP A1 (x_{EC}= 0.43, 16.5 MW NBI at Z_1=0.156 m, 16.5 MW at Z_2= -0.417 m) and OP at A2 (right) A2 (x_{EC} = 0.43, 16.5 MW NBI at Z_1=0.156 m, 33 MW at Z_2=Z_3= -0.417 m)

Improvement of stability by EC and NBI variation. For the case A2 variation of the deposition of the ECRH&CD by steering of the equatorial launcher (figure 3) for the reference NBI geometry helps to provide the operation comfortably far from the MHD stability limits.

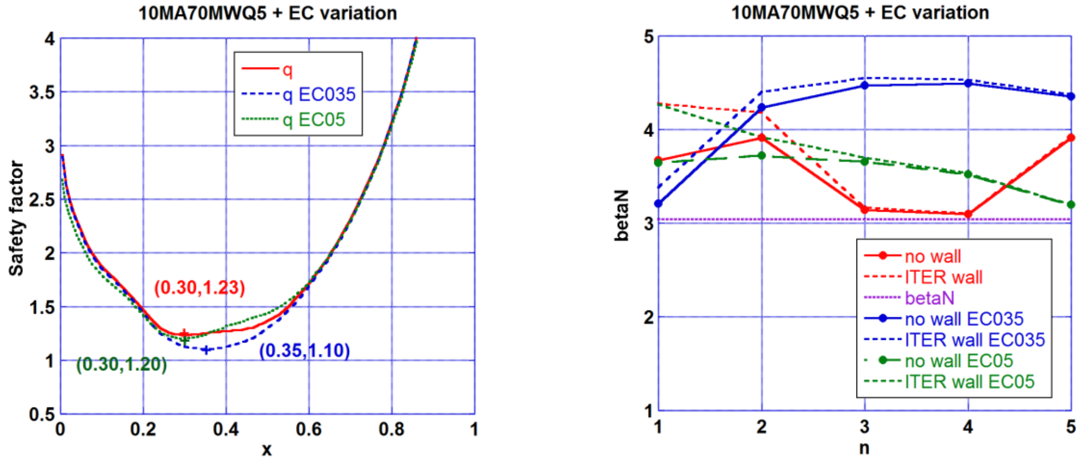

Figure 3. Stability control by ECRH&CD variation for the operational point A2.

Variation of the 3rd NBI modifies the ECRH&CD optimization (figure 4). In particular for Z_3 = 0.056 m the only stable OP corresponds to x_{ECEL}=0.5. For Z_3 = Z_{in} = 0.156 m the safety factor drops below 1 for all variations of the ECCD making such configuration unstable to sawteeth. The n=1 limiting β_N drop for the EC035 case is caused by infernal mode destabilization due to wide low shear region near q_{min}=1.028.

Discussion and conclusions. The ITER goal Q=5 SS Operation in ITER looks possible w/o

ITBs, LHCD and ICCD, with 33-49.5 MW of NBI + 20-30 MW of ECRH&CD in the range I_p = 9-10 MA with high $l_{i3} \sim 0.8$-0.95, $\beta_N \sim 3$, $n/n_{GW} \sim 0.7$-0.8, provided a high confinement can be reached: $H_{y2.98} \sim 1.4$-1.6. Control of profiles of plasma pressure and current density by ECH&CD and NBI variations foreseen by ITER design enables keeping operation within the MHD stability limits. The temperature and density scale lengths, $R/L_T \sim 5$-6, $R/L_n \sim 1.3$, sufficient to achieve the confinement required for SSO in ITER are in good agreement with first principle transport and DIII-D experiments [9]. The SSO in ITER is within the technical design limitations for CS/PF magnets' system [10] and extrapolated divertor power loads [6]. The reduced requirements, Q = 4, f_{NI}= 0.9, make an operation comfortably far from the MHD stability limits. To strengthen the basis for this scenario in ITER dedicated experiments are required in lower SN configuration with high density n > 0.5 n_{GW}, and $q_0 \sim 2$-3. The SOLPS simulations are required for high power/low current (q > 4) operation with tungsten divertor to refine the core-edge integration requirements of this scenario.

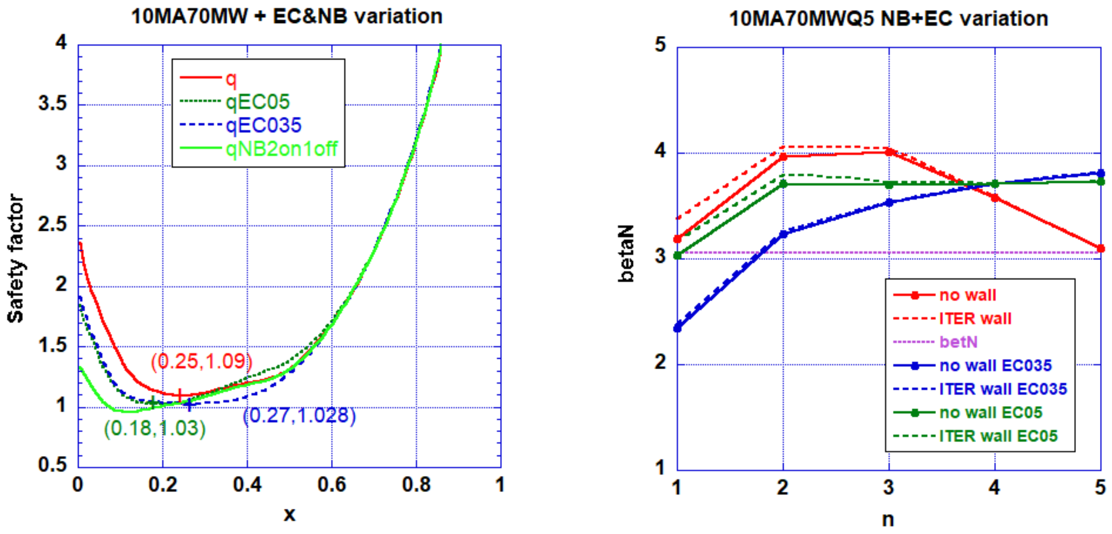

Figure 4. Stability control by NBI and ECRH&CD variation for the operational point A2

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