PFPO plasma scenarios for exploration of long pulse operation in ITER

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Abstract. Long Pulse Scenarios (LPSs) in ITER at Pre-Fusion Power Operation (PFPO), foreseen in the ITER Research Plan (IRP) [1], are assessed using 1.5D transport simulations within the ASTRA framework [2]. Such assessment is required to predict the operational space for LPS operation in PFPO, as well as to estimate which physics processes for LPS operation at Fusion Power Operation (FPO) could be validated at PFPO. An important issue is to minimize lifetime consumption of the Central Solenoid (CS). The maximum pulse length achievable in PFPO with no consumption of CS lifetime ($I_{CS} \leq 30$ kA) has been assessed for different heating schemes and confinement regimes in He and hydrogen plasmas (figure 1b). The operational space of LPS is explored through density scans (figures 2, 4) to determine the operational space with H&CD mix suggested for steady state phase of ITER operation [3] with acceptable NBI and ECH shine through loss (with the ECH calculated by OGRAY code [4]). Similarity of LPS PFPO and low density operation is studied including the MHD stability analysis with KINX [5] and TAE stability with high-n kinetic ballooning code HINST [6].

Flat-top length. Plasma operation with maximum current in the CS coils $I_{CS} \leq 30$ kA allows unlimited number of discharges, from the point of view of the CS operation. Here we assess the maximum duration of plasma current flattop in scenarios, when the CS discharge starts with initial currents in the coils of about +30 kA, and +20 kA. Maximum possible flat-top duration depends on the flux available for the flat-top, $\Delta\Psi_{FT}$, and loop voltage, U_{loop}: $\Delta t_{FT} = \Delta\Psi_{FT}/U_{loop}$. Available flux, $\Delta\Psi_{FT}$, depends on the premagnetization of the CS and flux consumption at current ramp-up phase. The flux, available for the flat-top can be approximated by the following expression: $\Delta\Psi_{FT} = C1 - C2 I_p$, where I_p is the flat-top plasma current. For fully charged CS $C1$=240 Vs, $C2$=14 Vs/MA, for charge current +30 kA, $C1$=158 Vs, $C2$=15.8 Vs/MA, and for +20 kA, $C1$=107.4 Vs, $C2$=16 Vs/MA. Note that the current flat-top length at PFPO for fully charged CS was early assessed for L-and H- mode operation. The factors for rescaling of the data from [7], [8] for lower CS currents +30 kA, and +20 kA, are displayed at figure 1(a).

The loop voltage, U_{loop}, is calculated by self-consistent 1.5D scaling based transport modelling

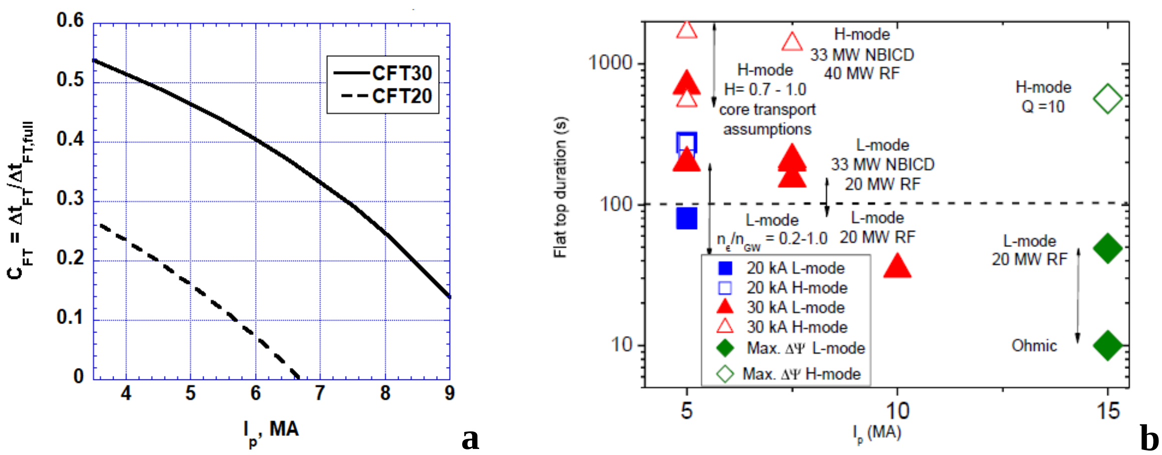

Figure 1 (a) Rescale of the flat top duration from fully charges CS. (b) Flat-top duration versus plasma current level for a range of premagnetization currents and scenarios for each current level.

for Ohmic, L-mode and H-mode regimes with H&CD parameters designed for ITER. For the H-mode the pedestal height and width were fitted to provide the EPED1 predictions with the SOLPS boundary conditions [9]. The results of simulations are presented in figure 1(b).

Similarity of LPS at PFPO and FPO. Note that low density target plasma at full power, $P_{aux} = P_{aux,max}$, will be required at each shot for baseline scenario $B/I_p = 5.3T/15MA$ to provide

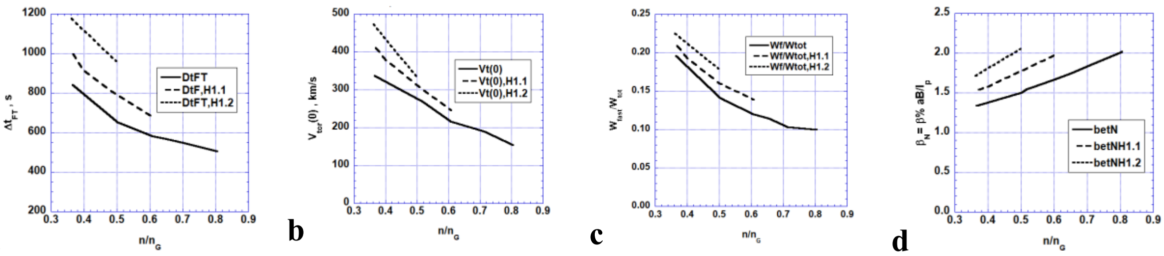

Figure 2. (a) flat-top length, (b) central toroidal velocity, (c) fraction of fast ion pressure, (d) normalized beta for DT operation with P_{NBI}=33 MW, P_{EC}=20 MW, B/I_p=5.3T/15MA for H-mode and improved H-mode $H_{y2,98}$= 1-1.2.

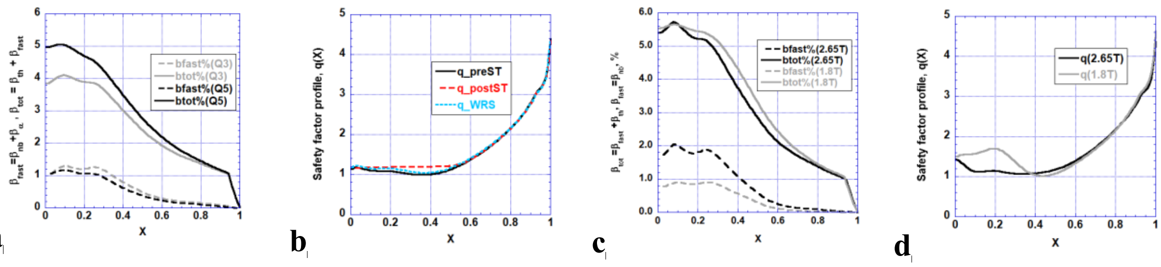

Figure 3. Low density DT operation with B/I_p=5.3T/15MA, P_{NBI}=33 MW, P_{EC}=20 MW: (a) fast ion and total normalised pressure, (b) safety factor evolution between the saw-teeth; Hydrogen H-mode operation: B/I_p=2.65T/7.5MA, P_{NBI}=33 MW, P_{EC}=20 MW, B/I_p=1.8T/5MA, P_{NBI}=10 MW, P_{EC}=30 MW (c) fast ion and total normalised pressure, (d) safety factor evolution between the saw-teeth.

transition from the L- to H-mode, $P_{sol} = P_\alpha + P_{aux} - P_{rad} > P_{L\text{-}H}(n)$, and further increase of the fusion gain, $Q = 5\, P_\alpha/P_{aux}$, up to Q = 10 by density increase. Such requirement follow from the density dependence of the alpha-heating, $P_\alpha \sim n^2$, and unfavourable density dependence of the

L-H power threshold, $P_{L-H} \sim n^{\nu}$, with $\nu \sim 0.7$- 1 [10], [11], above some critical density [12], $n > n_{L-H,crit} \sim 0.35\ n_G$ for ITER at $q \sim 3$. Such low densities, $n \sim 4.2\ 10^{19} m^{-3}$, are of the scale of those for one-half, one-third magnetic field operation, required for H-mode operation at the PFPO phase. Therefore, it is natural to assess which features of FPO LPS can be addressed at PFPO LPS. The results of 1.5D transport simulations for DT operation with P_{NBI}=33 MW, P_{EC}=20 MW, B/I_p=5.3T/15MA in the range $H_{y2,98}$=1-1.2, n/n_G> 0.35, are shown in figures 2, 3.

Simulating PFPO LPS we consider in more details hydrogen plasmas with NBI and EC H&CD, the mix assumed for FPO steady-state operation [3]. For half-field operation in hydrogen it is not possible to use ICRH minority heating scheme. To keep acceptable NBI shine-through loads at full energy, full power H-NBI (E_{nb}=870 keV, P_{NBI}=33 MW) we use plasma seeding by Neon [13]. To avoid shine-through of the EC waves we considered X-mode ECRH at B=2.65 T [14]. Global plasma parameter from the 1.5D transport modelling are presented on figure 4.

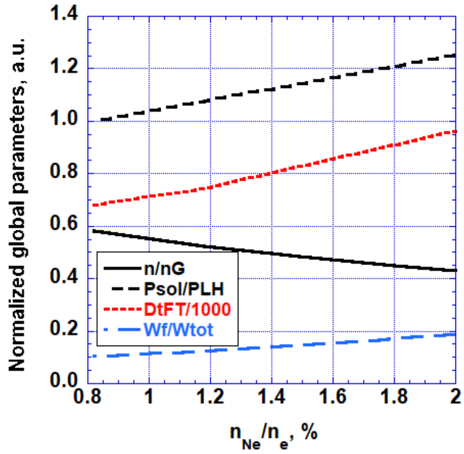

Figure 4. NBI shine-through control by Ne seeding, at $n=n_{NBshine}(n_{Ne})$, in Hydrogen LPS. 2.65T/7.5MA

For one-third field operation B=1.8T the NBI shine-trough loads is kept below the limits by reduction of the H0-NBI energy to E_{nb}=540 keV with the resulting reduction the NBI power to P_{NBI}=10 MW. In these scenarios in addition to NBI we consider 20-30 MW of the O-mode ECH. For ECCD we assume the same scheme EC launcher as for SS FPO [3].

Stability analyses. The results of the MHD stability analysis by KINX code [5] are presented in figure 5. The n=1 infernal/external kink mode stability beta-limit evolves between the STs depending of the proximity of safety factor minimum, q_{min}, to q=1, resulting in the following saw-tooth mixing. The other modes remain far from ITER-wall (weak wall stabilization for all n's) stability limits once q_{min} > 1. Note that such evolution is found to be similar in all low-density DT and Hydrogen cases considered here. To evaluate the relaxation of fast ions in the PFPO scenarios we apply a nonperturbative Critical Gradient Model (nCGM) [15]. It is based on a nonperturbative kinetic ballooning code HINST to compute the local AE growth rates with and without fast ions and gives essentially the same

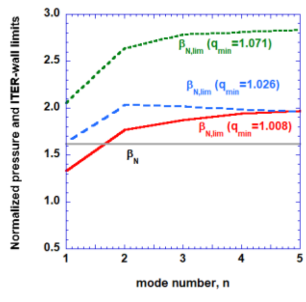

Figure 5. Evolution of the stability beta-limits for different toroidal mode numbers n between STs.

results as the perturbative CGM model. The contribution of the ITG is comparable with the drive by fast ions, and the resulting AE induced transport can reduce the fast ion pressure by as much as 13-17%.

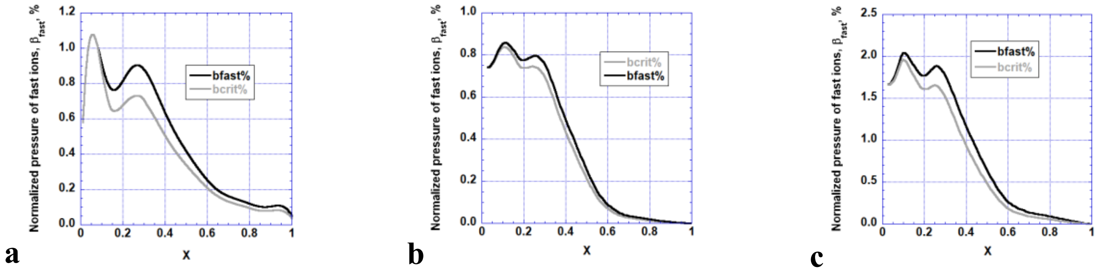

Figure 6. Initial and relaxed fast beam ion pressure profiles as predicted by the 1.5D nCGM model. Three cases are considered: (a) low density DT LPS with P_{aux} = 53 MW, B/I_p = 5.3T/15MA; (b) Hydrogen H-mode LPS with (b) P_{aux} = 40 MW, B/I_p = 1.8T/5MA, and (c) P_{aux} = 53 MW, B/I_p = 2.65T/7.5MA .

Discussion and conclusions. Simulations reveal many similarities of the low density FPO and PFPO LPS. These are, in particular, high fraction of the fast ion pressure, β_{fast}/β_{tot} ~ 10-25% (figures 2c, 3a, 3c, 4), impact of turbulence on fast ions (figure 6), wide zone of the weak reversed magnetic shear between the saw-teeth, long period of the ST (several tens of seconds), high central rotation (~ 400 km/s for τ_F/τ_E=2). The current drive efficiency and plasma conductivity in such scenarios are high, making possible LPS PFPO with the flat-top length Δt_{FT}~1000 s even with reduced CS currents +30 kA (figure 4) comparable with DT operation at fully charged CS (c.f. figures 1b, 4, 2a).

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