Simulating Burning Plasma Operation in ITER

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Introduction ITER will demonstrate the feasibility of burning plasma operation with a high ratio of fusion power gain Q~10 by operating D-T plasmas in the type-I ELMy H-mode regime. In this work, entry to burn, flat-top burning plasma operation and exit from burn have been investigated using CORSICA [1]. The CORISCA code self-consistently calculates the evolution of 2D free-boundary equilibria with both currents flowing in the surrounding conducting structures and plasma profiles computed with transport and sources, such as 1MeV deuterium neutral beams (NB), 53MHz ion cyclotron (IC), and 170GHz electron cyclotron (EC) heating and current drive. A total of 73 MW of auxiliary heating power is assumed to be available by combining 33MW NB, 20MW EC and 20MW IC. The waveforms of auxiliary heating powers are optimized for the plasma performance and to obtain high fusion power multiplication factor, Q. The effective charge (Z_{eff}) initially set to about 4.0 at the beginning of the ramp-up phase is reduced to 1.4~1.7 as the plasma density increases, and then increased to a higher value during the ramp-down as the plasma density decreases. Either Ar or W is used as a high-Z impurity species together with a low-Z impurity, Be. Sawteeth are assumed to be triggered when q_0<0.97 and the plasma temperature and current density profiles are modified within the inversion radius.

Modelling L-H and H-L transitions Low to high (L-H) and high to low (H-L) confinement transitions are triggered when the net power crossing the plasma separatrix (P_{tot}) becomes higher or lower than the L-H transition threshold power (P_{th}) obtained from the Martin scaling law [2]. During the L-H/H-L transitions, the plasma density has been increased/reduced linearly with a time constant, tauNe0, and the density profile has been also changed from L-mode (50% n_{GW}, parabolic shape) to H-mode (80~90% n_{GW}, flat at the core, hyperbolic tangent at the pedestal) with a faster shape transition time constant defined as tauNe0/5 [3]. To model the H-mode pedestal, firstly the hyperbolic tangent density profile at the pedestal has been adjusted with the pedestal top location estimated using the parameterized EPED1 model [4]. Then, the heat diffusivities computed using the Coppi-Tang transport model [5] have been feedback controlled to reproduce the estimated H-mode pedestal pressure. In this way, dithering between L-mode and H-mode is also modelled when the threshold and net powers are frequently crossing over each other.

Varying the density transition time-scale for L-H and H-L transitions The influence of the assumed density transition time-scale on L-H and H-L transitions has been examined, assuming Ar and Be as impurity species. When the plasma is in a limited configuration, the ratio of Ar to Be (n_{Ar}/n_{Be}) is set to 0.001, and then it is increased to 0.005 when the plasma becomes diverted. When the plasma has completed the L-H transition (t~70s), n_{Ar}/n_{Be} is increased further to 0.075, as if the Ar impurity is injected into the plasma to control the heat load to the diverter. During the flat-top phase, n_{Be}/n_e and n_{Ar}/n_e are set to about 1.8% and 0.14%, consistently with the assumption of Z_{eff}(flat-top)~1.7. Three cases with tauNe0=10s, 20s and 30s are compared, and this shows that the increase in the alpha particle heating power becomes slower as the density transition time-scale becomes smaller. However, the alpha particle heating powers become similar after the transient ramps, as the plasma operating conditions for the flat-top phase are not different. It appears that a slow density transition is favorable for reducing the total heating power around t=70s (see figure 1). It is also observed that if the density transition time-scale is reduced to a small value (~5s), P_{th} can be increased faster than the buildup of the alpha particle heating power. This introduces dithering of L-H/H-L transitions and forces the plasma to stay in an L-mode state (figure 1). It appears that the density transition time-scale is an important factor for controlling plasma dynamics for the entry to burn and burn control around the start of flat-top. Another comparison on H-L transitions shows that there is no clear dependency of tauNe0 on the burn exit as the decrease in the alpha particle heating power is much faster than the evolution of P_{th}. However, this requires a further study on the potential hysteresis characteristics for H-L transition in ITER. Note that active feedback control of the auxiliary heating power and/or fuel mix, which is useful for reducing the peak total power at the entry to burn, has not yet been attempted in this work.

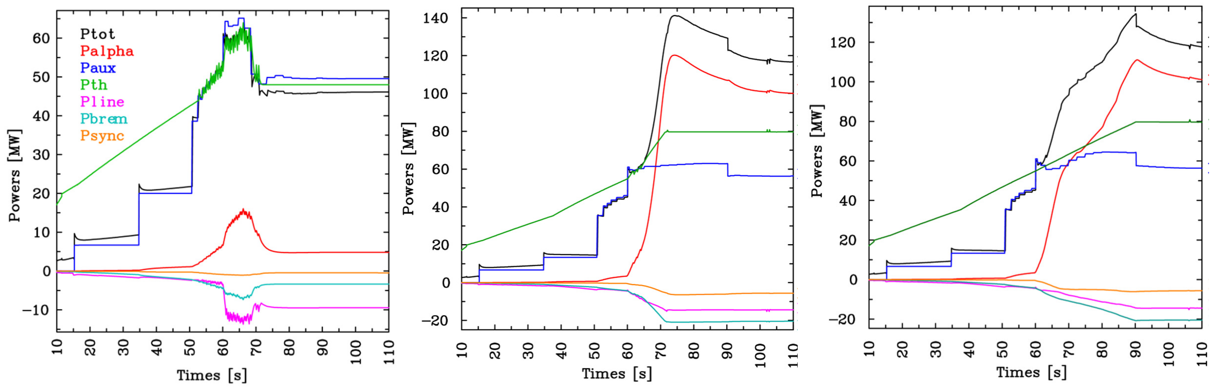

Figure 1. Evolution of powers during the current ramp-up and at the entry to burn. The density transition time-scale, tauNe0, has been varied from 5s (left) to 10s (centre) and 30s (right).

Varying the flat-top plasma density The flat-top plasma density plays an important role in operating the plasma with high performance, and also in achieving a high fusion power multiplication factor, Q. In this work, several cases with different flat-top densities have been compared. In the cases with Be and Ar impurities, n_{Be}/n_e~$1.79x10^{-2}$ and n_{Ar}/n_e~$1.35x10^{-3}$ were used with an assumption of Z_{eff} (flat-top)~1.7. In other cases with Be and W impurities, n_{Be}/n_e~$2.62x10^{-2}$ and n_{Ar}/n_e~$2.62x10^{-6}$ were used with an assumption of Z_{eff} (flat-top)~1.4. In both cases with different impurity species, similar changes in the plasma parameters have been observed when the volume averaged plasma density during the flat-top phase is varied from $8.82x10^{19}/m^3$ to $1.05x10^{20}/m^3$. As the flat-top density increases, the radiation powers increases and the pedestal temperature is reduced, whereas the estimated L-H transition threshold power is increased. Therefore, the margin for maintaining the plasma above the threshold power, $|P_{tot}-P_{th}|/P_{th}$, is reduced as the flat-top density increases. Another important observation made in this comparison is that the fusion power multiplication factor is not linearly increased with the flat-top density. The fusion power multiplication factor has increased up to about 10 in the Be/W impurity case at $\langle n_e \rangle \sim 9.37\times10^{19}/m^3$, however it is slightly reduced down to 9.6 at $\langle n_e \rangle \sim 1.05\times10^{20}/m^3$. This has happened mainly due to the changes in the pedestal temperature and radiation powers.

Varying the impurity concentration – Be/W cases In this study, W is assumed as a high Z impurity while Be is assumed as a low Z impurity. The impurity ion profiles are assumed to be proportional to the ion density profile. The W concentration (n_W/n_e) has been varied from 2.62×10^{-7} ($Z_{eff}\sim1.4$) to 5.24×10^{-5} ($Z_{eff}\sim1.67$), while the assumed Be concentration ($n_{Be}/n_e\sim 2.62\times10^{-2}$) and the density transition time-scale (tauNe0=20s) are not changed. Three cases are compared as shown in figure 3. The line radiation power is significantly increased when the W concentration is increased. The plasma stayed in L-mode when the assumed W concentration is about 5.24×10^{-5}. A similar study performed with a fixed Z_{eff} (flat-top)~1.7 (where n_{Be}/n_e is modified as n_W/n_e varies) has also shown that the marginal W impurity concentration for the entry to burn at 15MA ITER baseline operation is about 3.0×10^{-5}.

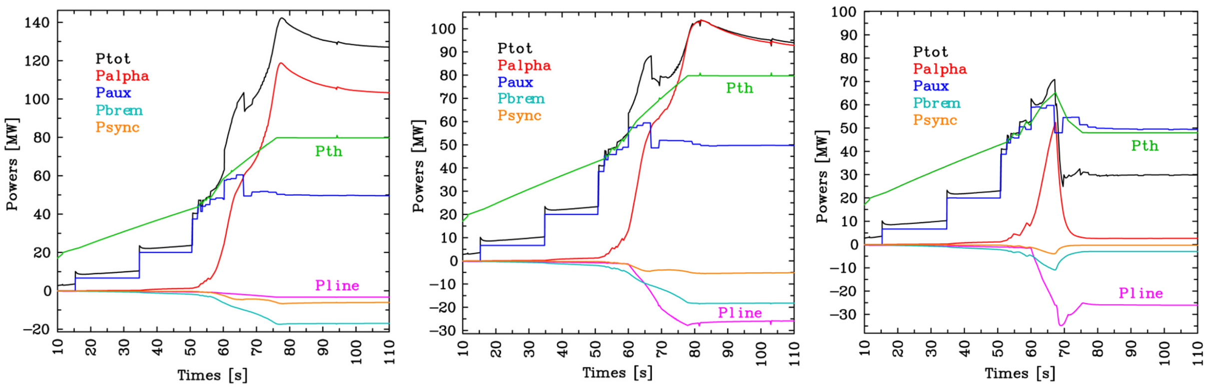

Figure 2. Evolution of powers during the current ramp-up and entry to burn. The W impurity concentration, n_W/n_e, and Z_{eff} have been varied from [2.62×10^{-7}, 1.4] (left) to [2.62×10^{-5}, 1.53] (centre) and [5.24×10^{-5}, 1.67] (right). The Be impurity concentration (n_{Be}/n_e) of 2.62×10^{-2} is unchanged.

An optimized scenario for 15MA ITER baseline operation An optimized scenario for the 15MA baseline ITER operation has been developed including all the improved modelling aspects for the entry to burn, flat-top burning plasma operation and exit from burn (see figure 3). The plasma, initially in an inboard limited configuration, is assumed to quickly grow and to be diverted around t=12s and the plasma current is ramped up to 15MA at t=60s. The current flat-top is assumed to end at t=500s, although the flat-top duration can be further extended within the coil current, force and field limits. The plasma current is then ramped down relatively slowly compared to the ramp-up phase, to avoid instabilities associated with the high plasma internal inductance. During the ramp-down phase, the plasma stays in a diverted configuration while it is slowly moving downward. The application of auxiliary heating powers during the ramp-up and ramp-down has been optimized to trigger L-H and H-L transitions within the operation constraints, such as the coil limits, NB shine-through density limit and IC power coupling. The fusion power multiplication factor (Q) of 9.5 and the plasma confinement enhancement factor ($H_{98}(y,2)$) of 1.03 have been achieved with about 50MW of auxiliary heating power during the flat-top. The volume averaged electron density and impurity concentrations (n_{Be}/n_e and n_{Ar}/n_e) were $9.37\times10^{19}/m^3$, 1.8% and 0.14%, respectively.

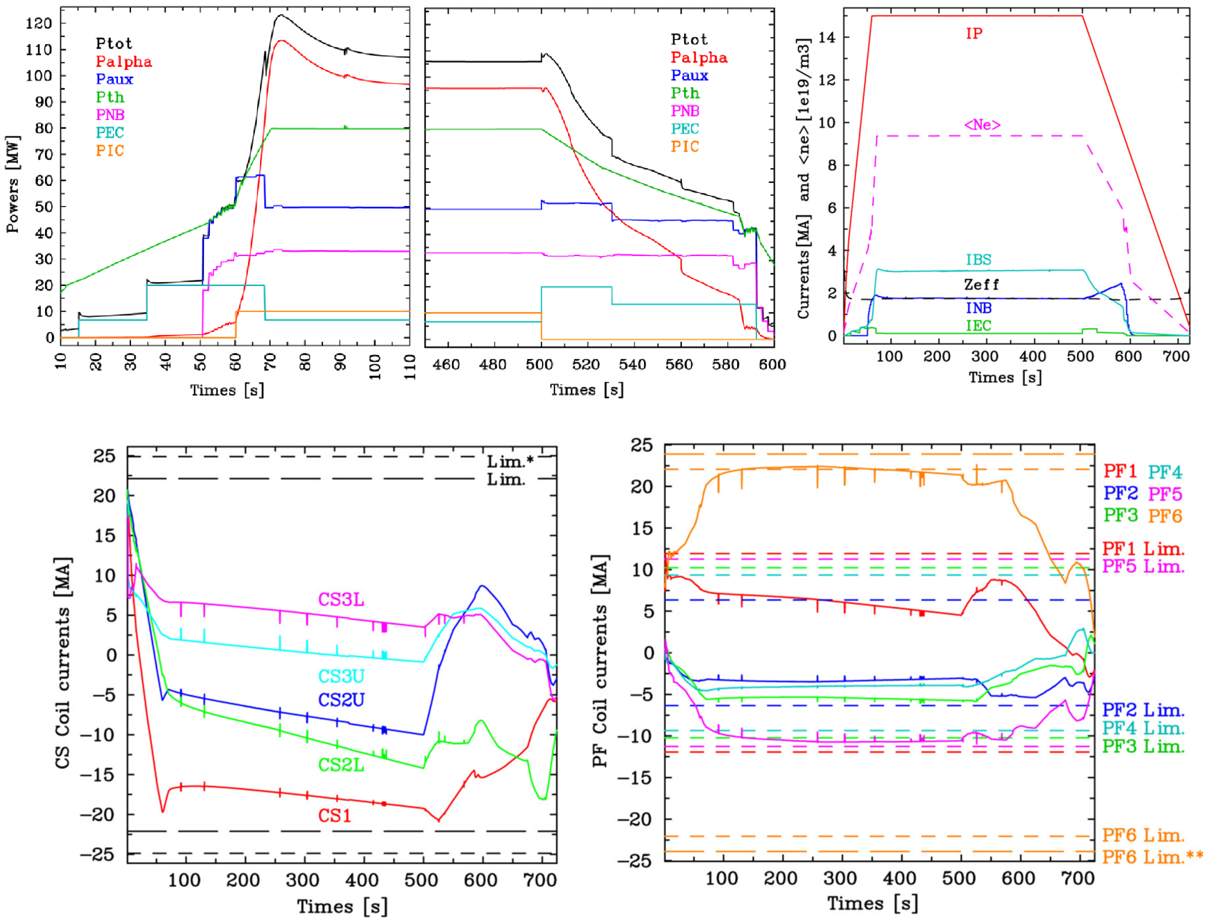

Figure 3. Evolution of powers (top left), currents, volume-averaged density and Z_{eff} (top right), CS coil currents (bottom left), and PF coil currents (bottom right). The coil current limits are indicated as dashed lines (and ** represent the extended current limits at reduced applied B-field and/or coil sub-cooling conditions)*

Summary and Conclusions In this work, the entry to burn, flat-top burning plasma operation and exit from burn have been investigated with improved modelling capabilities. Feasible high Q burning plasma operation scenarios have been developed for the ITER baseline operation within its operation constraints, such as the coil limits and heat loads. It has been observed that the W concentration needs to be maintained at a low value ($n_w/n_e <$ ~1.0×10^{-5}) to avoid the radiative collapse and early termination of the discharge. This work will be the basis for further optimization study, which will be necessary as the understanding of burning plasma physics improves.

Disclaimer ITER is the Nuclear Facility INB no. 174. This paper simulates plasma physics processes, neutron production and fusion performance during ITER operation; nevertheless the nuclear operator is not constrained by the results of this paper. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References

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