Tritium-Concentration Requirements in the Fueling Lines for High-Q Operation in ITER

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One of the most fundamental control problems arising in ITER and future burning-plasma tokamaks is the regulation of the plasma temperature and density to produce a determined amount of fusion power while avoiding undesired transients. ITER is designed to achieve a ratio of fusion power to auxiliary power, Q, of 10. The reactor's high plasma density ($> 1 \times 10^{20} m^{-3}$) and low burn fraction ($\sim 1\%$) will require high deuterium (D) and tritium (T) fueling rates. Gas puffing will have a low fueling efficiency ($< 1\%$) due to poor neutral penetration [1]. Therefore, the initial phase of ITER will rely on two pellet injectors located on its magnetic high-field-side (HFS) for deep core fueling. The D pellet injector (with pellets of 100% D nominal concentration) and the D-T pellet injector (with pellets of 10%D-90%T nominal concentration) are planned to have maximum throughputs of $120\,Pa\,m^3/s$ and $111\,Pa\,m^3/s$, respectively [2]. However, limitations in the tritium plant subsystems could result in a lower T concentration. Even if the nominal concentration could be initially achieved, it might not be possible to sustain it for the total duration of long pulses. This not only imposes burn-control challenges [3] but also raises serious concerns over having sufficient concentration of T in the fueling lines to sustain long-pulse high-Q operation. In this work, a volume-averaged model of ITER's burning plasma is used to assess the feasibility of accessing $Q = 10$ operation for different levels of T concentration. Operation points characterized by $Q = 10$ are sought within ITER's limits for fueling rates and auxiliary heating powers. The results are presented in the form of Plasma Operation CONtour (POPCON) plots that span the density-temperature space. The minimum tritium concentration that can maintain the plasma at $Q = 10$ is determined for different particle-recycling assumptions. Although this work is concerned with the design parameters of ITER, the analysis can be extended to other future burning-plasma reactors such as DEMO.

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Introduction

Tight regulation of the plasma temperature and density to produce a determined amount of fusion power while avoiding undesired transients is required for ITER to operate at $Q = 10$, where Q denotes the fusion power to external power ratio. To attain this goal, the ITER baseline will rely on three heating and current drive (H&CD) systems to supply external power and one pellet injection system (PIS) to provide deuterium (D) and tritium (T) refueling. The three H&CD systems provide 20 MW of electron cyclotron heating, 20 MW of ion cyclotron heating, and 33 MW of neutral beam injection [1]. The PIS consists of two pellet injectors that can fire 5 mm pellets ($\sim 6 \times 10^{20}$ atoms) at a maximum repetition rate of 16 Hz. The D injector and D-T injector supply, respectively, pellets that have a nominal concentration of 100% D and 10%D-90%T [2]. However, the concentration of T in the fueling lines may fall below its nominal value, particularly during long high-Q pulses. Along with the resulting burn-control challenges [3], this presents concerns over having adequate T refueling to maintain operation at desired states. Accounting for ITER's actuator limits and the T concentration of the pellets, the accessibility of steady-state, $Q = 10$ operation points is analyzed in this work. The results are determined over the density-temperature space and processed into Plasma Operation CONtour (POPCON) plots. Plasmas with different particle recycling and confinement conditions are compared.

The Plasma Model

The plasma is modeled by one-dimensional ion density (deuterium density n_D, tritium density n_T and alpha particle density n_α) and energy density (plasma temperature T) rate equations. The radial profiles of the particle densities are assumed to be flat. The radial profile of the temperature has the shape $T(\vec{r},t) = T_0(t)[1-(\phi/\phi_0)]^{\gamma_t}$, where T_0 is the central plasma temperature, ϕ is the toroidal magnetic flux coordinate (at the plasma edge $\phi = \phi_0$) and $\gamma_t = 1.85$ [4]. This assumed profile shape approximates the predicted profiles for ITER [5]. The volume average of the one-dimensional equations reduce them to a zero-dimension model given by

$$\frac{d}{dt}n_D = -\frac{n_D}{\tau_D} - n_D n_T \langle\sigma v\rangle_V + f_{eff} S_D^R + S_D, \quad (1)$$

$$\frac{d}{dt}n_T = -\frac{n_T}{\tau_T} - n_D n_T \langle\sigma v\rangle_V + f_{eff} S_T^R + S_T, \quad (2)$$

$$\begin{aligned}
\frac{d}{dt}n_\alpha &= -\frac{n_\alpha}{\tau_\alpha} + n_D n_T \langle\sigma v\rangle_V, & (3)\\
\frac{d}{dt}\left[\frac{3}{2}nT\right] &= -\frac{3nT_0}{2(1+\gamma_t)\tau_E} + Q_\alpha n_D n_T \langle\sigma v\rangle_V + P_{aux} & (4)\\
&\quad + A_h Z_{eff} I_p^2 a^{-4} T_0^{-3/2}\left(1+\frac{3\gamma_t}{2}\right) - A_b Z_{eff} n_e^2 \frac{T_0^{1/2}}{1+\gamma_t/2},
\end{aligned}$$

where P_{aux} is the external heating power, S_D and S_T are, respectively, the external fueling rates of deuterium and tritium, and $Q_\alpha = 3.52$ MeV is the energy deposited into the plasma from each fusion alpha particle. With T_0 expressed in keV, the ohmic heating power (P_{ohm}) and bremsstrahlung radiation power (P_{brem}) coefficients are, respectively, $A_h = 2.8\times10^{-15}$ MW/m^3 and $A_b = 5.5\times10^{-43}$ MW/m^3 [6].

In addition to the D, T and α ion species, the plasma is assumed to contain an impurity density n_I with atomic number Z_I. The quasi-neutrality condition, $n_e = n_D + n_T + 2n_\alpha + Z_I n_I$, defines the electron density. The effective atomic number and the total plasma density are $Z_{eff} = (n_D + n_T + 4n_\alpha + Z_I^2 n_I)/n_e$ and $n = n_D + n_T + n_\alpha + n_I + n_e$, respectively. The tritium fraction of the plasma is defined as $\gamma = n_T/(n_D + n_T)$. The fusion reactivity, $\langle\sigma v\rangle$, is determined by evaluating at T_0 the formulation found in [7]. To account for the radial temperature profile, $\langle\sigma v\rangle$ is multiplied by a correction factor, G, [4] to obtain its volume average, $\langle\sigma v\rangle_V$.

The IPB98(y,2) H-mode scaling law for the energy confinement time, τ_E, is,

$$\tau_E = 0.0562 H I_p^{0.93} R^{1.97} B^{0.15} M^{0.19} \varepsilon^{0.58} \kappa^{0.78} n_e^{0.41} P_{total}^{-0.69}, \qquad (5)$$

where H_H is the enhancement factor, $P_{total} = (Q_\alpha S_\alpha + P_{aux} - P_{brem} + P_{ohm}) \times V$ is the total plasma power in MW, and V is the plasma volume. The ITER values of the parameters in (5) are listed in [8]. The particle confinement times are $\tau_\alpha = k_\alpha \tau_E$, $\tau_D = k_D \tau_E$ and $\tau_T = k_T \tau_E$.

The recycling flux of deuterium and tritium from the reactor walls are modeled as,

$$\begin{aligned}
S_D^R &= \frac{1}{1-f_{ref}(1-f_{eff})}\left\{f_{ref}\frac{n_D}{\tau_D} + \left(1-\gamma^{PFC}\right)\times\left[\frac{(1-f_{ref}(1-f_{eff}))R^{eff}}{1-R^{eff}(1-f_{eff})} - f_{ref}\right]\left(\frac{n_D}{\tau_D}+\frac{n_T}{\tau_T}\right)\right\},\\
S_T^R &= \frac{1}{1-f_{ref}(1-f_{eff})}\left\{f_{ref}\frac{n_T}{\tau_T} + \gamma^{PFC}\times\left[\frac{(1-f_{ref}(1-f_{eff}))R^{eff}}{1-R^{eff}(1-f_{eff})} - f_{ref}\right]\left(\frac{n_D}{\tau_D}+\frac{n_T}{\tau_T}\right)\right\},
\end{aligned}$$

where f_{eff}, f_{ref}, R^{eff} and γ^{PFC} are constants that define the quality of the recycling [9].

The L-H mode transition threshold power, expressed in MW, for a D-T plasma is given by $P_{thresh} = 4.3 M^{-1} B^{0.772} n_e^{0.782} R^{0.999} a^{0.975}$. The total plasma power must be above this threshold power for the plasma to be in H-mode [10]. The ratio of the fusion power to the power externally put into the plasma is $Q = E_{fus} n_D n_T \langle\sigma v\rangle_V/(P_{aux} + P_{ohm})$ where E_{fus} = 17.6 MeV.

The D-T pellet injector fuels the plasma at a rate of S_{DT}^{line} with pellets containing a tritium concentration of γ_{DT}^{line}. The D pellet injector fuels the plasma at a rate of S_{D}^{line} with pellets containing a tritium concentration of γ_{D}^{line}. Therefore, the external fueling rates, S_D and S_T, are formulated as,

$$\begin{aligned} S_D &= (1-\gamma_{DT}^{line})S_{DT}^{line} + (1-\gamma_{D}^{line})S_{D}^{line}, && (6)\\ S_T &= \gamma_{DT}^{line}S_{DT}^{line} + \gamma_{D}^{line}S_{D}^{line}. && (7)\end{aligned}$$

POPCON Analysis Results

In the following analysis, the steady-state plasma conditions for $Q = 10$ operation are studied in the density-temperature space. The system of four equations (1)-(4) in steady-state ($d/dt = 0$) is solved for four unknowns. The unknowns are the alpha particle density fraction $f_\alpha = n_\alpha/n_e$, the external fueling rate of deuterium S_D, the external fueling rate of tritium S_T, and the impurity density fraction $f_I = n_I/n_e$. With $Q = 10$, the auxiliary power, P_{aux}, is determined from the expression for Q. The solution is found repeatedly over a grid of fixed n_e and T_0 values. All of the plasma conditions (i.e. τ_E) can be calculated from the four unknowns, the electron density and the central temperature. The resulting contour lines are plotted in the n_e-T_0 space.

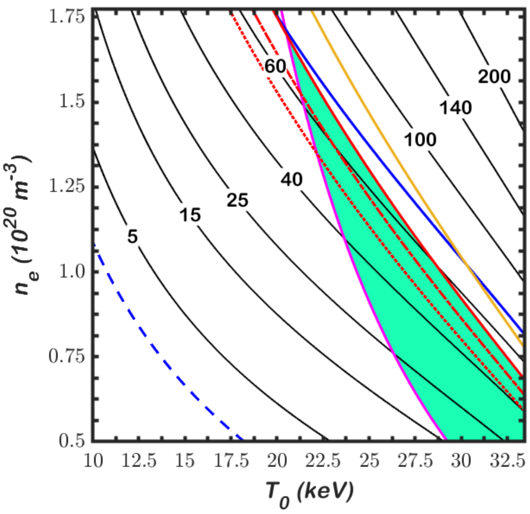

Figure 1: Results with auxiliary power [MW] isolines (black) for plasma with $k_D = k_T = 1.2$, $k_\alpha = 1.6$ and $f_{eff} = 0.2$.

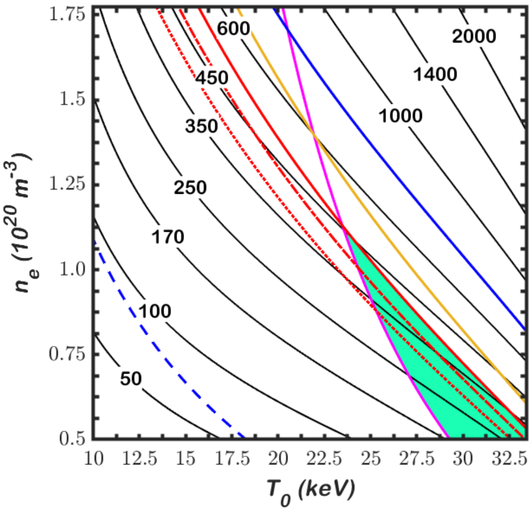

Figure 2: Results with fusion power [MW] isolines (black) for plasma with $k_D = k_T = k_\alpha = 1$ and $f_{eff} = 0$.

The two scenarios discussed in this section consider only $Q = 10$ operation and the following fixed constants: $\gamma_D^{line} = 0$, $H_H = 1$, $\gamma = 0.5$, $Z_I = 10$ (Neon), $f_{ref} = 0.5$, $R_{eff} = 0.6$ and $\gamma^{PFC} = 0.5$. Fig. 1 shows the contours of constant auxiliary power for a plasma with recycling ($f_{eff} = 0.2$) and high particle confinement ($k_D = k_T = 1.2$, $k_\alpha = 1.6$). Fig. 2 shows the contours of constant fusion power for a plasma with no recycling ($f_{eff} = 0$) and low particle confinement ($k_D = k_T = k_\alpha = 1$). In both figures, multiple lines mark the saturation curves of the ITER actuators. The dashed-blue line marks where P_{aux} = 0. Below this line, the auxiliary power is negative and the results are physically meaningless. The solid-blue line denotes where P_{aux} = 73 MW. The yellow line marks where the D injector saturates at 16 Hz with γ_{DT}^{line}=90%. Where the D-T injector hits 16 Hz with γ_{DT}^{line}=90%, γ_{DT}^{line}=80% and γ_{DT}^{line}=70% is plotted using the solid-red, dashed-dotted-red and dotted-red lines, respectively. On the magenta line, the total plasma power, P_{total}, equals the threshold power P_{thresh} (the plasma is in H-mode above this line). The green zone marks the steady-state operable space with $Q = 10$ for the given ITER plasma ($\gamma_{DT}^{line} = 90\%$). Here, the actuator saturation limits are not violated and the plasma is in H-mode.

Conclusions and Future Work

Due to enhanced confinement and recycling conditions, the plasma plotted in Fig. 1 has a much larger $Q = 10$ operable space than that plotted in Fig. 2. In both figures, the three red lines indicating D-T injector saturation (16 Hz) show how a decreasing T concentration (γ_{DT}^{line}) can shrink the Q = 10 operable space. The steady-state, Q = 10 operable spaces of the ITER plasmas depicted in Fig. 1 and Fig. 2 vanish when γ_{DT}^{line} drops below 30% and 60%, respectively. Future work may include extending this study to other Q conditions, studying sensitivity of the results, and applying this analysis to other burning reactors such as DEMO.

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