

Exploratory Studies of Power Generation Control in Tokamak Fusion Power Plants

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Introduction

Here we report some results of our exploratory studies regarding changes in the plasma operating conditions in order to modify the total power generation in a tokamak fusion power plant. In this work we show how proper modifications of the operating point of the plasma can be done in order to adjust the power generated to external demands. The studies were performed using a nonlinear two temperature 0D model of a tokamak with the ITER design parameters, in which the operating point and thus the power generation are adjusted by proper adjustment of the D-T refueling rate, a neutral He-4 beam and the auxiliary heating to ions and electrons.[1, 2] Using Plasma OPERating CONtourn plots (POPCON),[3] we identify the optimal operating conditions, i.e. those that maximize the Q-gain factor.

The equations we use are volume average of the particle density and energy balance equations,

$$\begin{aligned}
 \frac{\partial n_{DT}}{\partial t} &= S_{\text{ref, DT}} - S_{\text{fusion}} - S_{\text{transp, DT}} \\
 \frac{\partial n_{\alpha}}{\partial t} &= S_{\text{ext, } \alpha} + S_{\text{fusion, } \alpha} - S_{\text{transp, } \alpha} \\
 \frac{\partial \mathcal{E}_e}{\partial t} &= P_{\text{aux, e}} + P_{\text{fusion, e}} + P_{\text{ohm}} - P_{\text{equil. e-i}} - P_{\text{rad, e}} - P_{\text{transp, e}} \\
 \frac{\partial \mathcal{E}_i}{\partial t} &= P_{\text{aux, i}} + P_{\text{fusion, i}} + P_{\text{equil. e-i}} - P_{\text{transp, i}}
 \end{aligned} \tag{1}$$

which describe the evolution of a quasi-neutral plasma composed by 50:50 D-T fuel and helium ash, with a small amount of impurities (Be and Ar). The plasma heating takes place by the thermalization of the energetic alpha particles produced by fusion and independent external auxiliary heating to electrons and to ions, with a small contribution of joule heating. The electron and ions temperatures are assumed different but with the same radial profile, $T_{e,i}(r,t) = T_{e,i}[1 - (r/a)^2]^\gamma$; the particle densities are assumed to be homogeneous.

The reference operating point will be taken, as $n_{e,0} = 1.01 \times 10^{20} \text{ m}^{-3}$, for the electron density; $T_{e,0} = 23.6 \text{ keV}$ and $T_{i,0} = 23.0 \text{ keV}$ for the central temperatures for the electrons and the

ions. The nominal value of the helium ash fraction is $f_\alpha = 0.045$, and it will be kept constant for all conditions considered here. In addition it will be assumed that only 90% of the energetic alpha particles produced deposit their energy in the plasma (the rest is anomalously lost before they are thermalized); we assume that during thermalization energetic alpha particles deposit 85% of their energy to the electrons and 15% to the ions.

Plasma Operating Conditions Contourn Plots

In order to study different operating conditions, here we assume that the steady state conditions of interest are those that satisfy the electron and ion temperatures relation $(T_e - T_i)/T_e = 0.0254$, with the fraction of helium ash fixed to 0.045. Thus the electron density and the electron temperature define completely the new operating conditions. Thus, after volume average in Eq. (1) and assuming steady state we fix electron density and temperature, and solve Eqs. (1) for $P_{\text{aux}, e}$ and $P_{\text{aux}, i}$ the auxiliary heating power to electrons and to ions, $S_{\text{ref}, \text{DT}}$, the DT refueling rate and S_α the rate of injection of neutral He₄ atoms. These parameters must be non-negative in order to obtain physically feasible conditions. The gain factor Q_G is defined as the ratio of the energy generation rate in the plasma due to the fusion reactions to the total auxiliary heating power,

$$Q_G = \frac{\langle P_{\text{fusion}} \rangle_{\text{vol}}}{\langle P_{\text{aux}, e} + P_{\text{aux}, i} + P_{\text{ohmic}} \rangle_{\text{vol}}}, \quad (2)$$

with $P_{\text{fusion}} \approx 5 \times P_\alpha$. The fusion power takes into account the energetic neutrons produced in the DT fusion reactions. In what follows we show contourn plots of possible operating conditions obtained with $\tau_\alpha = \tau_p = 5\tau_E$ and the IPB98(y,2) scaling law for the energy confinement time,[4]

$$\tau_{\text{IPB98}} = 0.0562 H_H I^{0.93} R^{1.97} B^{0.15} M^{0.19} \epsilon^{0.58} \kappa^{0.78} n_e^{0.41} P_{\text{net}}^{-0.69}. \quad (3)$$

H_H is a factor used to express the degree of enhancement that might be expected over the current mean prediction. Here we take $H_H = 1$. The values of these parameters are based on the design parameters of ITER.[5]

In Fig. (1) we show POPCON plots in $T_e - n_e$ space, for some relevant reactor quantities. However, not all the $T_e - n_e$ space is accesible for the operation: the region to the left of the almost-vertical red line requires $P_{\text{aux}, i} < 0$, i.e. power extraction from the ions, thus only the region to the right of this line is relevant. In Fig. (1-left) the $Q_G = \text{const.}$ contours are shown together with $P_{\text{fusion}} = \text{const.}$ contours. We notice that, for a given value of P_{fusion} , the maximum possible gain is obtained when the boundary line given by $P_{\text{aux}, i} = 0$ is reached; therefore, these are the optimal points one should aim for the operation of the reactor. Fig. (1-right) shows the $P_{\text{aux}, \text{total}} = \text{const.}$ contours and it is seen that when we move along a line $P_{\text{fusion}} = \text{const.}$ the

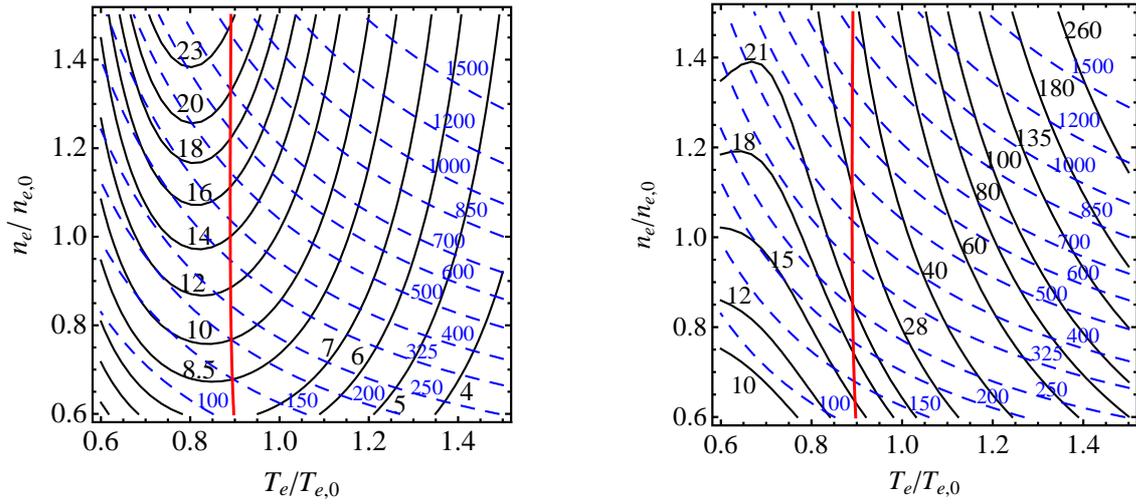


Figure 1: Contour plots of the Q-Gain in Eq. (2) (left plot, solid line) and the total auxiliary power in MW (right plot, solid line). In both figures we also show the contour plot of the total fusion power in MW (dashed lines) for the different operating scenarios.

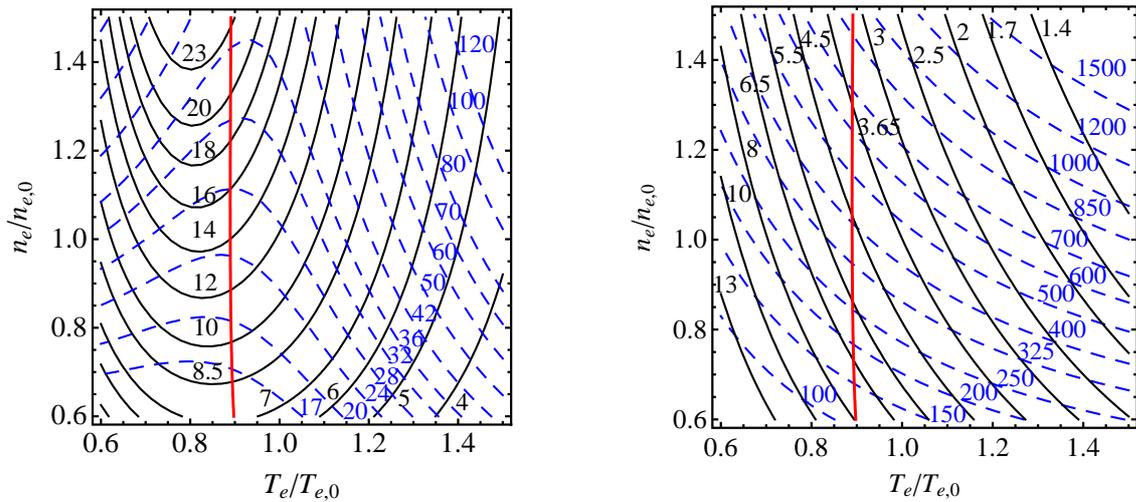


Figure 2: Left plot: Contour plots of the auxiliary heating power to electrons in MW (dashed) and the Q-gain (solid); right plot: the energy confinement time in seconds as obtained from Eq. (3) (solid) together with the total fusion power (dashed).

total auxiliary heating decreases as we approach the boundary line $P_{\text{aux}, i} = 0$. Thus the optimal operating point has the minimum possible value for which $P_{\text{aux}, i} \geq 0$. Similarly, in Fig. (2) we compare Q_G with $P_{\text{aux}, e}$ on the left and on the right τ_{IPB98} with P_{fusion} using contour plots. It is concluded that at the optimal operational points both P_{fusion} and $P_{\text{aux}, e}$ increase in proportion to Q_G , so larger gains are obtained only for larger P_{fusion} which requires larger input power

to electrons. It is observed from Fig. (2-right) that for $P_{\text{fusion}} = \text{const.}$, the confinement time increases as the optimal point is approached, as one would expect. The red boundary line also represents the path that one should follow in order to increase the total fusion power while keeping maximum Q_G at all times. In addition to increase the $S_{\text{ref, DT}}$ refueling rate, this path requires supplying auxiliary heating only to the electrons.

It is possible to parametrize the optimal values for the plasma density and the electron temperature, so that a desired fusion gain may be programmed by controlling the density and temperature of the plasma. Using a polynomial fit, a reasonable approximation for the density is obtained for second degree, but the temperature has a weaker and nonmonotonic dependence which requires a higher degree polynomial. For a given maximum power gain Q_{GM} they are given by,

$$n_e = 0.141 + 0.0664Q_{GM} - 0.000357Q_{GM}^2 \quad (4)$$

$$T_e = 0.981 - 0.0246Q_{GM} + 0.00264Q_{GM}^2 - 0.00014Q_{GM}^3 + 3.8 \times 10^{-6}Q_{GM}^4 - 3.9 \times 10^{-8}Q_{GM}^5$$

We have also explored the operation of the reactor with no alpha particles source ($S_\alpha = 0$) and found that this is indeed possible if the helium ash density fraction $f_\alpha = n_\alpha/n_e$ is allow to vary freely. Other study we have made is the variation of the H factor which would result when better confinement modes are reached. When H increases over 1 larger Q_G values are obtained. These results will be reported elsewhere.

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