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Analysis of ITER Radiative Edge Operating Scenarios

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1. Introduction

Recent calculations [1-5] have suggested that an impurity seeded radiative mantle is likely to play a key role in helping to reduce the peak divertor heat loads that are anticipated during the operation of the International Thermonuclear Experimental Reactor (ITER). Results from most of the leading experiments (e.g. [6-8]) also appear to support the feasibility of reliable tokamak operation with high edge radiating fractions.

In the present work, we have compensated increased radiation losses by changing slightly the operating point to obtain ignited or near-ignited ($Q \geq 300$) operating points with enhanced radiation from the plasma edge. In addition, we have implemented transport models that predict confinement degradation at high radiating fractions, in accordance with experimental observations from ASDEX-U and JET [6-7]. We have also studied the sensitivity of our predictions to assumptions on the He exhaust, which has been recently shown to be an important issue [9].

2. Models and Methods

Our simulations are performed using our 1½-D core transport code GTWHIST, coupled to non-coronal equilibrium impurity transport routines and a simple but comprehensive SOL/divertor model [2].

Two different transport models have been used in the present simulations. The first, referred to as the *fixed shape* transport model [3], consists of local transport coefficients of a fixed radial shape with a multiplier which is adjusted at each time step so that the global energy confinement follows the ITER93P ELMy thermal confinement scaling. The second transport model, referred to as the *JET* transport model, is an empirical model consisting of neoclassical, Bohm and GyroBohm contributions [10] according to which,

$$\chi_{e,i}^{JET} = \chi_{e,i}^{neo} + \alpha_{e,i}^{B} \frac{\left|\nabla(n_e T_e)\right|}{n_e B_T} a q^2 \left\langle L_{T_e}^{*} \right\rangle_{\Delta V}^{-1} + \alpha_{e,i}^{GB} \frac{\left|\nabla T_e\right|}{B_T} \rho_i \qquad (1)$$

where the non-local term $\left\langle L^{*}_{T_e}\right\rangle^{-1}_{\Delta V} \equiv \left(T_e(\rho = 0.85) - T_e(\rho = 1)\right)/T_e(\rho = 1)$ depends on the edge temperature conditions. The non-local term allows us to simulate cases where the global confinement degrades following impurity injection. The coefficients in the JET model are adjusted only once to obtain the reference operating point and remain constant for all the subsequent simulations.

3. Results of Impurity Seeding Simulations

We base our calculations on the reference operating points for the ITER EDA design parameters (R_0 = 8.14 m, a = 2.80 m, P_{fusion}= 1.5 GW, I_p = 21 MA) for both transport models and for two different values (4 and 10) of the thermal alpha to energy confinement times ratio $\rho_{He} = \tau^{*}_{He}/\tau_E$.

In our previous work [1-4], our simulations of impurity seeded radiative mantle operating scenarios for ITER were performed starting from a reference ITER operating point and injecting impurities, using auxiliary power to compensate for the increased core radiation losses. As a result, the obtained solutions corresponded to high-Q ($Q \geq 25$), sub-ignited, operating points. In Fig. 1, the total radiated power from inside the separatrix is plotted vs. the impurity concentrations (Ne, Ar and Kr) for this case [3]. These results have been derived using the local form of the JET transport model and assuming that ρ_{He} = 10.

3.1 Fixed Shape Transport Model

For the fixed shape transport model, two different approaches have been used to obtain ignited operating points with impurity seeding. In the first, the fueling is increased, moving the operating point to higher densities and lower temperatures in the n-T space, while the overall level of confinement remains the same (τ_E = $0.85\times\tau_E^{ITERH93P}$). In the second approach, the fuel density is kept constant and equal to its value at the reference operating point, while the confinement is improved to a level necessary to obtain ignition. Such a confinement improvement could be realized, for example, by operating at a higher plasma current and accepting as a trade-off a shorter burn time.

In Fig. 2, the total power that is radiated from inside the last closed flux surface (LCFS) is plotted vs. the average impurity concentration (Ne, Ar and Kr) for the case of ρ_{He} = 4 and constant H factor (H = 0.85). The corresponding increase in the electron density is shown in

Fig. 3, where the volume average electron density is plotted vs. the total radiated power for the three impurity cases.

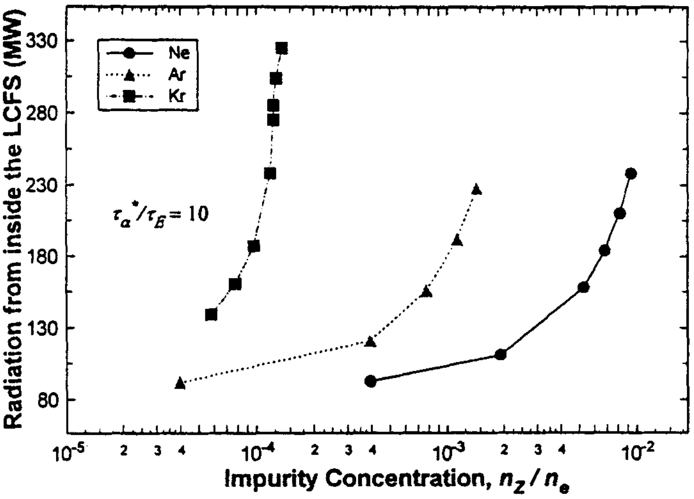

Fig. 1: Radiation from inside the LCFS vs. impurity concentration for the local JET transport model and ρ_{He} *= 10 using auxiliary power to compensate for core radiation losses [3]*

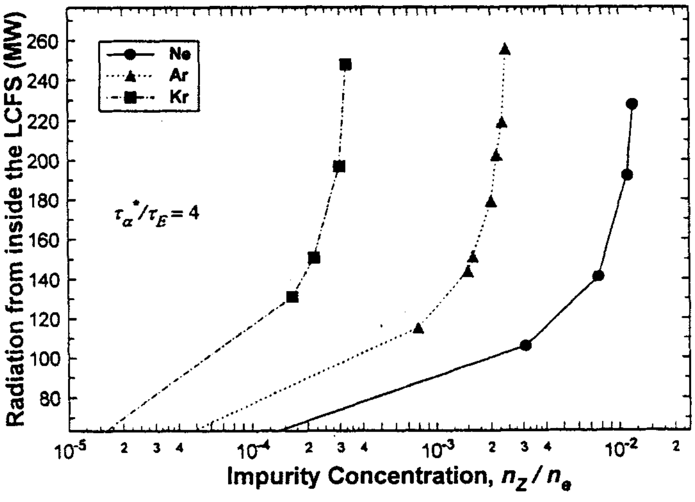

Fig. 2: Radiation from inside the LCFS vs. impurity concentration for the fixed shape transport model

It can be seen from Fig. 3, that the required density increases as we move from high to low Z impurities. For example, radiating 150 MW of power from inside the separatrix and maintaining ignition would require an increase of the density by a factor of 1.06, 1.12 and

1.23 for Kr, Ar and Ne respectively. Since the reference electron density is very close to the Greenwald density limit for ITER, these ratios represent the required increase above this limit as well. Similar results have been obtained for the case of $\rho_{He} = 10$.

For the constant density and improved confinement case, the required concentrations for radiating a certain amount of power from within the separatrix are about the same as the ones for the constant confinement case for similar values of ρ_{He}. The required improvement in confinement in order to maintain ignition depends on the impurity species (lowest for Kr, highest for Ne) and the desired amount of radiated power. Figure 4 shows the required *H*-factor for the case of $\rho_{He} = 4$. Similar amounts of confinement improvement are required for the $\rho_{He} = 10$ case.

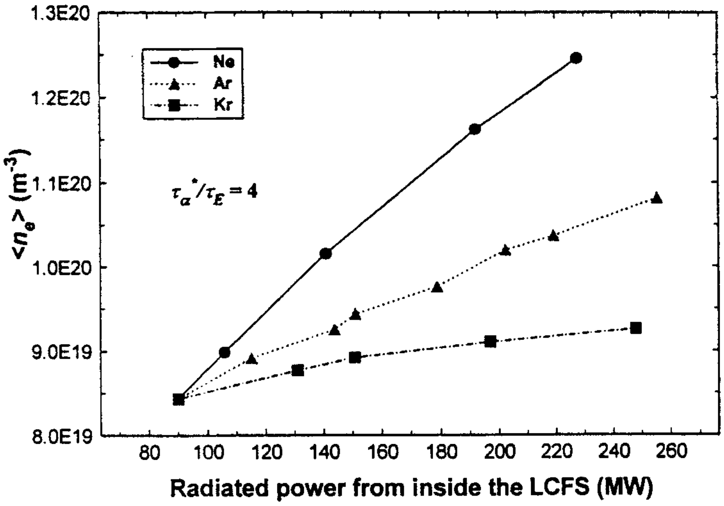

Fig. 3: Average electron density vs. radiated power for the fixed shape transport model.

3.2 Non-local JET Transport Model

Similar results have been obtained for the non-local JET transport model and are shown in Figs. 5 and 6 for the case of $\rho_{He} = 4$. In Fig. 5, the total radiated power from inside the separatrix is plotted vs. the Ne, Ar and Kr impurity concentrations. The results are very similar to those for the constant confinement fixed-shape case (Fig. 2). However, the maximum power that can be radiated while maintaining ignition is smaller for the non-local JET transport model (maximum radiation fraction 0.65 vs. 0.90 for the fixed-shape transport model case) due to the confinement degradation caused by the decrease of the edge temperature following the impurity injection, as can be seen in Fig. 6.

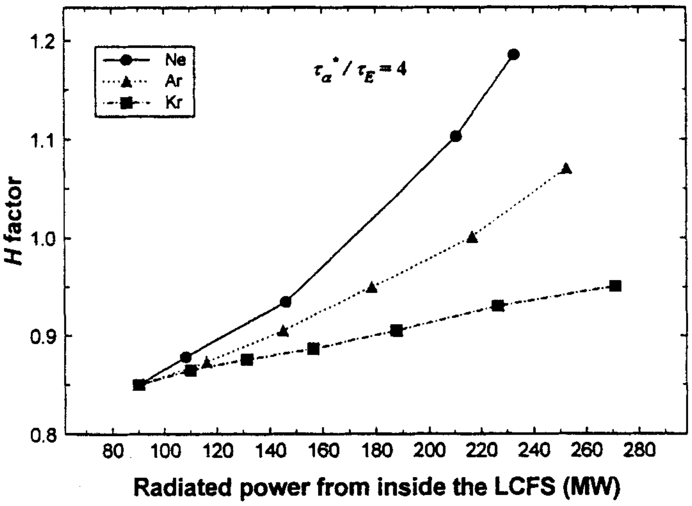

Fig. 4: H factor relative to ITER93P global scaling vs. radiated power from inside the LCFS

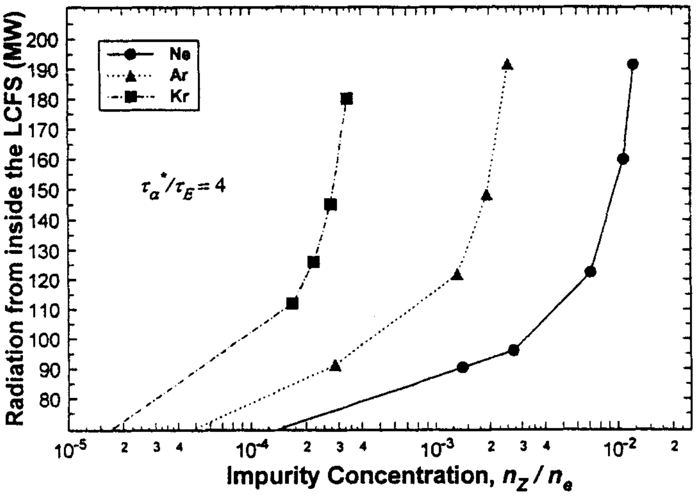

Fig. 5: Radiation from inside the LCFS vs. impurity concentration for the non-local JET transport model

4. Z_{eff} Scaling

Recently [11], a scaling for the plasma Z_{eff} based on results from a multi-machine database of radiative plasma experiments has been proposed. According to this scaling, Z_{eff} =

$1+7P_{rad}/(S\,\bar{n}_e^2)$, where P_{rad} is the total radiated power, S is the plasma surface area and $\bar{n}_e$ is the line average electron density in units of 10^{20} m^{-3}. We have examined the predictions of this scaling against the values of the central Z_{eff} from the results of our simulations and found that the formula overestimates the Z_{eff} for Kr by 20-30% and underestimates it for Ne by 16-25 %, while it agrees within 5% for Ar.

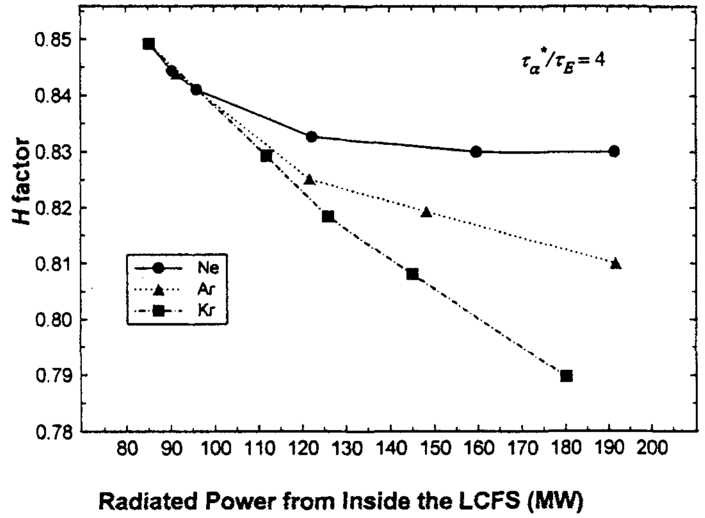

Fig. 6: H factor relative to ITER93P global scaling vs. radiated power from inside the LCFS

5. Conclusions

Our results demonstrate that it is possible to obtain ignited operating points for ITER with a strong radiative edge. This is true, even in the case of the non-local JET transport model which predicts a degradation of the global energy confinement with increasing radiated power.

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