**Transport Simulations of ITER Helium
Exhaust Using Recent Data from TFTR,
TEXTOR and JT-60**

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Insufficient helium exhaust can seriously degrade the performance of any fusion reactor and has recently been identified as a potentially significant issue for ITER. The effects of variations of the ratios D^{He}/χ_i , D^{He}/D^D , v^{He}/D^{He} and of the sawtooth period on helium exhaust in ITER are studied with BALDUR code transport simulations. Recent measurements of D^{He}/χ_i at TFTR, of D^{He}/D^D at TEXTOR and of v^{He}/D^{He} at TFTR, TEXTOR

and JT-60 are found compatible with sustained ignition and helium exhaust requirements for ITER. Ignition is found to be critically sensitive to the ratio v^{He}/D^{He} , particularly at the plasma edge, and to reduced sawtooth period. These critical dependencies are moderated for reduced helium recycling at the separatrix and for hollow particle diffusivity profiles.

1. Introduction

Recently there has been considerable interest in the projected accumulation/exhaust of helium ash from the ITER reactor [1–8]. Buildup of thermalized alpha particles to high concentrations can quench a reactor burn. It is now well known that the balance between long energy confinement time with sufficient particle loss rates leads to the requirement $\tau_p/\tau_E \leq 10$ for ignition at ITER, the exact value being most sensitive to helium transport boundary conditions at the separatrix. In the last year, the first measurements, some radially resolved, of transport coefficients for helium impurities in predominantly deuterium plasmas have been obtained at the TFTR [9,10], TEXTOR [11,12] and JT-60 [13] tokamaks. This paper presents the effects on simulations of ITER burn and helium transport, of particle transport coefficients in the range observed. In the next section the transport model assumptions are presented. The following section presents the results of the simulations and the last section summarizes the conclusions.

2. Transport Model Assumptions

As in two previous studies [1,2] anomalous transport was scaled from JET H-mode data, normalized to the ITER89P τ_E scaling relation, and the radial profiles of χ_i , χ_e , D were assumed similar to JET's:

$$\chi_e(r) = \chi_{eo}(3 + 5 r/a)$$

$$\chi_i = \chi_e/2$$

$$D = \chi_i/2$$

Again, we note that TFTR observes more hollow $\chi(r)$ profiles and $\chi_i/\chi_e \geq 2$ [14]. Our $\chi(r)$ profile is more pessimistic from the point-of-view of helium accumulation spoiling sustaining ignition. Increased χ_i/χ_e would make little difference because $T_i \approx T_e$. In our simulations, particle transport is controlled by an anomalous diffusivity D , pinch v , and recycling coefficient R at the separatrix as well as by the effects of sawteeth and a soft-beta limit [2].

Baseline reference assumptions are that $D = \chi_i/2$, $v = 0$, $R_{He} = 0.95$ with all species obeying the same transport except where noted. Also, we set $\frac{n_{He}(a)}{n_e(a)} = 0.1$. This constraint is set because of the need by the pumping system for a finite (minimum) helium concentration to effect helium exhaust at

finite pumping speed. Furthermore, $n_e(a) = 3.6 \times 10^{19} \text{cm}^{-3}$, consistent with acceptable divertor operating conditions at 1 GW fusion power. In earlier work [2] we showed that a separatrix recycling coefficient $R_{He} = 0.95$ was consistent with sustained ignition in ITER; helium concentrations reached only 3.2% after a 200 second pulse length. For application to the ITER H-mode scenario, no anomalous inward pinch was used in the baseline comparison. As in [2] sawteeth ($\tau_{ST} = 30 \text{ sec}$) are included in the baseline simulations. All simulations were carried out with the 1-D BALDUR transport code [15,16].

3. Results

3.1. *Effect on helium exhaust of ratio τ_D/τ_{He}*

Hillis [11,12] has shown that the TEXTOR pumped limiter can attain $R_{He} = 0.92$ and that the ratio τ_D/τ_{He} is in the range 0.33–1.0. These measurements were made in the L-mode, beam-heated regime. In contrast, it is planned that ITER will operate in H-mode. These typically have flat density profiles. Lacking helium transport data for H-modes, we model ITER with $D_{He}/D_D = (0.33\text{--}1.0)$, i.e., that τ_D/τ_H is fixed. The simulations discussed in this section were carried out with $R_{He} = 0.92$.

Figure 1 shows the effect of varying D_{He}/D_D from 0.33 to 1.0 equivalent to $9 > \frac{\chi_{eff}}{D_{He}} > 3$, $\chi_{eff} = (\chi_e + \chi_i)/2$. After 200 seconds of burn we find that significant helium accumulation does not occur in this range of variation of the ratio of the particle diffusivities.

3.2. *Effect on helium exhaust of the ratio D^{He}/χ_i*

Synakowski [9,10] has shown that on TFTR the radially resolved ratio $D^{He}/\chi_i = 1$, within a factor of 2. Transport simulations were carried out to see the effect of varying this ratio from 0.5 to 2. Here as in the baseline simulations, D was identical for all species. In Fig. 2 are shown the results. Helium accumulation rises and total alpha power decreases at the smaller values of the ratio D^{He}/χ_i . Ignition in ITER is sustained for all values of D^{He}/χ_i considered.

3.3. *Effect on helium exhaust of inward particle pinch*

Neoclassical particle transport theory, applied to tokamaks with “standard” profiles of current, density, and pressure, generally gives a small inward velocity on hydrogen (the Ware pinch) and a larger Z -dependent inward ve-

locity on trace impurities. A strong outward velocity on helium may develop if higher Z-impurities are abundant in the plasma core [17]. In L-mode experiments at TFTR [9], TEXTOR [11] and JT-60 [13] and enhanced confinement supershot experiments at TFTR [10], significant inward helium pinches were observed in plasmas without appreciable core contamination by high-Z impurities. Data is not yet available for helium transport coefficients in H-mode.

In neoclassical theory, trace impurity convective transport is driven mostly by $\nabla n_{proton} \simeq \nabla n_e$. The coefficient describing convection is then given by

$$C_v^{\nabla n} = \frac{V}{D} \frac{n_e}{\nabla n_e},$$

with this definition Synakowski [10] has found $C_v^{\nabla n} \simeq 2-3$ for $r/a < 0.4$ in supershot plasmas and $C_v^{\nabla n} \simeq 1$ in L-mode plasmas, although the role of convection in the center ($r/a < .25$) of the L-mode is not clear owing to the presence of sawteeth. The TEXTOR data led to $C_v^{\nabla n}$ always less than 2.5, with lower values at higher plasma density.

Another common method used to define convection is to relate the pinch velocity directly to the diffusion coefficient. The expression generally used is

$$C_v = \frac{V_a a^2}{2Dr},$$

where V_a is the pinch velocity at the separatrix. This satisfies the requirement that the pinch velocity be zero at $r = 0$. In the absence of sources and sinks and in steady state, $\Gamma = 0$, and $C_v = 1$ implies a Gaussian steady state radial profile (regardless of whether D is constant or not) [18].

Sugie [13] found $C_v = 1.0$ – 1.5 at JT-60. Synakowski has measured $C_v = C_v^{ss}(r) = \Sigma A_n(r/a)^n$, $A_n = 53.69, -407.4, 1113.4, -1285.1, 531.05$ where $v^{He} = 2DC_v(r)/a^2$ for helium in TFTR enhanced confinement supershot experiments [10] (Fig. 3).

On TFTR radial measurements of D/V , (i.e. C_v), were made. No parameterization of the data through use of a constant C_v value was necessary. TEXTOR and JT-60 measurements were limited to a few radial points. This necessarily led to radially constant C_v from these experiments. Distinctions in various values of C_v across the plasma can be made only with profile information. Figure 3 shows that characterization of the data by a simple constant C_v would be wrong for the TFTR supershot.

Knowledge of C_v at the edge in the TFTR supershot is dependent on error bars which are still being evaluated. But it is clear that V is inward there and larger than in the rest of the plasma.

Designating $C_v^{He} = C_v$ for helium, Figure 4 shows the effect of varying C_v^{He} from -2.0 to +2.0 . $C_v = 0$ for hydrogen species as for the baseline simulations. Table 1 shows results from a series of simulations to study the effect of R_{He} , sawteeth and C_v^{He} on fusion burn. For $C_v^{He} = 2$, the ignition is quenched by the buildup of helium ash (case ITR229, Table 1). B2 code calculations of helium in the ITER scrapeoff and divertor plasma by Braams [8] indicate that $R_{He} \leq 0.5$ may be achievable at the last closed flux surface. BALDUR simulations with this value of the helium recycling coefficient do not lead to quenched ignition even for $C_v^{He} = 2$. We found helium accumulated to $12. \times 10^{21}$ particles and that 155 MW of alpha power was achieved (case ITR251 in Table 1).

Cases ITR251 and ITR255, with $C_v^{He} = 2$, differ only in the presence of sawteeth. We see that sawteeth result in less helium ash and greater fusion power. Case ITR259 with reduced helium pinch, $C_v^{He} = 0.$, led to lower helium accumulation (6.6×10^{21}) and larger fusion power (196 MW) after 200 seconds

For $C_v^{He} = C_v^{SS}(r)$ as in the TFTR supershot, ITER case ITR261 results in increased helium accumulation (9.2×10^{21}) and lower alpha power (175

MW). The accumulation of helium ash is strongly sensitive to the magnitude of the helium pinch particularly at the plasma edge. Simulations with the helium pinch/diffusivity ratio as in the TFTR enhanced confinement case were found consistent with sustained ignition because C_v was not large at the plasma edge.

4. Effect on helium exhaust of reduced sawtooth period for several particle diffusivity profiles

Extrapolation of observed sawtooth periods to the reactor regime cannot be done with any certainty as yet. The sawtooth model of Park and Monticello [19] indicates ITER would achieve $10 < \tau_{ST} < 30$ seconds.

Sawteeth flatten the density and temperature profiles periodically and thereby are effective in moving helium ash (as well as energy) partway toward the plasma edge [7]. The present simulation profiles before and after a sawtooth event are shown in Fig. 5. The $q=1$ surface is shown, marking approximately the extent of flattening of the temperature and density profiles for ITER.

In this section we investigate the effect of sawteeth on helium ash re-

removal for different profiles of the particle transport diffusivity. The three diffusivities (Fig. 6) are

$$D_1 = D_o(1 + 5/3x),$$

$$D_2 = D_o(1 + 50x^2/3),$$

$$D_3 = D_o.$$

The profile of D_1 has been scaled from JET H-mode data. D_2 has a variation similar to the L-mode cases for which helium transport was studied at TFTR and TEXTOR. D_3 is a constant diffusivity.

In Figs. 7-9 are shown the effect on helium accumulation and alpha heating power of the variation of sawteeth period for the three diffusivity models. It is seen that for models D_1 and D_2 , with increased transport toward the plasma edge, the sawtooth period has no effect on developed alpha power until τ_{ST} drops to between 1 sec and 3 seconds. At this point τ_E drops to 2.3 seconds from 2.6 seconds because of flatter time-averaged profiles. However, for constant diffusivity, if the sawtooth period drops to between 3 and 10 seconds, ignition is quenched as the buildup of helium in the plasma core becomes too great. The constant diffusivity model provides too little transport near the plasma edge for adequate helium exhaust.

Another important factor for particle transport simulations in next generation reactors is the role of ELMS in H-mode transport. There is a need for a database on ELMS to study their effect on particle and thermal transport under a variety of experimental conditions and for the formulation of models and scalings to the reactor regime.

5. Summary and Conclusion

Transport simulations of ITER have been carried out with helium transport data from recent L-mode experiments at TEXTOR and JT-60, and from L-mode and supershot experiments at TFTR. Recent measurements of $D/\chi_i = 1.0$ on TFTR and $D^{He}/D^D = (0.33-1.0)$, $R_{He} = 0.92$ on TEXTOR are consistent with simulations of sustained ignition in ITER. Helium exhaust and sustained ignition are found sensitive to the magnitude of helium pinch and to a reduced sawtooth period. However, if R_{He} is reduced to 0.5, sustained ignition in ITER is found for C_v^{He} as measured on the three tokamaks. Helium exhaust and sustained ignition are found less sensitive to the ratios D^{He}/D^D and D^{He}/χ_i . Simulations with helium pinch measured for the TFTR enhanced confinement supershot were also consistent with sustained

ignition in ITER.

While the observed relation between D and χ_i , for example, can be related to microinstability theories, the origin of the anomalous inward pinch remains a mystery. On TFTR the large range in behaviors of V (small outside of $r/a = 0.4$ in the supershot, large inside and perhaps large at the edge; small everywhere for the balanced L-mode, but large, inward and anomalous everywhere in the rotating L-mode) underscores our lack of understanding of a potentially critical issue for fusion. To improve predictive simulations for ITER and other next generation reactors, further measurements, and theoretical studies are needed for particle transport coefficients ($v^{He}(r)$, $D^{He}(r)$, R_{He}) and sawtooth period scalings in H-mode experiments.

References

- [1] M.H. Redi, S.A. Cohen, "Effects of Particle Transport on Helium Ash Accumulation and Sustained Ignition in ITER", Fusion Tech., in press.
- [2] M.H. Redi, S.A. Cohen, "Influence of MHD Effects and Edge Conditions on ITER Helium Ash Accumulation and Sustained Ignition", PPPL-2703, J. Nucl. Mat, in press.
- [3] D. Reiter, G. H. Wolf, H. Kever "Burn Condition, helium particle confinement and exhaust efficiency" Nucl. Fusion 30, p. 2141 (1990).
- [4] R. J. Taylor, B. D. Fried and G. J. Morales, "Burn Threshold for Fusion Plasmas with Helium Accumulation" submitted to Comments on Plasma Phys. Controlled Fusion; PPG-1290 (March 1990).
- [5] R. Behrisch, V. Prozesky "Power and Particle Exhaust for a Fusion Plasma" Nucl. Fusion, 30, p. 2166 (1990).
- [6] S. Cohen, B. J. Braams, J. Brooks, J. Cummings, F. Englemann et al, "Power and Particle Control for ITER", Thirteenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Washington, D.C. (1990), paper IAEA-CN-53/F-3-3.

- [7] G. H. Miley, S. C. Hu and V. Varadarajan, "Epithermal and Thermal Alpha-particle Transport and Control", Fusion Tech. , in press.
- [8] B. Braams, Workshop on Edge Plasma Physics for BPX and ITER. 15-17 Jan. 1991, PPPL
- [9] E. J. Synakowski, B. C. Stratton, P. C. Efthimion, R. J. Fonck, R. A. Hulse et al, "Measurements of Radial Profiles of He^{2+} Transport Coefficients on TFTR", Phys. Rev. Lett. 65, 18, p 2255 (1990).
- [10] E. J. Synakowski, Workshop on Edge Plasma Physics for BPX and ITER, 15-17 Jan. 1991, PPPL.
- [11] D. L. Hillis, K. H. Finken, J. T. Hogan, K. H. Dippel, R. A. Moyer, et al. "Helium Exhaust and Transport Studies with the ALT-II Pump Limiter in the TEXTOR Tokamak", Phys. Rev. Lett. 65, p. 2382 (1990).
- [12] D. L. Hillis, Workshop on Edge Plasma Physics for BPX and ITER. 15-17 Jan. 1991, PPPL.
- [13] T. Sugie, K. Itami, H. Nakamura, H. Kubo, K. Tobita, et al "Impurity Control and Helium Exhaust Experiment in JT-60", Thirteenth International Conference on Plasma Physics and Controlled Nuclear Fusion

- Research, Washington, D.C. (1990), paper IAEA-CN-53/A-V-4.
- [14] C. E. Bush, N. L. Bretz, E. D. Fredrickson, K. M. McGuire, R. Nazikian, et al, "Limiter H mode Experiments on TFTR" Thirteenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research. Washington, D.C. (1990), paper IAEA-CN-53/A-IV-4.
- [15] C. E. Singer, D. E. Post, D. R. Mikkelsen, M. H. Redi, A. McKenney, et al, "BALDUR: A One-Dimensional Plasma Transport Code," Computer Phys. Comm. 49, (1988)275-398.
- [16] M. H. Redi, "Standard Test Cases for the BALDUR Transport Code", Computer Phys. Comm. 49, (1988)399-407.
- [17] B. Coppi, G. Rewoldt, and T. Schep, Phys. Fluids 19, 1144 (1976).
- [18] B. C. Stratton, A. T. Ramsey, F. P. Boody, C. E. Bush R. J. Fonck, et al. "Impurity Behavior in TFTR Discharges", Nucl. Fusion 27, p. 1147 (1987).
- [19] Park and Monticello, "Sawtooth Oscillations in Tokamaks", Nucl. Fusion 30, p. 2413 (1990).

Table 1 Results of simulations with varied R_{He} , C_v , sawteeth

case	R_{He}	C_v^{He}	ignited	sawteeth	N_{He}	P_a
ITR229	0.95	2.	no	yes	13.9×10^{21}	49MW
ITR251	0.5	2.	yes	yes	12.0	155
ITR255	0.5	2.	yes	no	14.0	135
ITR259	0.5	0.	yes	no	6.6	196
ITR261	0.5	C_v^{ss}	yes	no	9.2	175

Figures

Fig. 1. The effect of the variation of the ratio D^{He}/D_h on the total alpha power and helium accumulation at 200 seconds.

Fig. 2. The effect of the variation of the ratio D^{He}/χ_i on the total alpha power and helium accumulation.

Fig. 3. Profile of $C_v^{SS}(r)$ for helium transport in TFTR superset.

Fig. 4. The effect of the variation of v^{He}/D on the total alpha power and helium accumulation at 200 seconds.

Fig. 5. Simulated electron temperature profiles before and after a sawtooth event.

Fig. 6. Radial profiles for three particle diffusivities $D_1 = D_o(1 + 5/3 x)$, $D_2 = D_o(1 + 50/3 x^2)$, $D_3 = D_o$.

Fig. 7. The effect of the variation of sawtooth period on total alpha power and helium accumulation of the particle diffusivity $= D_1$.

Fig. 8. The effect of the variation of sawtooth period on total alpha power and helium accumulation of the particle diffusivity $= D_2$.

Fig. 9. The effect of the variation of sawtooth period on total alpha power and helium accumulation of the particle diffusivity = D_3 .

PPPL#91X0109

FIG. 1

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