EFFECTS OF PARTICLE TRANSPORT ON HELIUM ASH ACCUMULATION AND SUSTAINED IGNITION IN THE ITER DESIGN

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Abstract

The buildup of helium ash in the proposed ITER experiment has been studied in a series of simulations with the BALDUR transport code. Using radially dependent thermal diffusivities which were scaled from JET values, we studied the role of particle transport coefficients and edge recycling on helium poisoning of ignition. A sustained ignition was obtained when the exhaust of helium from the edge plasma was allowed to exceed 10% of the helium flux into the edge plasma from the core plasma, and the ratio of particle (He ion) to thermal diffusivities, D/χ , was larger than 1/4. The simulations included the effects of sawtooth oscillations, radiative as well as conductive energy loss channels, and density profile variations.

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1. INTRODUCTION

Computer simulation of the multiple, nonlinear processes occurring during the time evolution of high temperature plasmas is an essential component in the design of fusion reactors. With models for each of these nonlinear interactive processes (such as radiation, sawteeth, and particle and thermal transport) benchmarked to data from current experiments, simulations required for planning future reactors can be obtained. The physics and resulting plasma parameters of different machine designs and operating scenarios can be tested and evaluated through computer modelling studies. In this spirit, a quantitative prediction was sought for the magnitude and time scale of the effects of helium ash accumulation in the International Tokamak Experimental Reactor (ITER) design.

Zero-dimensional modeling of ITER behavior [1] indicated that a transport-determined particle confinement time yielding helium ash concentrations as large as 15% in steady state would be short enough that D/T fuel dilution would not quench ignition in ITER. For a limited range of operating parameters, we examined the correctness of this estimate. We emphasized a study of the importance of both helium particle transport and edge exhaust on sustained ignition for the ITER experiment.

This paper is organized as follows: In Section 2, we discuss the transport simulations, including a brief description of the transport code, the ITER parameters, and the transport coefficients. The simulation results are presented and discussed in Section 3 and Section 4 comprises a summary and conclusion.

2. TRANSPORT SIMULATIONS

2.1. *The Transport Code*

The one-dimensional BALDUR transport code has been used to simulate ITER to study the role of particle transport on helium ash poisoning. The BALDUR code [2,3] solves diffusion equations for electron and ion energy and particle densities for two hydrogenic and up to four non-hydrogenic ion species, and a diffusion equation for the poloidal magnetic field. The

transport equations are:

$$\frac{\partial n_a}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} (r \Gamma_a) + S_a \quad a = D, T, O, He \quad (1)$$

$$\frac{\partial E_j}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} (r q_j) + Q_j \quad j = i, e \quad (2)$$

$$\frac{\partial B_\theta}{\partial t} = \frac{c^2}{4\pi} \frac{\partial}{\partial r} \left[\frac{\eta}{r} \frac{\partial (r B_\theta)}{\partial r} \right], \quad (3)$$

where n_a is the number density of species a , E_j is the energy density of thermal ions or of electrons, and B_θ is the poloidal magnetic field. q_j and Γ_a are the energy and particle fluxes

$$q_j = -n_j \chi_j \frac{\partial}{\partial r} T_j, \text{ and} \quad (4)$$

$$\Gamma_a = -D_a \frac{\partial}{\partial r} n_a + A_a n_a V_a, \quad (5)$$

and S_a and Q_j are the particle and energy source rates (such as the electron-ion equilibrium energy transfer rate and the radiated power), χ_j is the thermal diffusivity for $j = e$ (electrons) or i (ions), D_a is the particle diffusivity, V_a is the particle convective velocity, A_a is a "convection" multiplier. In this study we have assumed a convection multiplier $A_a = 3/2$. Particle sources, such as continuous gas puffing and ionization to maintain electron density profiles, and energy sources, such as alpha particle and ohmic heating, are computed in detail during each time step of a simulation. Particle and energy losses are computed also in detail for convection, conduction, radiation, *etc.* The models, equations, and differencing are described in Refs. [2, 3].

A Kadomtsev-like sawtooth model was used in some of the simulations. The sawtooth mixing model simulates internal disruptions by flattening the temperatures and densities of all species including fast alphas, helium ash, and oxygen. The sawtooth period was obtained by substituting into the scaling law obtained by Monticello and Park [4] from their recent calculations of solutions of the full nonlinear resistive three-dimensional MHD equations.

Effects of radiation were included by calculating hydrogenic bremsstrahlung and by setting the total impurity radiation to be a specific fraction of the overall plasma heating. The set fraction of radiated power, 30%, is less than the newest ITER specifications (40%) [5], hence these simulations give

a somewhat optimistic result for the required χ_e value for ignition. Impurity radiation was assumed to have a radial profile peaked toward the outside, consistent with extensive MIST code simulations [6].

With the present ITER TF ripple specification [1], the alpha particles are well confined at 20 MA. Moreover, the slowing down time is ≤ 2 sec. So the simplest alpha slowing-down model with very fast local plasma heating is adequate. The fusion alphas slow down on the flux surface of birth, and individual alpha trajectories are not computed.

A limiter boundary condition was used for all simulations with the edge temperatures and densities set to the values: $T_e(a) = 0.5 \text{ keV}$, $n_e(a) = 1.0\text{--}50 \times 10^{18}/\text{m}^3$. These values are to be compared with 2-d fluid code simulations [7], which typically give separatrix values of $T_e(s) \sim 100\text{--}500 \text{ eV}$, and $n_e(s) \sim 2\text{--}4 \times 10^{19}\text{m}^{-3}$. In these simulations, the main effect of a low $n_e(a)$ is to increase the effective helium particle confinement time due to the deeper penetration of recycling neutrals. In the BALDUR simulations, recycling is handled by returning to the plasma as neutral gas at energy of 40 eV, the fraction R_a of each ionized plasma species a which has left the plasma by convection and diffusion. All refuelling is by edge recycling. No pellet or beam fuelling is assumed.

In order to study the stability of ignition, initial conditions of volume-averaged electron and ion temperatures at 25 keV and electron density at $1. \times 10^{20}/\text{m}^3$ at the plasma center were assumed. In Ref. [8] can be found POPCON plots which illustrate the ignition point chosen here. This starting point is clearly in the ignited region for the χ values assumed and offset-linear ITER scaling. (No auxiliary heating is supplied.) The plasma was allowed to evolve under the assumed particle and energy loss transport coefficients, and thermal stability or instability was observed.

2.2. ITER Parameters

Parameters similar to the 1988-89 ITER Conceptual Design [1] physics phase were used for this simulation study. As a one-dimensional transport code was used for this elongated cross-section machine, we set the effective minor radius $r_m = \sqrt{ab} = 3.1 \text{ m}$. Also, $R = 5.8 \text{ m}$, $I_P = 20 \text{ MA}$, $B_Z = 5.1 \text{ T}$, $q_a = 2.1$, $\bar{n}_e = 8.3 \times 10^{19}\text{m}^{-3}$. The ratio of deuterium to tritium was maintained at 1.0 by gas puffing. The only impurities in the simulations are

O and He ash. The initial Z_{eff} , before the generation of He ash, was set to 1.4 consistent with Ref. [5].

2.3. Transport Coefficients

Particle and energy transport coefficients continue to be a much researched topic [9-14]. Basic questions remain, such as whether transport is diffusive [15], i.e., proportional to ∇T and ∇n but not $(\nabla T)^2$, $(\nabla n)^2$ or $(\nabla T)(\nabla n)$, and whether there is fixed ratio between particle and energy transport [16] coefficients (an Einstein relation) or losses. Because these issues have not been resolved, we have based our simulations on the standard form for anomalous diffusive transport embodied in Eqs. (1)–(5).

As described below, experiments on large tokamaks have given broadly different values for transport coefficients. Though we are apparently obliged in our simulations to scan a broad range, $\chi_e + \chi_i$ is nearly fixed for ITER because of the ignition requirement and beta and density limits. Thus, the transport parameters varied most in our scans is D . JET has extracted χ_e and χ_i coefficients for a variety of discharge types, *e.g.*, H-mode, L-mode, high ion temperature mode, sawtooth-free mode, He⁺⁺ plasmas, *etc.*, and by a variety of experimental techniques, *e.g.*, profile analysis and heat pulse propagation [17,18,19]. In most, but not all, JET discharges, χ_e and χ_i rise with increasing minor radius by a factor of 10. For the hot ion mode, JET finds $\chi_e/\chi_i \sim 1/5$; for earlier H-mode discharges [17,18], a quite different ratio was reported, $3 > \chi_e/\chi_i > 1$. We have chosen the latter ratio because the ITER design is based on H-mode operation. Recent JET analyses [20] (constrained to physically meaningful scaling laws) generally indicate a small heat pinch term in the transport equation.

Measurements of χ_e and χ_i on TFTR [21] show a stronger increase with minor radius up to a factor of 50 for supershots. For these plasmas, convection is more important than diffusion in the core region, *i.e.*, $n_i \chi_i \nabla T_i / T_i \Gamma_i < 1$. In contrast to the JET high- T_i discharge analyses, TFTR finds for $r/a > 0.2$, $\chi_e(r)/\chi_i(r) \sim 1$ and $\chi_e(r)/\chi_i(r) \sim 4$ for $r/a < 0.2$. The absolute value, at $r = a/2$ for χ_e is $\sim 0.4 \text{ m}^2/\text{s}$ for TFTR supershots, $2.5 \text{ m}^2/\text{s}$ for JET H-mode and $\sim 0.4 \text{ m}^2/\text{s}$ for JET high- T_i discharges. Note that χ_i (hot-ion mode) is $\sim 2 \text{ m}^2/\text{s}$ at $r/a = 0.5$.

Based on the above data, we have selected the following assumptions for

$\chi_e(r)$ and $\chi_i(r)$.

$$\frac{\chi_e(r)}{\chi_i(r)} = 2 \quad (6)$$

$$\chi_e(r) = \chi_{eo} \left(3 + 5 \frac{r}{a} \right). \quad (7)$$

The absolute value of χ_{eo} was set by comparison with energy confinement scaling laws which roughly yield $\chi_e \propto P^{1/2}/I_p R$. This gives, for the baseline 1990 ITER design of $I_p = 22$ MA, $R = 6$ m, and $P_\alpha = 200$ MW, $\chi_{eo}^{\text{ITER}}/\chi_{eo}^{\text{JET}} \approx 0.3 \rightarrow 0.5$, and an energy confinement time $\tau_E = 2\text{--}4$ sec.

First comparisons at JET of D and χ in OH and H-mode plasmas were made in 1986–1988 [17,18]. In the region $0.5 < r/a < 0.7$, the ratio is $\chi_e/D = 7 \pm 3$. More recently [22], values as high as 12 have been reported. Informally, there are suspicions that such high χ_e/D values are due to the fact that most of these experiments were performed by heat and density pulse propagation methods rather than steady-state profile analysis.

For TFTR supershots the first analysis of both particle and heat transport have shown $Q_i/\Gamma_i T_i \sim 3/2 \rightarrow 5/2$ for $r/a < 0.3$. Here we use $Q_i \equiv q_i - 3/2 \Gamma_i T_i$. Recently [23], analyses of D has been made using the Degas code. For supershots, where beam fueling is the dominant source of particles for $r/a < 0.5$, balanced NBI was seen to cause $\times 2$ decreases in D with increasing particle density, $\bar{n}_e$ increasing from 2 to $4 \times 10^{18} \text{ m}^{-3}$. The ratio of $\chi_e(a/2)/D(a/2)$ for these experiments showed a wide scatter, 0.5 to 5.0 even at the same heating power. This ratio slightly increases at higher $\bar{n}_e$.

These experiments indicate that χ/D is not fixed. Therefore, we have chosen a widely varying χ/D ratio, ranging from 0.44 to 7.0 , to parametrize our scans of transport coefficients. We cannot decrease χ much (25%) below the value selected, without a beta limit problem. Similarly, $\chi_e - \chi_i$ cannot increase more than 25% without jeopardizing ignition. In essence, we are examining the effects of core helium transport and edge helium recycling under the assumption that thermal transport is adequate for ITER ignition.

Note that a fixed value of χ/D does not mean an equal (or even radially constant) ratio of $Q/\Gamma T$. As shown schematically in Fig. 1, the differing ∇n and ∇T profiles for H-mode and supershots can give quite different $Q/\Gamma T$ profiles. In Fig. 1, D and χ were chosen to vary radially across the plasma, as described in Eq. (7). The different $n(r)$ profiles (H-mode vs. supershot)

are qualitatively consistent with the differing refuelling locations (core for supershots, edge for H-mode). For the ratio $\chi/D = 3$, Q/IT is ≈ 2.5 times lower for supershots than for H-modes, in qualitative agreement with the differing JET and TFTR results described earlier.

In the BALDUR simulations, $D = A\chi_e/7$ where A was varied from 1 to 16. In addition to specifying a D value, we have included a small particle pinch term in the Γ equation, consistent with many experiments. This anomalous pinch velocity is given by $V = 0.2 D r/a^2$ [24]. Transport of all species, He, D, T, and O, was assumed to be the same.

2.4. Limiter/Divertor Model

The BALDUR code used a limiter boundary condition while the ITER design specifies a divertor. The main difference between these, with respect to the exhaust of helium ash, is in the definition of recycle coefficients. For limiter machines, the recycle coefficient, R_L , is defined by the re-emission from the limiter material of the hydrogenic species. But, in a long-pulse duration machine, the divertor plate will reemit 100% of the impacting ions. The loss of particles in a divertor machine is determined by the exhaust of gas by the divertor pumps.

The recycle coefficient for a divertor machine is then given by

$$R_D = 1 - \Gamma_{pumps}/\Gamma_{out}$$

where Γ_{pumps} = number of particles/sec exhausted by the pumps, Γ_{out} = number of particles/sec transported radially outward across the separatrix. In a 2-d fluid divertor simulation [25], ambiguity arises in determining Γ_{out} because the outflux depends on poloidal angle. Near the plasma midplane the particle flux is out, but near the divertor region the particle flux is back into the plasma. Therefore, Werley, *et al.*, have defined Γ_{out} to include only the radially outward moving particles, not the net of the outward plus inward particles. Depending on pump configuration and plasma parameters, they find R_D to vary between 0.7 and 0.95.

The BALDUR simulations set different values for recycling of the different species. D, T, and O recycling are set to 0.998. He recycling was varied between 0.5 and 1.0 to encompass the 2-d predictions and possible future improvements in helium exhaust techniques.

3. SIMULATION RESULTS

3.1. Simulations with low edge density $n_e(a) = 1 \times 10^{18}/\text{m}^3$

We find that a sustained ignition with 320 MW of alpha heating is obtained with the above transport coefficients, if $A=2$, as long as the helium edge recycling is kept very low, $R_{he} \lesssim 0.5$, (Fig. 2). (This high fusion power results from low radiation losses, as discussed later.) The (volume-averaged) ion temperature and fusion power climb with time for $\sim 20 \rightarrow 30$ seconds, consistent with a build-up of helium ash to a steady-state value of 3.5% of n_e . However, with $A=1$ and even this low helium recycling condition, the ignition is quenched after about 20 sec. This corresponds to a core helium concentration of $\sim 13.5\%$. Note that $A=1$ corresponds to particle transport diffusion being scaled directly from χ_e using the JET derived ratio $\chi_e/D = 7$.

If the helium edge recycling is equal to that assumed for deuterium and tritium, $R_{he} = 0.998$, a sustained ignition cannot be obtained, even if the particle diffusion, for all species, is increased by setting A as high as 16. Figure 3 shows the central ion temperature and the total alpha heating power as a function of time for the case with $A = 2$, corresponding to $\chi_e/D = 3.5$.

Improved energy confinement does not improve the ignition margin when helium ash transport is slow and/or edge recycling high. When the assumed χ_e and χ_i were reduced by a factor 4, while retaining $R_{he} = 0.998$ and $A=1$, a sustained ignition was not obtained (Fig.4). The increased core temperature causes helium ash build up in the plasma center more rapidly, even when only energy confinement is improved, but particle confinement is held constant. At temperatures above 70 keV the fusion cross section begins to fall off, giving less heating increment per temperature rise than at lower temperatures. Continued improvement of χ_e does not lead to a corresponding improved P_α^{tot} .

In order to obtain a sustained ignition in ITER, it was necessary to reduce the edge recycling of helium, which causes an increase in the effective particle confinement time. Improved edge helium exhaust is necessary. The recycling coefficient for helium was reduced to 0.9, 0.8, and 0.5 (for low edge densities $\sim 10^{18}\text{m}^{-3}$). Only for $R_{he} = 0.5$ was a sustained ignited plasma obtained (Fig. 5). For this case $\tau_{He} = N_{He}/(\alpha\text{-creation-rate}) \approx 6.6$ seconds after 40 seconds.

We found that the addition of radiation and sawteeth did not quench the ignition. With 30% radiation and with sawtooth losses included, the simulations exhibited reduced temperatures but still a sustained ignition. The sawtooth period was obtained from the semi-empirical scaling found by Park and Monticello [5] using their 3-d, nonlinear, resistive MHD equilibrium code, $\tau_{ST} = 9R^2(T)^{3/2}/Z_{eff} = 27 \text{ sec}$. Here τ_{ST} is in msec, the major radius R in meters, and the peak electron temperature T in keV.

Figures 6-9 show plasma parameters for this simulation ($A=2$, $R_{\text{helium}}=0.5$, $R_{\text{deuterium}} = R_{\text{oxygen}} = R_{\text{tritium}} = 0.998$, 30% radiation and with sawtooth losses). The transport simulation was run to 200 sec to show the effect of sawteeth on long-pulse operation. Clearly, though sawteeth redistribute the internal energy, the approximate n^2T^2 dependence of the fusion rate makes this of little importance as long as the sawteeth inversion surface is inside $r/a \sim 0.5$.

Figure 6 shows the evolution of the alpha particle heating profile and the volume-integrated alpha heating. When sawteeth and radiation losses are included $P_{\alpha}^{\text{tot}} = 274 \text{ MW}$ at 200 sec. This should be compared to the 320 MW obtained without these losses (Fig. 3). Figure 7 shows the evolution of the central densities and temperatures for both electrons and ions for the case with realistic radiation and sawtooth losses. The sharp increase in T_{eo} at 27 sec arises from the abrupt transfer of magnetic energy to electron thermal energy following the first sawtooth event. This heating may well be useful in the initial ignition processes. The evolution of central ion temperature can be compared to Fig. 2a for the same case without radiation and sawteeth. The peak ion temperature is reduced from 75 keV to 59 keV. The mean ion temperature is 19 keV, the mean electron temperature is 16 keV, the total $\beta_p = 0.90$ and $\beta_T = 6\%$, $\tau_E = 2.7 \text{ sec}$, $n\tau = 2 \times 10^{20} \text{ sec/m}^3$. Note that β_T does not exceed $\beta_{TROYON} = 3.5 I_P/(aB) = 6.5$, since the half radius $a = 2.1$. Figure 8 shows the accumulation of helium ash at 10 sec and 200 sec and the very flat density profile found from the particle transport model used. At 200 sec the alpha particle slowing-down time is 1.5 sec, the accumulation of helium ash is 4%, and the ratio of fast alpha particles to total ions is 0.006.

3.2. Simulations with increased $n_e(a)$

Simulations have also been carried out with edge density increased to $n_e(a) = 3 \times 10^{19}/\text{m}^3$. We find that with increased edge density, a sustained ignition is obtained with helium recycling = 0.9.

A higher edge electron density causes ionization of recycling helium closer to $r = a$. This causes a build up of helium near the edge and a greater outflux ($\Gamma = -D\nabla n$) due to both a high $n_{He}(a)$ and a shorter scale length in the ∇n term. The addition of sawteeth does not quench this ignition. Figure 10 shows $T_{io}(t)$ and $P_{\alpha}^{tot}(t)$ for this case. In Fig. 11 is shown the accumulation of helium at 200 seconds for this case and for the case with lower edge density. Accumulation of helium ash is 7% at 200 sec. In this simulation β_T does exceed the β_{TROYON} , $\beta_T = 7.2$. In future work, χ will be increased to enforce the beta limit. (Had we used $I_p = 22\text{MA}$ and the full B_o capacity, the β limit would not have been exceeded.) The requirement of reduced helium recycling is substantially relaxed when the plasma edge density is raised. If the helium recycling is raised to 0.998, the ignition is quenched after 25 seconds.

3.3. Discussion

Perkins and Haney [8] have carried out a complementary study with POP-CON plots of ITER ignition probabilities. They have shown that helium ash accumulation of 10% prohibits a stable ignition with 100 MW of fusion power unless additional auxiliary power is provided. Other recent simulations of ITER by Kaiser [26] and Besseludennov [27] exhibit plasma temperatures in the range seen in the present simulations. Neither Kaiser nor Besseludennov include the effects of helium dilution on ignition.

The general trends are clear from the limited results presented. Increased edge density is beneficial, as are increased D and decreased R_{helium} . Future work will concentrate on establishing a more detailed boundary for ignited and high- Q operation as functions of edge conditions (particularly, $n_e(a)$ and recycling coefficient). The basic conclusion, that sustained ignition may be obtained with χ/D values near the low end of the experimentally observed range and R_{He} in the theoretically predicted range, emphasizes the need for better understanding of the processes responsible for controlling D and R_{He} in experimental devices. The additional benefits of reduced helium content,

such as lower requirements for energy confinement, β , and loop voltage, make this research particularly rewarding.

4. SUMMARY

Thermal and particle transport coefficients scaled from JET data do not result in sustained ignition unless helium edge recycling is sufficiently low, $\lesssim 0.5 \rightarrow 0.9$, depending on edge density. Simulations show that helium particle transport is a critical issue for sustained ignition and that reduced helium recycling is an important objective. A possible method for reduced recycling of the helium ash has been suggested by Wilson and Hosea [28] through selective rf heating of helium near the plasma edge or in the divertor region.

Materials such as vanadium which selectively pump helium are being studied by Argonne National Laboratory [29].

ACKNOWLEDGMENTS

We are glad to acknowledge valuable conversations with D. R. Mikkelsen, B. Stratton, G. Bateman, and C. E. Singer.

This work was supported by U. S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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FIGURE CAPTIONS

- Fig. 1. (a) Schematic normalized plasma profiles for H-mode and supershots,
(b) Schematic radial variation of transport coefficients χ/D , and transport ratios Q/IT .
- Fig. 2. (a) Evolution of central ion temperature for $A=2$, $R_{he} = 0.5$.
(b) Integrated alpha heating for $A=2$, $R_{he} = 0.5$.
- Fig. 3. (a) Evolution of central ion temperature for $A=2$, $R_{he} = 0.998$,
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- Fig. 4. Integrated alpha heating for $A=1$, $R_{he} = 0.998$, and χ_e and χ_i reduced by a factor of 4.
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- Fig. 9. (a) Electron temperature profiles at 10 sec and 200 sec,
(b) Ion temperature profiles at 10 sec and 200 sec.
- Fig. 10. (a) Electron and ion central temperatures for $A = 2$, $R_{he} = 0.9$, $n_e(a) = 3 \times 10^{19}/m^3$,
(b) Total alpha heating power for $A = 2$, $R_{he} = 0.9$, $n_e(a) = 3 \times 10^{19}/m^3$.
- Fig. 11. Helium ash profiles at 200 sec for $A = 2$, $R_{he} = 0.9$, $n_e(a) = 3 \times 10^{19}/m^3$ and for $A = 2$, $R_{helium} = 0.5$, $n_e(a) = 1 \times 10^{18}/m^3$.

NORMALIZED TEMPERATURES AND DENSITIES

FIG. 1a

HEAT FLUX/ T * Gamma

FIG. 1b

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10a

FIG. 10b

FIG. 11