Influence of MHD Effects and Edge Conditions on ITER Helium Ash Accumulation and Sustained Ignition

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Abstract

Dilution of reacting species by build-up of helium ash and its effect on ignition in the ITER tokamak have been studied in a series of simulations with the one-dimensional BALDUR transport code. Thermal diffusivities, obtained from ITER scaling laws and with radial variations observed in JET, gave $\tau_E \approx 2-4$ sec. Refuelling of deuterium and tritium maintained constant electron density, while carbon recycling was 100% and the helium ash recycling was varied from 1.0 to 0.5.

Including MHD effects, specifically sawteeth and beta limits, we find that ignition can be sustained for 200 seconds with $R_{helium} = 0.95$. These simulations, the only non-zero-dimensional, time-dependent simulations thus far made for ITER plasmas, emphasize that edge plasma conditions, MHD behavior, and helium particle transport are critical synergistic issues for sustained ignition.

1. Introduction

It has been known for over twenty years that the ratio of alpha particle confinement time to the total energy confinement time must be less than 10 for a sustained ignited fusion reactor. The well-known[1] 0-d result can be obtained from the following two equations. The rate of change in the alpha density is given by $\dot{N}_\alpha = N_D N_T < \sigma v >_f - N_\alpha/\tau_{p,He}$. and the rate of change in the plasma energy is $\dot{W} = N_D N_T < \sigma v >_f E_\alpha - 3((N_D + N_T + N_e)T_e)/2\tau_E$. Thus, in steady-state $\tau_{p,He}/\tau_E = (N_\alpha/N_e)(E_\alpha/3kT_e) \lesssim 10$. We assume $T_e \sim T_i$ and $N_e \sim N_D + N_T$. The "usual" assumptions are that $N_\alpha/N_e < 0.1$ because of beta limits and fuel dilution and that $T_e \sim 10 \rightarrow 20$keV for similar reasons as well as the Lawson minimum.

Recently this has been the subject of several 0-d modelling studies. Taylor, Fried and Morales[2], Reiter, Wolf and Kever[3] and Behrisch and Prozesky[4] have examined large regions of $N\tau T$ space, mostly well beyond allowed β limits. For useful operational planning, more detailed simulations are required to evaluate the effects of plasma profiles, recycling, and divertors on ignition. Haney and Perkins[5] have calculated POPCON plots for ITER ignition probabilities and have shown that helium ash accumulation of greater than 10% prohibits a stable ignition unless additional auxiliary power is provided. Uckan *et al.* [6] have studied fast alpha diffusion and helium accumulation for TIBER and ETR in 1-1/2-d. The dilution effect of impurities and helium ash were studied in 1-d simulations of ignited plasmas for INTOR by Singer[7] and in 1-1/2-d simulations for CIT by Stotler and Bateman[8]. In earlier 1-d studies, we[9,10] showed that ignition in ITER at low density ($n_e = 8.3 \times 10^{19}/m^3$, Zeff =1.4, $P_{rad}/P_{heat} = 0.1$) cannot be achieved if the helium recycling is 0.998. We also showed that reducing χ/D or reducing both χ_e and χ_i does not prevent helium poisoning if the recycling of helium is high. Lower helium content allows a reduced plasma current required for ignition in ITER: at 10% helium, 22 MA is required; at 5% helium only 17 MA is required.

In this paper, we emphasize the importance of helium particle transport, edge exhaust, and MHD effects on sustained ignition for the physics phase of the ITER experiment. Sawteeth and β-limits, although causing enhanced energy losses, also transport particles, including helium. This effect can be important in ignited operation. We choose thermal and particle transport models, guided by recent JET experimental data and ITER energy confinement scaling laws, and models of MHD transport effects, motivated by recent theoretical research, to establish a baseline scenario with which we can study the role of the helium recycling coefficent.

2. Transport Simulations

2.1. The Transport Code

The one-dimensional BALDUR transport code [11,12] is used here to study the role of transport in helium ash poisoning. The fraction of radiated power is set by the newest ITER specifications (40%) (Cohen[13]). Impurity radiation was assumed to have a radial profile peaked toward the outside, consistent with extensive MIST code simulations (Cummings[14]). With the present ITER TF ripple specification, the alpha particles are well confined.

A limiter boundary condition was used for all simulations with the edge temperatures and densities set to the values: $T_e(a) = 0.2\,keV, T_i(a) = 0.25\,keV, n_e(a) = 0.34 \times 10^{20}/\mathrm{m}^3$. These values are to be compared with 2-d fluid code simulations (Werley[15]), which typically give separatrix values of $T_e(s) \sim 0.1$–0.5 keV, and $n_e(s) \sim 0.2$–$0.4 \times 10^{20}m^{-3}$. In the BALDUR simulations, recycling is handled by returning to the plasma as neutral gas at a specified energy the fraction R_a of each ionized plasma species a which has left the plasma by convection and diffusion.

Initial conditions of volume–averaged electron and ion temperatures at (10 keV) and line averaged electron density ($1.2 \times 10^{20}/m^3$) were chosen corresponding to Physics Phase specifications. This starting point is clearly in the ignited region for the χ values assumed, *i.e.* defined by ITER offset-linear or power scaling relations.

2.2. ITER Parameters

Parameters similar to the 1988–89 ITER Conceptual Design [16] high density 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 $r_m = \sqrt{ab} = 3.1\, m$. Also, $R = 5.8\, m$, $I_P = 20\, MA$, $B_Z = 5.1\, T$, $q_a^{cyl} = 2.1$, $\overline{n_e} = 1.2 \times 10^{20} m^{-3}$. The ratio of deuterium to tritium was maintained at 1.0 by gas puffing. The only impurities in the simulations are carbon and He ash. The initial Z_{eff}, before the generation of He ash, was set to 1.3 [13].

2.3. Transport Coefficients

Particle and energy transport coefficients continue to be a much researched topic. Basic questions remain, such as whether transport is diffusive (Rewoldt[17]), and whether there is fixed ratio between particle and energy transport coefficients (Mynick[18]) or between particle and energy transport losses. Because these issues have not been resolved, we have based our simulations on the standard form for anomalous diffusive transport.

As described below, experiments on large tokamaks have given broadly different values for transport coefficients. Based on JET data, we have selected the following radial dependence for $\chi_e(r)$ and $\chi_i(r)$: $\chi_e(r)/\chi_i(r) = 2$, $\chi_e(r) = \chi_{eo}(3 + 5\ r/a)$. The absolute value of χ_{eo} was set by comparison with ITER energy confinement scaling laws. This gives, for the baseline 1990 ITER design of $I_p = 22$ MA, R = 6m, and $P_\alpha = 200$ MW, $\chi_{eo}^{ITER}/\chi_{eo}^{JET} \approx 0.3 \rightarrow 0.5$, and an energy confinement time τ_E = 2–4 sec.

Experiments indicate that χ/D is not fixed. Motivated by JET[19,20] and by TFTR[21] data and by our earlier work[9,10] where this ratio was varied from 0.44 to 7.0, we have chosen $\chi/D = 4$. No particle pinch was assumed. Transport of all species, He, D, T, and C, was assumed to be the same.

In Sec. 3, we will see that with these thermal diffusivities the simulations far exceed the beta limit and we are required to apply a beta limit model. Thus, we cannot decrease χ_e. Similarly, $(\chi_e + \chi_i)$ cannot increase more than 25% without jeopardizing ignition. In essence, we are examining the effect of core helium transport and edge helium recycling under the assumption that thermal transport is adequate for ITER ignition.

2.4. *Simulation of MHD Effects on Transport*

MHD plasma modes are known to transport particles and energy through sawteeth, disruptions, *etc.* We have included certain MHD effects on transport with a Kadomtsev-like sawtooth model and a model for a soft beta limit, *i.e.*, no disruptions. The sawtooth mixing model simulates internal disruptions due to the m=1 internal kink mode, by flattening the temperatures and densities of all species including fast alphas, helium ash, and carbon. For the sawtooth period we used the semi-empirical scaling which Park and Monticello[22] obtained from equilibrium solutions of the fully nonlinear, three-dimensional, toroidal, resistive MHD equations: $\tau_{ST}(\mathrm{sec}) = 0.009\ \mathrm{R(m)}^2\ \mathrm{T(keV)}^{3/2}/\ Z_{eff} \sim 30$ sec. This result depends on the MHD approximation being valid, but does include trapped particle effects in that the resisitivity is neoclassical.

The Troyon beta limit was found from a study of the stability of tokamak plasmas to pressure driven n=1 external kink and high n ballooning modes, for optimized pressure profiles. Three-dimensional MHD stability studies by Manickam[23] have shown that for nonoptimized pressure profiles, the steepness of the pressure profile can reduce the g factor, and the maximum beta ($\beta_{Limit} = gI/aB$), restricting operation to values of g below 3.5. We have devised a beta limit transport model which increases χ_e, χ_i and D_a if $\beta > \beta_{limit}$. In order to prevent oscillatory behavior in T_e, T_i, n_e, *etc.*, transport must be enhanced above the beta limit with a controlled forcing function which rises smoothly and steeply, once β exceeds β_{Troyon}. We replace the transport coefficients of the last section by $\{\chi_e^{MHD}, \chi_i^{MHD}, D^{MHD}\} = \{\chi_e, \chi_i, D\} \cdot h(\beta)$ where $h(\beta) = \{1 + S(1 + \tanh\ [a(\beta - \beta_{limit} - 1/a)])\}$ which ensures that β is held to just below β_{Limit}. S is the strength of the forcing function, taken to be 10.0, and $1/a$ is the width of the function, taken to be 0.1. With this model of the beta limit we maintain $\beta = \beta_{limit}$ at $g = 2.3$, in ignited conditions. This is the maximum value of g found by Manickam for shaped plasmas with low edge q ($q_a \sim 2$), having presssure profiles with peaking factor=3.75 as in these simulations. 0-d models typically use $1.8 < g < 2.5$.

Fast alphas are not caused to diffuse anomalously by this means. Radeztsky has shown that fast beam ions appear to diffuse classically on TFTR[24]. However, recently Zweben has reported new measurements on TFTR of triton loss which indicate that MHD can cause significant fast particle losses in supershot plasmas [25].

2.5. *Limiter/Divertor Model*

The BALDUR code simulations used a limiter boundary condition with no scrapeoff layer, 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 recycling coefficients. For limiter machines, the recycling coefficient, R_L, is defined by the re-emission from the limiter material of each species. As no scrapeoff modelling has yet been included, the recycling coefficient used here describes the return of neutrals to the plasma proportional to the net outward plasma flux across the last closed flux surface.

The recycling coefficient for a divertor machine is 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 Werley[15] has defined Γ_{out} to include only the radially outward moving particles. Depending on pump configuration and plasma parameters, they find R_D to vary between 0.7 and 0.95. In contrast, the ratio of ion flux to the divertor plate versus neutrals pumped is 100-1000. The BALDUR simulations set different values for recycling of the different species. Refuelling of D, T maintained constant electron density, carbon recycling was 100%, and helium recycling was varied between 0.5 and 1.0, to encompass the 2-d predictions and possible future improvements in helium exhaust techniques.

3. Results and Discussion

The distilled results of a large number of 1-d simulations are shown in Table 1. Six cases are presented after a 200 second pulse length. They illustrate the effects of different helium recycling coefficients and whether or not sawteeth and the beta limit transport model are active. The final Z_{eff}, temperatures, *etc.*, all result from the time evolution of the simulations, given the initial conditions and models described in Sec. 2. Cases A–D all include the beta limit model and sawtooth losses. Cases E and F, which do not include modelling of MHD transport, use helium recycling = 0.998 and = 0.95.

For the high density physics phase ITER specifications, we find a sustained ignition is obtained with helium recycling $\lesssim 0.95$ (Table 1). There is no significant improvement in the parameters if the helium recycling is lowered to 0.5, the lower value being difficult to obtain operationally.

For the ITER ignition in case C, at 200 sec the alpha particle slowing–down time is 0.6 sec, the accumulation of helium ash is 2.4%, and the ratio of fast alpha particles to electrons is 0.001. Central helium accumulation rises rapidly with increasing helium recycling. Case A, with quenched ignition, shows helium ash of 15.2% at 200 seconds. Imposing the β limit model in case B (compared to case F) significantly reduces the helium fraction and the alpha power, hence the heat load to the divertor, for the same value of R_{helium}. At 200 seconds case E is no longer ignited but case F is ignited with 13.7% helium.

Figure 1 shows the evolution of the central electron and ion temperatures for case C, a sustained ignition, and for case A, a quenched ignition. The build-up of central helium is also shown in this figure. The sharp increase in T_{eo} at 30 sec (Fig. 1b) arises from the abrupt transfer of poloidal magnetic field energy to electron thermal energy following the first sawtooth event. This heating may well be useful in the initial ignition processes.

Figure 2 shows the evolution of the total alpha heating, the neutron production rate, the central electron and ion densities, and the total toroidal beta for case A. The electron density rises after ignition is quenched as the fast alphas rapidly slow down and helium ash builds up. There is a sharp burst in the alpha heat transferred to the bulk plasma after each sawtooth event, due to the faster slowing down of the alphas when the central electron temperature drops. As the fast alpha population is then depleted, the alpha heating rate drops until the central temperatures and densities have increased. The neutron rate does not show these bursts, but decreases briefly after each sawtooth until temperatures and densities are restored to average values. The central temperature evolution for this ignited plasma looks more like "comb" teeth than "sawteeth". The temperatures rise and round off rapidly after each sawtooth due to the combined effects of strong alpha heating and the imposed beta limit. The presence of sawteeth does not quench the ignition in cases B–D, where recycling is reduced to 0.95, 0.9 and 0.5. Sawteeth redistribute the internal energy, but the strong n^2T^2 dependence of the fusion rate and flat n_e profile make this of little importance if the sawteeth inversion surface is inside r/a $\sim$ 0.5, or if the sawtooth period is much longer than the temperature rise time as here.

0-d models miss the effects of radial variations in transport and gradients of plasma profiles on ignition. We have $\chi/D = 4$ for all cases, but for quenched case A, $\tau_{p,He}/\tau_E = 75$ at $r = a/4$ and $\tau_{p,He}/\tau_E = 0.2$ at $r = a$, while $Q/\Gamma T = 5$. For ignited case C, $\tau_{p,He}/\tau_E = 3$ at $r = a/4$ and $\tau_{p,He}/\tau_E = 0.4$ at $r = a$, while $Q/\Gamma T = 2$. Simply multiplying by $1/(1-R)$ to approximate the effect of edge recycling on particle confinement would lead to $\tau_{p,He}^{caseA}/\tau_{p,He}^{caseC} = 50$, whereas this ratio for the simulations is 77, at a/4 near the plasma center, and is 0.7 at the edge.

A lower edge density has been shown[9,10] to require much lower helium recycling condition. The high 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 general trends are clear: increased edge density is beneficial, as are increased D and decreased R_{helium}. The beta limit model, which increases D for helium but not for fast alphas, also is beneficial to a sustained ignition.

Inclusion of simple models for MHD effects on transport due to sawteeth and the beta limit assist ignited operation by reducing helium accumulation and power loading. A number of important questions however remain. First, what is the effect of a beta limit on transport? Is the model used here experimentally justified? If MHD effects tend to increase energy transport and not particle transport, additional reduction of R_{helium} would be required for sustained ignition. Are fast alpha particles also transported at an increased rate near the beta limit? This could jeopardize ignition. Second, what is the nature of the sawtooth phenomena and how does it affect plasma profiles for an ignited tokamak near the beta limit? Are all species affected equally? Densities as well as temperatures? Are there radial variations not present in the usual Kadomtsev model? What effect would non-Kadomtsev-like sawteeth, [having $q(0)$ always $<< 1$, as suggested by recent experiments], have on ignited ITER simulations? Finally, what are the fundamental thermal and particle transport processes underlying current plasma physics results and how might they be modified in a machine like ITER?

4. Summary

Thermal and particle transport coefficients scaled from JET data do not result in sustained ignition unless helium edge recycling is sufficiently low, $\lesssim 0.95$. The basic conclusion, that sustained ignition may be obtained with χ/D values near the low end of the experimentally observed range in JET, but above the TFTR values, 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. A possible method for reduced recycling of the helium ash has been suggested by Wilson and Hosea[26] 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 at Argonne National Laboratory (Brooks[27]). In addition, we note that a reduced helium content carries lower requirements for energy confinement and loop voltage. The beta limit model used here is seen to affect helium ash buildup as strongly as R_{helium}. Simulations show that helium particle transport is a critical issue for sustained ignition and that reduced helium recycling and improved understanding of the beta limit are important objectives.

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TABLE 1: Simulation Results for High Density ITER Scenario

	τ_E (sec)	R_{he}	Z_{eff}	T_{oe} (keV)	$<T_e>$ (keV)	T_{io} (keV)	$<T_i>$ (keV)	P_α^{tot} (MW)	n_{he}/n_e (%)	β_T (%)	Ignited ?
A[a]	3.0	0.998	1.6	3.6	1.5	3.6	1.5	0.5	15.2	0.5	no
B[a]	2.4	0.95	1.4	27.5	7.9	31.1	8.1	194	3.2	3.2	yes
C[a]	2.4	0.9	1.4	27.5	7.8	31.0	8.1	199.	2.4	3.3	yes
D[a]	2.3	0.5	1.4	27.4	7.8	30.9	8.0	203.	1.7	3.2	yes
E[b]	4.0	0.998	1.6	6.6	1.6	6.3	1.6	1.4	17.2	0.5	no
F[b]	3.5	0.95	1.7	59.6	25.6	85.9	32.5	469.	13.7	12.1	yes

[a] β limit and sawtooth models included; results at 200 sec.

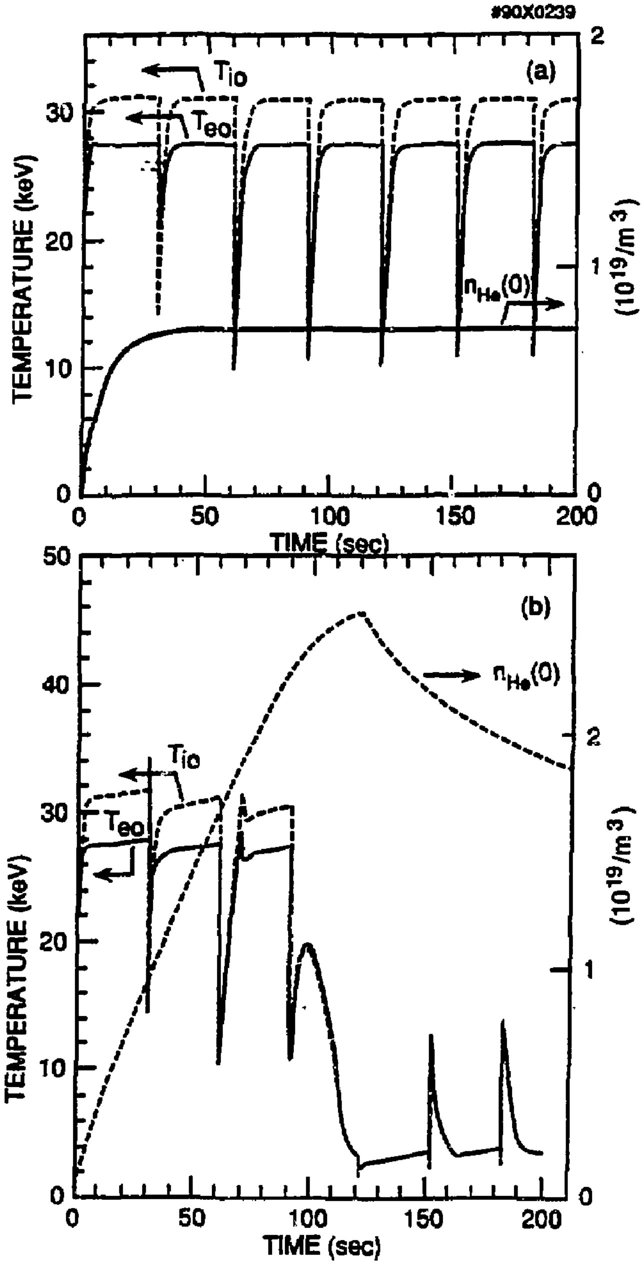
[b] β limit and sawtooth models not included; results at 200 sec.

Figure Captions

Fig. 1. (a) Evolution of central electron and ion temperatures and central helium accumulation for case C with helium recycling equal to 0.9.

(b) Evolution of central electron and ion temperatures and central helium accumulation for case A with helium recycling equal to 0.998.

Fig. 2. Evolution of central electron and ion density, total plasma heating, neutron rate and toroidal beta for case A.



#90X0239
(a)
T_{io}
T_{eo}
$n_{He}(0)$
TEMPERATURE (keV)
($10^{19}/m^3$)
TIME (sec)
(b)
$n_{He}(0)$
T_{io}
T_{eo}
TEMPERATURE (keV)
($10^{19}/m^3$)
TIME (sec)

FIG. 1

#90X0240

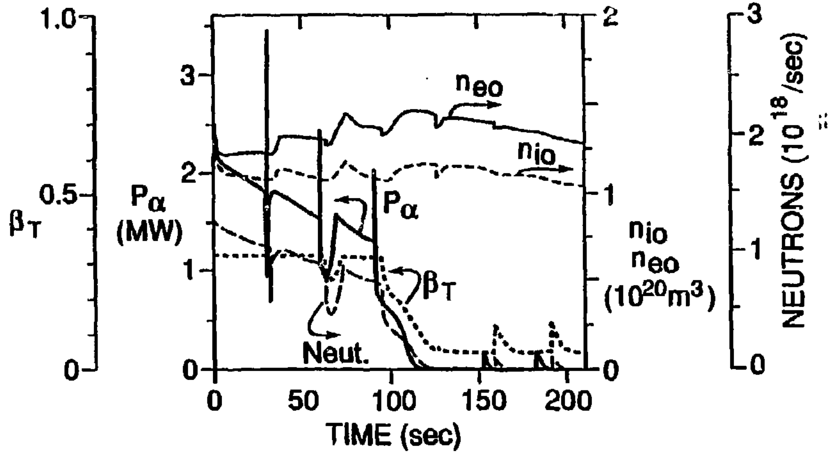


FIG. 2