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HELIUM ACCUMULATION EFFECTS USING BENCH MARKED 0-D MODEL

by

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Introduction

- Helium "ash" accumulation is a key issue relative to our ability to achieve a steady-state ignited tokamak.

- 1-D transport simulations using the BALDUR code have been used to examine the correlation between the global helium particle confinement time and the edge exhaust (or recycling) efficiency.

- This provides a way to benchmark the widely used 0-D model.

- Burn conditions for an ITER-like plasma with various helium edge recycling coefficients are examined.

0-D Model-Effective Helium Confinement Time

- Assumptions:

  All the plasma species have the same temperature.

  A single species impurity, in addition to helium, is included separately.

  Profiles of the densities and temperature have the form $x = x_0 \left(1 - \frac{r^2}{a^2}\right)^{\alpha_x}$ for $x = n, T$.

  Hot α-particles fully thermalize in the plasma before they are lost.

- The following equations are used to find the ash density level and the burn parameter for the plasma:

  - Steady-state power balance equation

    $$P_\alpha + P_{OH} + P_{aux} - P_{con} - P_{rad} = 0$$

    where

    P_{con} = power loss due to transport processes,

    P_{rad} = power loss due to radiation (P_{rad}),

    P_α = alpha heating power,

    P_{OH} = the ohmic heating power (generally, negligible in a reactor-grade plasma),

    P_{aux} = external heating power.

  - equation for quasi-neutrality

    $$n_e = n_{DT} + 2n_\alpha + Zn_z$$

  - Helium particle density balance equation

    $$\frac{n_\alpha}{\tau^*_\alpha} = \frac{n^2_{DT}}{4} \langle\sigma v\rangle$$

- Here the helium particle confinement time τ^*_α represents the <u>effective confinement time</u> discussed next.

Effective Helium Particle Confinement Time[1]

- Distinguish two "kinds" of helium particles by the location of their sources:

  Species 'a' is born in the plasma core by fusion reactions and they eventually leave by crossing the plasma boundary in to the edge plasma region for the first time. Let their total number be N_{α}^{a} and their mean confinement time be τ_{α}^{a}.

  Species 'b' consists of all the helium particles returning to the plasma due to recycling. This provides an effective "source" of helium ions that peak near the plasma edge. Let their total number be N_{α}^{b} and their mean confinement time be τ_{α}^{b}.

- Confinement time τ_{α}^{b} will be different from τ_{α}^{a} because the recycled particles are mainly subject to transport processes characteristic of the outer zone of the plasma.

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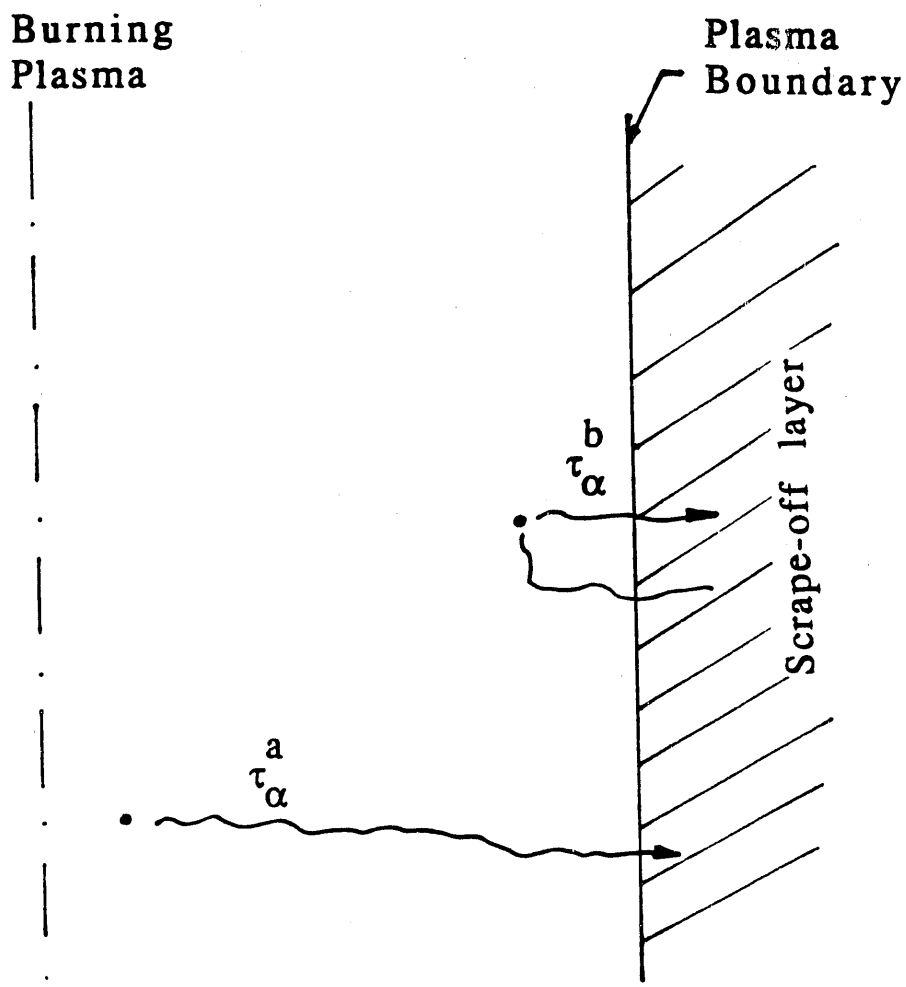
[1] D. Reiter, et al., Jül-2342, Jan. 1990, ISSN 0366-0885.

Illustration of the Characteristics of the Trajectories of Two "kinds" Helium Particles



Species 'a' is born in the plasma core by fusion reactions and they eventually leave by crossing the plasma boundary in to the edge plasma region for the first time.

Species 'b' consists of all the helium particles returning to the plasma due to recycling.

- Assume the recycling coefficient is R_{eff}. Then, in steady-state

$$S_{fus} - \frac{N_\alpha^a}{\tau_\alpha^a} = 0$$

$$R_{eff}\left(\frac{N_\alpha^b}{\tau_\alpha^b} + \frac{N_\alpha^a}{\tau_\alpha^a}\right) - \frac{N_\alpha^b}{\tau_\alpha^b} = 0$$

where S_{fus} is the total number fusion reaction rate.

- Hence, total number of helium $N_\alpha = N_\alpha^a + N_\alpha^b$ becomes

$$N_\alpha = S_{fus}\left[\tau_\alpha^a + \left(\frac{R_{eff}}{1-R_{eff}}\right)\tau_\alpha^b\right]$$

- This gives the effective helium ion confinement time τ_α^* for the 0-D model as

$$\tau_\alpha^* = \tau_\alpha^a + \left(\frac{R_{eff}}{1-R_{eff}}\right)\tau_\alpha^b.$$

1-D BALDUR Simulations

- 1-D BALDUR code solves

$$\frac{\partial n_a}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_a) + S_a \quad , \quad a = \text{ion species}$$

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

$$\frac{\partial B_\theta}{\partial t} = \frac{c^2}{4\pi}\frac{\partial}{\partial r}\left(\frac{\eta}{r}\frac{\partial(rB_\theta)}{\partial r}\right) - c\frac{\partial}{\partial r}(\eta J_{beam})$$

- Recycling of helium as neutrals at wall.
- Refueling of D, T to maintain constant electron density.
- Transport coefficients used: (cf. M. Redi and S. Cohen, PPPL-2703)

  Electron thermal diffusivity:

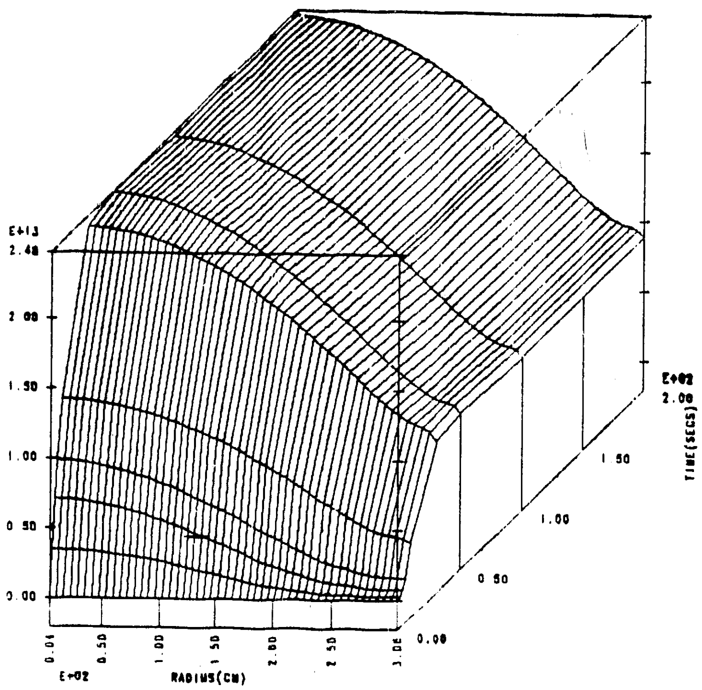
$$\chi_e = 10^3\left(3 + 5\frac{r}{a}\right) \qquad \text{cm}^2/\text{sec}$$

  Assume $\chi_i \sim \frac{1}{2}\chi_e$.

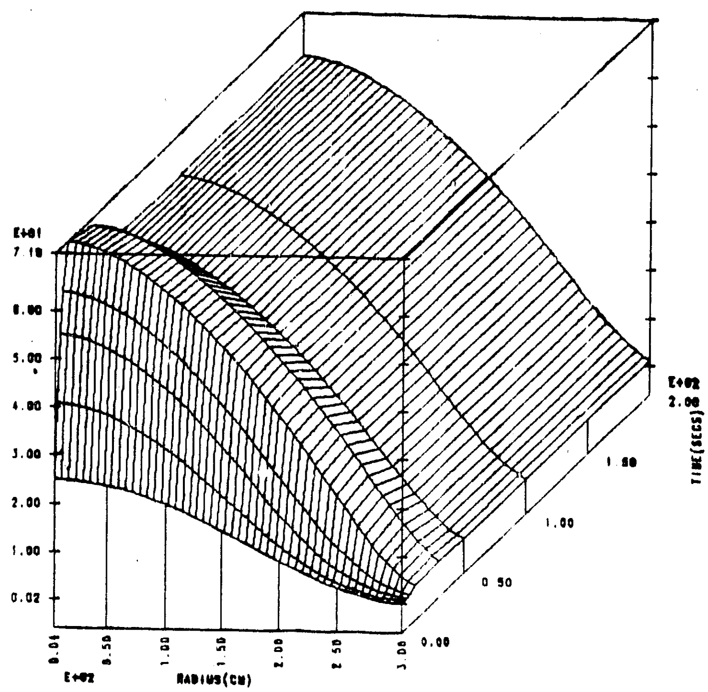
$$D_{DT} = D_{He} \sim \frac{1}{4}\chi_e.$$

- An example of the 3-D plots of the evolution of T_i and n_α: (R_{eff} = 0.95)

n_α



T_i



Equilibrium is reached well before the run is stopped at 200 seconds.

- Various helium edge recycling coefficients are considered (R_{eff} = 0, 0.5, 0.7, 0.8, 0.9, 0.95, and 0.98). Plasma is ignited in all these cases.

- Plasma parameters used in the simulations:

  $\bar{n}_e = 1.2 \text{ e } 20 \text{ m}^{-3}$, $\bar{n}_{carbon} \approx 0.01\bar{n}_e$

  $a = 3.1$ m, $R = 5.8$ m, $I_p = 20$ MA, $B_z = 5.1$ T.

- Simulations run up to ~ 200 seconds. Plasma reaches equilibrium at that time. For present purpose, no sawteeth, no soft β limit, etc.

Determination of τ_α^a and τ_α^b for 0-D model

- Let $\tau_\alpha^{BALDUR}(R_{eff}) \equiv N_\alpha / S_{fus}$ from BALDUR simulation with recycling coefficient R_{eff}.

- Then, $\tau_\alpha^a = \tau_\alpha^{BALDUR}(R_{eff}=0) \Rightarrow \tau_\alpha^a = 8.18$.

- Calculate τ_α^b using τ_α^a and $\tau_\alpha^*(R_{eff}=0.9) = \tau_\alpha^{BALDUR}(R_{eff}=0.9)$

  $\Rightarrow \tau_\alpha^b = 0.55$.

Comparison between 0-D Correlation and 1-D BALDUR Results

- Comparison of the helium ion confinement time of bench marked 0-D model with BALDUR runs for various R_{eff}:

Effective Helium Particle Confinement Time	Recycling Coefficient						
	0.98	0.95	0.90	0.8	0.7	0.5	0.0
τ_{α}^{*}	35.08	18.61	13.12	10.37	9.46	8.73	8.18
τ_{α}^{BALDUR}	33.57	18.44	13.12	10.40	9.49	8.75	8.18

— Good agreement found over broad range of ignited plasmas. Larger divergence as plasma $\rightarrow$ subignition.

- Determination of the energy confinement time for 0-D model:

  The energy confinement τ_E for the 0-D model is assumed to be a constant, and is bench marked against the 1-D run with $R_{eff} = 0$. (i.e. $\tau_E = \tau_E^{BALDUR}(R_{eff} = 0)$)

- Comparison of f ($\equiv \tau_\alpha^* / \tau_E$) of bench marked 0-D model with BALDUR runs for various R_{eff}:

$\frac{\tau_\alpha^*}{\tau_E}$	Recycling Coefficient						
	0.98	0.95	0.90	0.8	0.7	0.5	0.0
0-D	10.90	5.99	4.26	3.38	3.08	2.84	2.65
1-D	9.01	5.43	4.05	3.30	3.03	2.82	2.65

Good agreement found over broad range of ignited plasmas. Larger divergence as plasma → subignition.

Bench marked Burn Conditions for an ITER-like Plasma

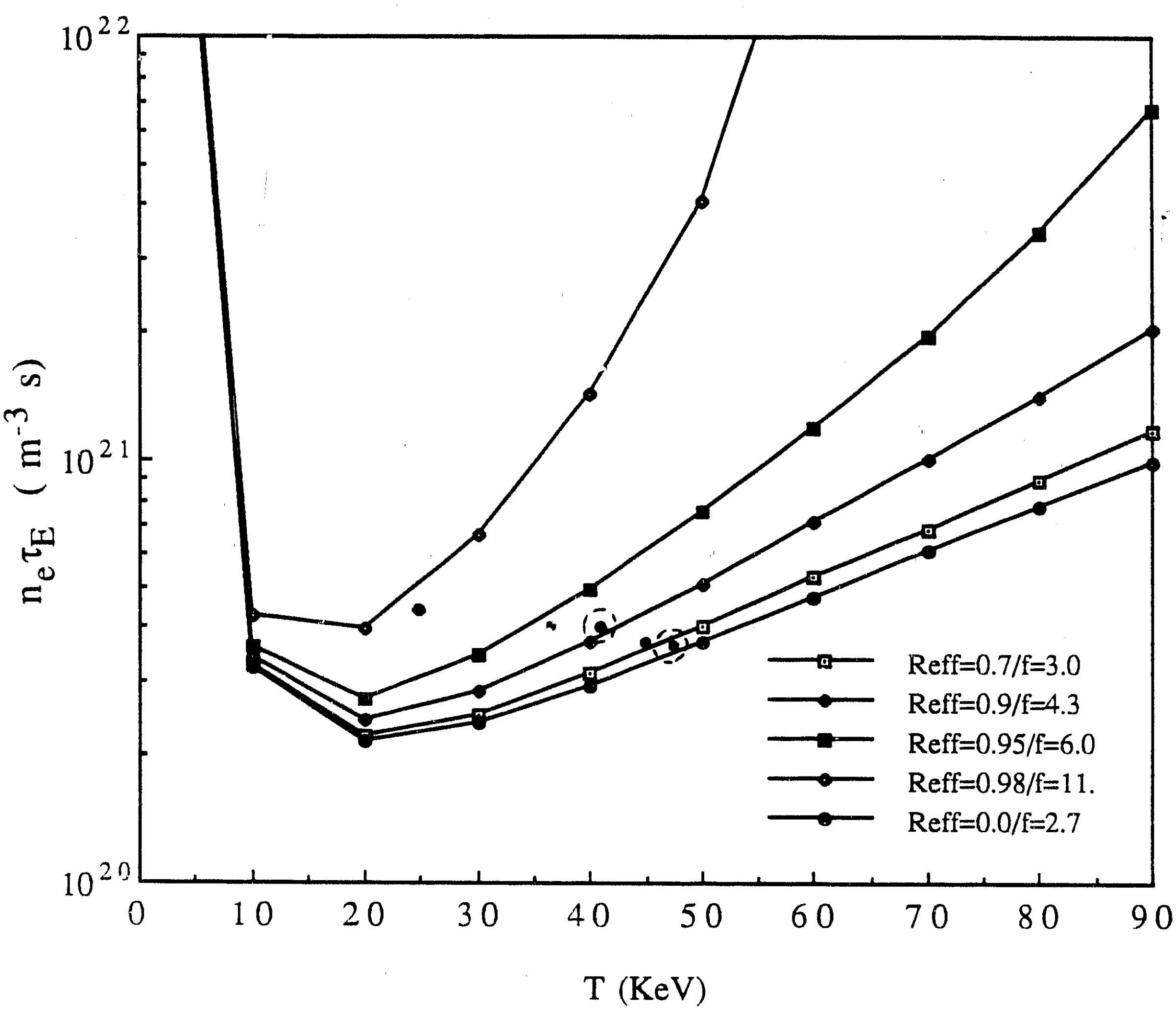


Fig 1. Ignition parameter $n_e\tau_E$ vs. T with various recycling coefficient (R_{eff}). Additional 0.9% carbon contamination is included. Radiation losses are implicit in τ_E, and f is the ratio of τ_α^* to τ_E (with α_n = 0. and α_T = 0.5).

BALDUR runs:
⊙ R_{eff} = 0.0, • R_{eff} = 0.7, ⊙ R_{eff} = 0.9, • R_{eff} = 0.95, • R_{eff} = 0.98

Conclusions

- Prediction of the effect of recycling on helium confinement using the 0-D correlation between the effective helium particle confinement time and R_{eff} agrees with 1-D BALDUR results over a limited range.

- This technique allows 0-D approximation to cover an expanded range once bench marked against two BALDUR runs.

- Future work:
  - Include sawteeth, etc.
  - Analytic prediction of τ_{α}^{*}.

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