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Simulation Study of Burning Control with Transport Barrier

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Abstract

Dynamics of burning plasmas are studied by use of one dimensional simulation code with current diffusive ballooning mode model. Focusing on the effects of current profile control, burning performance is evaluated. The ohmic plasma is heated by additional heating and ignited state of the plasma is reached. Due to the formation of negative shear, improved confinement is obtained with the L-mode boundary condition. Controlling the external current drive, burning state is sustained longer than 1000 sec.

Keywords:

sub-ignition, negative shear, improved confinement, current drive

1. Introduction

The attainment of the self-ignited state of plasma is one of the objects of next step fusion research. By using the theoretical model scaling law τ_E, which could explain the characteristics of the L-mode and the high β_p-mode, a point model has shown that there is an ignition window which does not depend on H-mode [1]. These results provide a backup scenario when the H-mode condition shall turn out to be difficult to satisfy. Zero dimensional model has been extended to a 1-D transport model, in order to examine the impact of profile effect on the burning performance for ITER-like plasma [2]. The energy transport, He-ash particle transport, and poloidal magnetic field transport were solved with the transport coefficients obtained from a combination of neoclassical and CDBM (current diffusive ballooning mode) models [3]. It was found that the self-ignition is sustained within the time scale of burn-time even if parameters lie in the L-mode boundary condition. However, in the time scale of current diffusion, the safety factor can be unity and MHD instability becomes problematic. In this study, we introduce a model of sawtooth to take account of MHD effect, and investigate the burning performance. Controlling the current profile, the burning performance is examined. Choosing the ohmic plasma (quenched plasma) as an initial condition, the dynamics of internal barrier formation is investigated in detail.

The organization of this paper is as follows. In Sec. 2, basic equations and assumptions are shown. In Sec. 3, numerical results are shown. Summary and discussion are given in Sec. 4.

2. Model Equations

One dimensional energy transport, He-ash particle transport and poloidal magnetic field transport equations are solved. It is assumed that temperatures are equal for all species and alpha-particles are fully thermalized without escaping from the plasma. The energy transport equation is given by

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$$\frac{\partial}{\partial t}\frac{3}{2}n_e\left(2-f_{He}\right)T$$
$$=\frac{1}{4}n_e^2 f_i^2 E_\alpha\left\langle\sigma v\right\rangle+\frac{1}{r}\frac{\partial}{\partial r}rn_e\left(2-f_{He}\right)\chi\frac{\partial T}{\partial r}$$
$$+P_{aux}+P_{OH}-P_{br}, \qquad (2.1)$$

where the terms in R.H.S represent the power input from alpha-particles (with $E_\alpha = 3.52$ MeV, and $<\sigma v>$ indicates D-T fusion reaction rate [5]), the heat transport losses, the auxiliary heating term P_{aux}, the ohmic heating term P_{OH}, and the volume power losses with bremsstrahlung P_{br}, respectively. The values f_{He} and f_i indicate the ratios of helium and ion densities to electron density, respectively. The value χ is a bulk thermal diffusivity which is given as $\chi(r) = \chi_{NC} + C_k\chi_{TB}$, where χ_{NC} and χ_{TB} are neoclassical diffusivity [6] and CDBM (current diffusive ballooning mode) diffusivity [3], respectively. The value C_k is an adjusting parameter, and given as $C_k = 12$ after [7]. A validity of this model for L-mode plasmas has been discussed in Ref. [8]. The radiation loss is assumed to be dominated by the bremsstrahlung. The particle balance of He-ash is given by

$$\frac{\partial}{\partial t}n_e f_{He}=\frac{1}{4}n_e^2 f_i^2\left\langle\sigma v\right\rangle+\frac{1}{r}\frac{\partial}{\partial r}rD_{He}\frac{\partial n_e f_{He}}{\partial r}, \qquad (2.2)$$

where D_{He} is the particle diffusivity for He-ash. The ratio of χ to D_{He} *i.e.*, $\rho \equiv \chi/D_{He}$ is introduced and assumed to be constant.

The poloidal magnetic field evolves according to

$$\frac{\partial}{\partial t}B_\theta=\frac{\partial}{\partial r}\eta_{NC}\left[\frac{1}{\mu_0}\frac{1}{r}\frac{\partial}{\partial r}rB_\theta-J_{BS}-J_{LH}\right], \qquad (2.3)$$

where η_{NC} is the neoclassical resistivity and the bootstrap current J_{BS} [6] and lower hybrid current drive J_{LH} are anticipated as source terms.

The electron density profile is assumed to be constant and is characterized by two parameters, *i.e.*, the volume averaged electron density $<n_e>$ and density peaking factor δ. The electron density profile is fixed as $n_e(r) = (n_{e0} - n_e(a))(1 - r^2/a^2)^\delta + n_e(a)$. As the δ value increases, density profile peaks at the center.

The burning performance of D-T plasma is evaluated using ITER-like parameters (a = 2.8 m, R = 8.14 m, B_t = 5.64 T, κ = 1.75, δ = 1.0, $<n_e>$ = 8.0 × 10^{19} m^{-3}, I_p^{tot} = 20 MA, ρ = 3.0). The edge values are chosen as $n_e(a)$ = 10^{19}m^{-3} and $T(a)$ = 50eV, so that a typical boundary condition of L-mode is satisfied.

3. Burning Transport Analysis

3.1 The case without current drive

The initial $J(r)$ profile is chosen as $J(r) \propto 1 - (r/a)^2$ with $q(0) \simeq 1.5$, and total plasma current is fixed as I_p^{tot} = 20MA. The steady state ohmic plasma, which is obtained with this target current profile, is chosen as an initial condition. Solving Eqs. (2.1-3), the accessibility of ignited plasma is examined. First, autonomous formation of internal transport barrier and ignition of the plasma are shown with L-mode boundary condition. The auxiliary heating is constant in time and the profile of $P_{aux} = P_b = P_{b0}\exp[-(r/r_{Wb})^2]$ is used with r_{Wb} = 0.2m. Total auxiliary heating power is P_{aux}^{tot} = 60MW. The temporal evolution of central temperature is shown in Fig.1. At $t \geq$ 20sec, the alpha heating becomes dominant, and the improved confinement in the plasma core is attained. Figure 2 shows the temporal evolution of the thermal diffusivity. The formation of transport barrier is due to the negative shear effect which stabilizes the ballooning type mode. On the other hand, at the peripheral region where safety factor profile is monotonous, the confinement improvement is not observed. Figure 3 shows the temperature and the safety factor profiles at t ~ 50sec. The confinement improvement factor H ~ 2.0 is obtained over the ITER89P L-mode confinement law [9].

As the time passes, the current profile is modified substantially. The safety factor decreases, and MHD instability becomes problematic. In this study, a model is introduced to take account of the MHD effect, similar to the Kadomtsev model [4]. In the model, a crash is

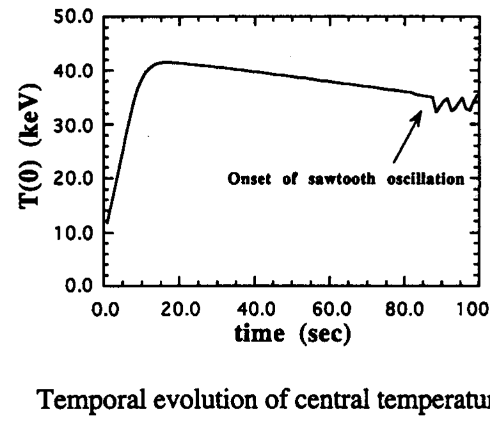
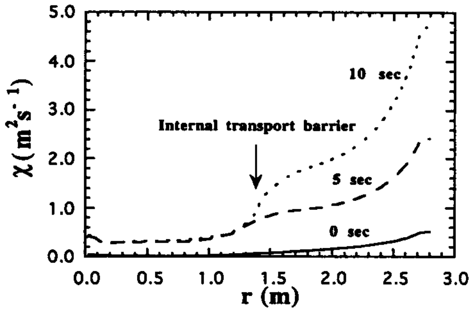
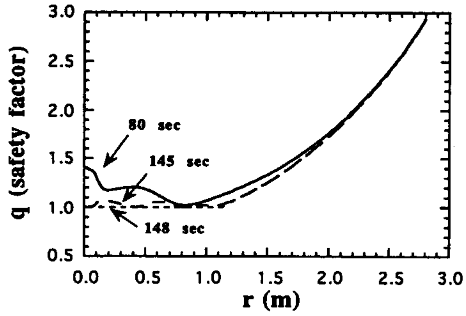


Fig. 1 The temporal evolution of central temperature at the initial phase without current drive is shown. Here the parameters are P_{aux}^{tot} = 60MW, $<n_e>$ = 8.0 × 10^{19}m^{-3}, I_p^{tot} = 20MA, ρ = 3.0, δ = 1.0. The sawtooth oscillation onsets at t ~ 85sec.



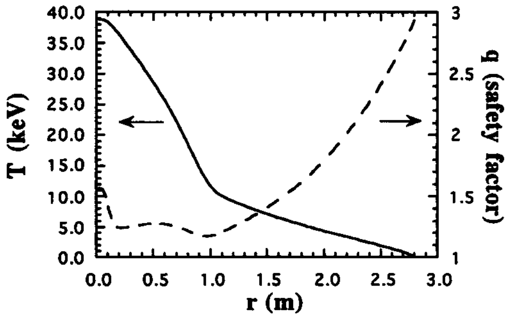
Temporal evolution of thermal diffusivity profile.

Fig. 2 The time slices of thermal diffusivity for t = 0, 5, 10sec. The internal transport barrier is formed autonomously at $r \sim 0.5a$.



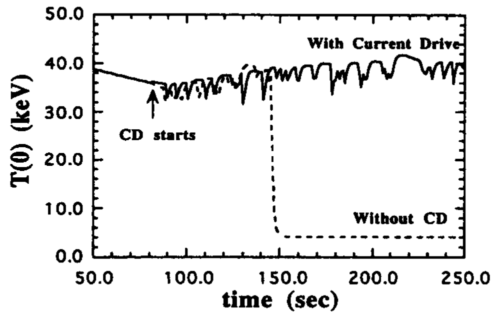
Crash of safety factor profile.

Fig. 4 The central safety factor goes to below unity at $t \sim$ 145sec. The crash propagates to $r \sim$ 1.1m.



Temperature and safety factor profiles at $t \sim 50\,sec$.

Fig. 3 The negative shear region corresponds to the location of transport barrier.



Temporal evolution of central temperature.

Fig. 5 The temporal evolution of central temperature is shown for the cases with and without current drive. In the case with current profile control, which are shown by solid curve, burning can be sustained.

assumed to occur if safety factor becomes below 1 in some region $r_1 < r < r_2$. At the onset, the pressure profiles, Helium density profile and helical flux are forced to become flat in the region $r_1 < r < r_2$. For these parameters, the minimum of safety factor goes to below unity, and the sawtooth oscillation sets in at $t \sim$ 85sec (see Fig. 1). If any current profile control is not applied, the central value of safety factor becomes below unity at $t \sim$ 145sec. Figure 4 shows a crash of safety factor profile. The internal transport barrier is lost, and the plasma turns to quenched state.

3.2 The case with current Drive

To sustain the burning state stationary, current profile control is applied for the central region (anti-current drive) and barrier region (current-drive). The initial profiles correspond to those at $t \sim$ 80sec which are obtained in the previous section. The total auxiliary heating is given by $P_{aux} = P_b + P_{ac} + P_c$ in this case. The total beam heating power is reduced to P_b^{tot} = 20MW. Then the power profile for LH anti-current drive is given by $P_{ac} = P_{ac0} \exp\{-r^2/r_{Wac}^2\}$ with P_{ac}^{tot} = 40MW and r_{Wac} = 0.4m. The power profile for LH current drive is given by $P_c = P_{c0} \exp\{-(r - 0.5a)^2/r_{Wc}^2\}$ with P_c^{tot} = 40MW and r_{Wc} = 0.2m. (Model and efficiency of the current drive is explained in [7].) Figure 5 shows the temporal evolution of central temperature with and without current drive. In the case with current drive, the crash of profile does not occur, and long term sustainment of burning is attained. The internal transport barrier is still sustained at ~ 1000sec, although the sawtooth oscillation occurs. The alpha heating power ~ $P_\alpha^{tot} \sim$ 350MW is obtained at $t \sim$ 1000sec. The ratio of the power given by fusion reaction to the auxiliary heating power is averaged over the time interval $t = 0 \sim$

1000sec, and it is obtained as $Q \sim 18$.

4. Summary and Discussion

One dimensional burning transport analysis is examined with current diffusive ballooning mode model. Focusing on the effects of current profile control, burning performance is evaluated. The sub-ignited state of the plasma, being associated with internal transport barrier, is obtained with the L-mode boundary condition. The improved confinement is obtained due to the effect of negative shear, and the coupling of the profiles of pressure, ash and current is shown to be crucial in the evolution of burning plasma. It is shown that the current profile control is important to sustain the burning state.

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