Tokamak Plasma Transport Simulation in the Presence of Neoclassical Tearing Modes

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For the prediction of the ITER plasmas, the effect of the neoclassical tearing mode (NTM) on the plasma confinement has been calculated using the 1.5-dimensional equilibrium and transport simulation code TOTAL. The time evolution of the NTM magnetic island has been analyzed using the modified Rutherford equation for a ITER normal shear plasma. The anomalous transport model used here is GLF23. The saturated magnetic island widths are w/a~0.048 at 3/2 mode and w/a~0.21 at 2/1 mode, and the reduction in fusion power output by NTM is 27% at the 3/2 mode, 82% at the 2/1 mode, and 89% at the 3/2 + 2/1 double mode. The stabilization effect of the electron cyclotron current drive (ECCD) with EC is also clarified. The threshold of ECCD power for the full stabilization is ~10[MW] against the 3/2 mode, and ~23[MW] against the 2/1 mode.

Keywords: ITER, tokamak, simulation, neoclassical tearing mode, electron cyclotron current drive, stabilization

1. Introduction

The neoclassical tearing mode (NTM) might limit the plasma pressure and would lead to a disruption in future tokamak reactors. The NTM makes the temperature profile flat inside magnetic island, and the central plasma temperature is reduced. Therefore, when the magnetic island is formed in the plasma, the fusion output power is decreased. The analysis and control of NTMs are one of the crucial issues in tokamak reactor [1]. The NTM is caused by a lack of the bootstrap current inside the magnetic island where the pressure profile is flattened [2]. The electron cyclotron current drive (ECCD) gives the NTM stabilization to replace the missing bootstrap current. The effect of NTM on the ITER plasma should be investigated, and the stabilization method of NTM should be clarified.

For the prediction of ITER plasmas, the time evolution of neoclassical tearing modes has been calculated by using the 1.5-dimensional (1.5-D) equilibrium and transport simulation code (toroidal transport linkage code TOTAL [3,4]). The magnetic island width is evaluated using the modified Rutherford equation [5,6]. In the simulation code, we used the GLF23 anomalous transport model that can simulate H-mode plasmas [7].

The purpose of this paper is to clarify the effect of the NTM magnetic island formation on the plasma confinement and to demonstrate its stabilization by the electron cyclotron current drive (ECCD) in ITER. In the next section, a numerical model is described. The details of modified Rutherford equation, the ECCD current profile and the current drive efficiency are also shown in this section. In section 3, simulation results are shown. The summary is given in section 4.

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2. Numerical model

The time evolution of NTM has been calculated using 1.5-D equilibrium and transport code (toroidal transport linkage code TOTAL [3,4]). The plasma equilibrium is solved by the free-boundary Apollo code [8], and the plasma transport is evaluated including the impurity dynamics [9]. The anomalous transport model used here is the glf23 [7] that can simulate H-mode plasmas.

2.1 Modified Rutherford equation

The time evolution of a NTM island width, *W*, is calculated according to the modified Ruther ford equation. Here, *W* is the normalized magnetic island width with respect to the minor plasma radius, *a*.

$$\frac{dW}{dt} = \Gamma_{\Delta'} + \Gamma_{BS} + \Gamma_{GGJ} + \Gamma_{pol} + \Gamma_{EC} \tag{1}$$

$$\Gamma_{\Delta'} = k_1 \frac{\eta}{\mu_0} \Delta'(W) \left\langle \left| \nabla\rho \right|^2 \right\rangle \tag{2}$$

$$\Gamma_{BS} = k_2 \eta L_q j_{BS} \left\langle \frac{\left|\nabla\rho\right|}{B_p} \right\rangle \frac{W}{W^2 + W_d^2} \tag{3}$$

$$\Gamma_{GGJ} = -k_3 \frac{\eta}{\mu_0} \varepsilon_s^2 \beta_{ps} \frac{L_q^2}{\rho_s L_p} \left(1 - \frac{1}{q_s^2}\right) \left\langle \left|\nabla\rho\right|^2 \right\rangle \frac{1}{W} \tag{4}$$

$$\Gamma_{pol} = -k_4 \frac{\eta}{\mu_0} g(\varepsilon_s, \nu_i) \beta_{ps} \left(\frac{\rho_{pi} L_q^2}{L_p} \right)^2 \left\langle \left|\nabla\rho\right|^2 \right\rangle \frac{1}{W^3} \tag{5}$$

$$\Gamma_{EC} = -k_5 \eta \frac{L_q}{\rho_s} \left\langle \frac{|\nabla \rho|}{B_p} \right\rangle f \eta_{EC} \frac{I_{EC}}{a^2} \frac{1}{W^2} \qquad (6)$$

Here, $\Gamma_{\Delta'}$ is the classical stability index defined as the logarithmic jump of the radial magnetic field perturbation across the rational surface [10]. Γ_{BS}, Γ_{GGJ}, Γ_{pol} and Γ_{EC} are the perturbed bootstrap current, the stabilizing effect of the field line curvature [11], the ion polarization current and the EC current effect [12]. ρ is the coordinate of the normalized minor radius. η, ε_s, β_{ps}, ρ_{pi} and ρ_s are the neoclassical resistivity, the inverse aspect ratio, the local poloidal beta, the poloidal Larmor radius normalized by minor radius a and the rational surface position, respectively. The scale lengths, L_q and L_p, are defined as $L_q=(dq/d\rho)^{-1}$ and $L_p=-(dp/d\rho)^{-1}$.

2.2 Modified Rutherford equation

In this paper, the EC current profile is modelled by a Gaussian distribution as

$$j_{EC} = j_{EC0} \exp\left(-C \left(\frac{\rho - \rho_s}{W_{EC}} \right)^2 \right), \qquad (7)$$

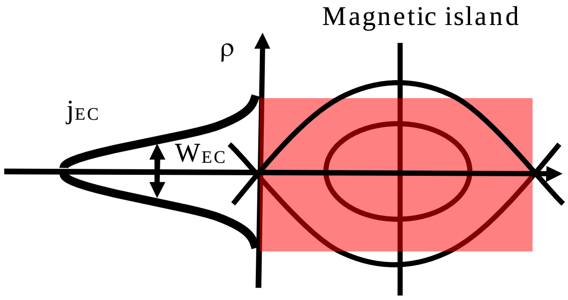

Figure 1. Model of EC current profile. The EC current density, j_{EC} is modelled by the Gaussian distribution.

where C=4ln2, j_{EC0} is calculated from the total EC current I_{EC}. The value ρ_s is the position of the current density peak. The efficiency of the EC current is given by [2]

$$\eta_{EC} = \frac{\int d\hat{\rho} \oint (d\alpha / 2\pi) \cos(m\alpha) \langle\langle j_{EC} \rangle\rangle}{\int d\hat{\rho} \oint (d\alpha / 2\pi) \langle\langle j_{EC} \rangle\rangle}, \qquad (8)$$

The value of I_{EC} is assumed to be proportional to the EC power, P_{EC}, as I_{EC} [kA]=4.35P_{EC}[MW] for the 3/2 mode and 4.15P_{EC}[MW] for the 2/1 mode [6].

3. Numerical result

Table 1 shows parameters of a typical ITER plasma analyzed in this paper. The local parameters at the rational surfaces of q=3/2 and 2/1 are shown table 2, where ρ_s,β_{ps} and j_{BS} are the normalized rational surface position, the local poloidal beta, and the local bootstrap current density, respectively. The coefficients of each term in the modified Rutherford equation used here are shown in table 3.

Table 1. Plasma parameters used here for ITER.

R_0 : major radius (m)	6.2
a : minor radius (m)	2.0
B_{t0} : toroidal field at R_0 (T)	5.3
I_P : plasma current (MA)	15
$\langle n_e \rangle$ (x 10^{20} m^{-3})	1.01
$\langle T_e \rangle$ (keV)	10.9
$\langle T_i \rangle$ (keV)	9.8
β	3.1

Table 2. Parameters relevant to the rational surface.

m/n	3/2	2/1
ρ_s	0.67	0.84
β_{ps}	0.65	0.46
J_{BS} (MA/m^2)	0.11	0.11

Table 3. Coefficients of each term in the modified Rutherford equation used here

k_1	1.0
k_2	10.0
k_3	1.0
k_4	1.0
k_5	5.0

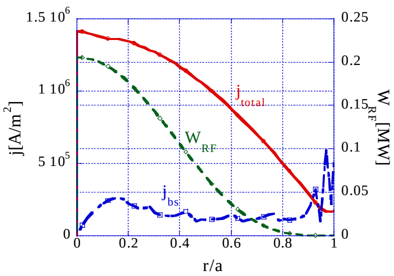

Figure 2. Plasma current density and input heating power profile as a function of normalized minor radius. The total input power is 40 MW, the average electron density is 1.0×10^{20} m^{-3} and the total current is 15 MA.

3.1 Reduction in plasma temperature and fusion power by NTM

In a ITER plasma the NTM magnetic islands are saturated around ten seconds after introducing the seed island. Figure 3 shows the electron temperature profile and the q profile when the magnetic island is saturated. The 3/2 mode island (q=1.5) exists at r/a=0.67, and the 2/1 mode island (q=2) exists at r/a=0.84. We assumed the transport coefficient is quite large inside the magnetic island. According to figure 3, the electron temperature at plasma center decreases due to the magnetic island formation. That is, the fusion power decreases too due to the NTM magnetic island. Table 4 shows the plasma parameters when the magnetic island exists in the plasma. Here, $T_e(0)$,

I_{BS}, I_{TOTAL} and Q are the central electron temperature, the total bootstrap current, the total current and the Q value, respectively. The Q value is defined by the ratio of the fusion output power to the input power. At 3/2 mode, the Q value decreases to 73% of no NTM case, at 2/1 mode, the Q value decreases to 18% of no NTM case, and at double tearing modes, the Q value decreases to 11% of no NTM. To reduce the magnetic island width is important in order to raise the fusion power output.

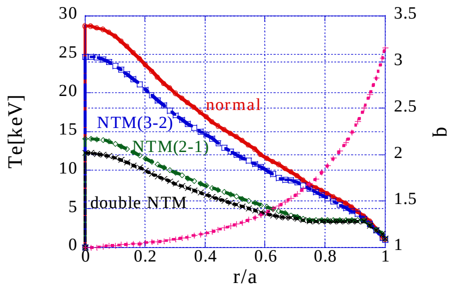

Figure 3. Electron temperature and safety factor q profile without and with 3/2, 2/1, and double neoclassical tearing modes.

Table 4. Central temperature, bootstrap current fraction and Q value in three cases

	Te(0)[keV]	I_{BS}/I_{total}(%)	Q
Normal	28.7	23.2	14.6
NTM(3/2)	24.9	20.3	10.7
NTM(2/1)	14.9	12.6	2.6
Double NTM	12.2	9.2	1.6

3.2 Time evolution and saturation of magnetic island width

The NTM magnetic island grows in time, and the island width is finally saturated. We assumes a seed island with w/a=0.05 introduced at time=30 [s]. Figure 4 shows the time evolution of the magnetic island width with 3/2, 2/1, and double modes. The 3/2 mode island width is saturated at w/a=0.048, and the 2/1 mode is saturated at w/a=0.21. As double mode, saturated each magnetic island width is nearly equal to single mode. The time constant for saturation is about 10 seconds. In 3/2 mode, the time for saturation of double mode is longer than single mode. In 2/1 mode, the time for saturation are same with single and double.

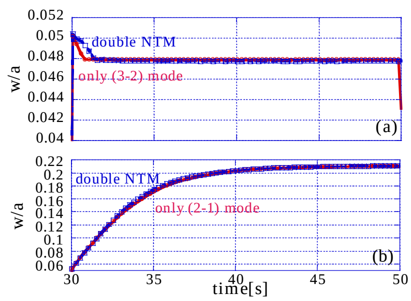

Figure 4. Time evolution of central temperature and magnetic island width of each modes (a) 3/2 mode, and (b) 2/1 mode.

Figure 5 shows the time evolution of every terms in the modified Rutherford equation as single mode. It should be noted that in equilibrium, the term $\Gamma_{\Delta'}$ changes from positive to negative.

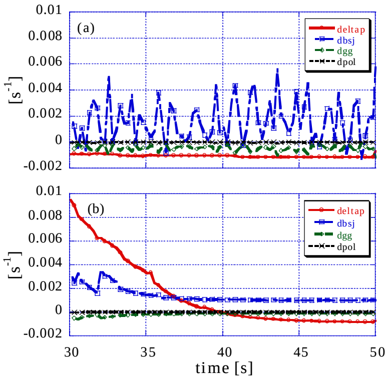

Figure 5. Total current and bootstrap current profile with (a) 3/2 and (b) 2/1 modes.

3.3 Time evolution and saturation of magnetic island width

We simulated the reduction in the magnetic island width by adding the electron cyclotron current drive (ECCD). Figure 6 shows the effect of the ECCD injected at 40[s] using the model described in section 3.2. The magnetic island width is fully erased by adding the large ECCD power. And, We simulated the different of reduction single and double mode. Figure 7 shows the reduction of magnetic island width in case of single and double. In 2/1 mode, their difference is very small. But in 3/2 mode, the effect of ECCD is big. Because, the temperature at 3/2 surface position in case of double is small in compare with single (Figure 3). The temperature at surface position 2/1 is same with double and single. We change the injection time of ECCD as shown in figure 8. Early injection of ECCD can easily reduce the magnetic island width. The value of the total EC current I_{EC} is assumed to be proportional to the EC power, P_{EC},

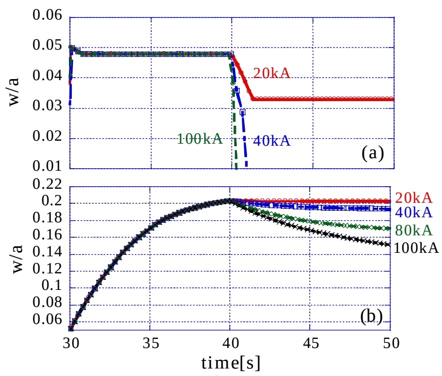

Figure 6. Time evolution of magnetic island width at (a) 3/2 mode and (b) 2/1 mode. Magnetic seed island with w/a=0.05 is introduced at time=30[s], and the EC current was injected from 40[s] with current width W_{EC}/a=0.04 and with EC total current of 20, 40, 100 and 200[kA].

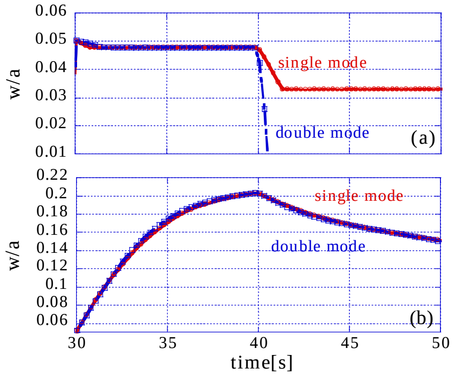

Figure 7. Time evolution of magnetic island of the seed island with w/a = 0.05 at time=30 [s] at (a) 3/2 mode injected current 20[kA], and (b) 2/1 mode injected current 100[kA]. The ECCD power is injected at time = 40 [s] in single (blue) and 3/2+2/1 double mode(red) case.

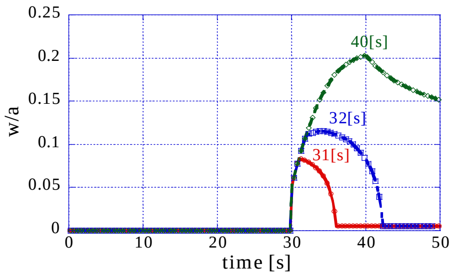

Figure 8. Time evolution of magnetic island of the seed island with w/a = 0.05 at time=30 [s]. The ECCD power of 100kA is injected at the time shown in the figure.

as I_{EC} [kA] = 4.35P_{EC}[MW] for the 3/2 mode and 4.15P_{EC}[MW] for the 2/1 mode. We need 10MW ECCD power for 2/1 mode stabilization, and 23MW for 3/2 mode stabilization, when the NTM is saturated.

4. Summary and discussions

The ITER plasma with the neoclassical tearing mode (NTM) is simulated using integrated transport code TOTAL. The anomalous transport model used here is GLF23, and the magnetic island width of NTM is calculated by the modified Rutherford equation. The magnetic island formation reduces the plasma temperature and the fusion output power. The decrease in the Q value due to NTM is estimated. The reduction in fusion output power by NTM is 27% at the 3/2 mode, 82% at the 2/1 mode, and 89% at the 3/2+2/1 double mode. The saturated magnetic island widths of each modes are w/a~0.048 at 3/2 mode and w/a~0.21 at 2/1 mode.

The Injection of ECCD is considered to stabilize the NTM and to recover the plasma confinement. We calculate the stabilization effect of ECCD with EC width w_{EC}/a=0.04. The threshold power for the NTM full stabilization by ECCD is ~10 MW against the 3/2 mode, and ~23 MW against the 2/1 mode.

For the reduction in ECCD power and the increase in the stabilization effects, the EC current width should be narrow. When the injection current width is half, the threshold power for the full stabilization is considered about half. The other method for ECCD power reduction is to modulate the EC current. The efficiency of ECCD can be raised by the current injection to the O point in magnetic island. The details of these analyses will be described somewhere in the future.

References

[1] ITER Physics Basis Editors *et al.*, Nucl. Fusion **39**, 2137 (1999).

[2] Hegna C C and Callen J D, Phys. Plasmas **4**, 2940 (1997).

[3] Yamazaki K and Amano T, Nucl. Fusion **32,** 633 (1992)

[4] Yamazaki K *et al.*, Fusion Engineering and Design **81**, 2743 (2006)

[5] Sauter O *et al*., Phys. Plasmas **4**, 1654 (1997)

[6] Hayashi N, Ozeki T, Hamamatsu K and Takizuka T, Nucl. Fusion **44**, 477 (2007)

[7] Waltz R E, Staebler G M, Dorland W, Hammett G W, Kotschenreuther M and Konings J A, Phys. Plasmas **4**, 2482 (1997)

[8] Yamazaki K, Amano T, Naitou H, Hamada Y and Azumi M, Nucl. Fusion **25**, 1543 (1985)

[9] Yamazaki K *et al*., J. Plasma Fusion Res. SERIES **7,** 102 (2006)

[10] Furth H P, Rutherford P H and Selberg H, Phys. Fluids **16,** 1054 (1973)

[11] Kotschenreuther M, Hazeltine R D and Morrison P J, Phys. Fluids **28**, 899 (1985)

[12] Wilson H R *et al*., Phys. Plasmas **3**, 248 (1996)