H-mode plasma transport simulation in ITER with effect of neoclassical tearing mode

Y Takahashi, K Yamazaki, H Arimoto and T Shoji

Nagoya University, Chikusa-ku, Nagoya 464-8603, Japan
E-mail: yamazaki@ees.nagoya-u.ac.jp

Abstract. 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 ITER normal shear plasmas. The anomalous transport model used here is GLF23. The saturated magnetic island widths are $w/a \sim 0.048$ at 3/2 mode and $w/a \sim 0.21$ at 2/1 mode, and the reduction in fusion power output by NTM is 27% at the 3/2 mode, and 82% at the 2/1 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 at high beta NTM island formation is $\sim 10$ MW against the 3/2 mode, and $\sim 23$ MW against the 2/1 mode.

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. Especially, we focused on the ITER plasma performance with the GLF23 transport model and evaluated the decrease in the output fusion power and $Q$ value due to NTMs, in addition to the ECCD feedback control as discussed in reference [6]. 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.
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 Rutherford equation. Here, $W$ is the normalized magnetic island width with respect to the minor plasma radius, $a$.

\[
\frac{dW}{dt} = \Gamma_x + \Gamma_{BS} + \Gamma_{GGJ} + \Gamma_{pol} + \Gamma_{EC}
\]

\[
\Gamma_x = k_1 \frac{\eta}{\mu_0} \Delta (W) \left( \left| \nabla \rho \right|^2 \right)
\]

\[
\Gamma_{BS} = k_2 \eta L_q j_{BS} \left( \left| \nabla \rho \right| \right) \frac{W}{B_p} \left( W^2 + W_d^2 \right)
\]

\[
\Gamma_{GGJ} = -k_3 \frac{\eta \varepsilon_s^2 \beta_p \rho_p L_p}{\mu_0} \left( 1 - \frac{1}{q_s^2} \right) \left( \left| \nabla \rho \right|^2 \right) \frac{1}{W}
\]

\[
\Gamma_{pol} = -k_4 \frac{\eta g(\varepsilon_s, \lambda)}{\mu_0} \left( \frac{\rho_p L_p}{L_q} \right)^2 \left( \left| \nabla \rho \right|^2 \right) \frac{1}{W^3}
\]

\[
\Gamma_{EC} = -k_5 \eta \left( \frac{L_q}{B_p} \right) \left( \left| \nabla \rho \right| \right) \frac{I_{EC}}{a^2} \frac{1}{W^2}
\]

Here, $\Gamma_x$ is the classical stability index defined as the logarithmic jump of the radial magnetic field perturbation across the rational surface [10]. $\Gamma_{BS}$, $\Gamma_{GGJ}$, $\Gamma_{pol}$ and $\Gamma_{EC}$ are the perturbed bootstrap current, the stabilizing effect of the field line curvature [11], the ion polarization current and the EC current effect [12]. $\rho$ is the coordinate of the normalized minor radius. $\eta$, $\varepsilon_s$, $\beta_p$, $\rho_p$ and $\rho_i$ 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 $L_q = q(dq/d\rho)^{-1}$ and $L_p = -p(dp/d\rho)^{-1}$.

2.2. EC current

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

\[
j_{EC} = j_{EC0} \exp \left( -C \left( \frac{\rho - \rho_s}{W_{EC}} \right)^2 \right)
\]

as shown in figure 1. Here, $C = 4\ln2$, and $j_{EC0}$ is calculated from the total EC current $I_{EC}$. The value $\rho_s$ is the position of the current density peak, and $W_{EC}$ is the width of the localized EC current. For an ITER plasma given in Table 1, we assumed for simplicity that the value of $I_{EC}$ is proportional to the EC power, $P_{EC}$, as $I_{EC} [kA] = 4.35 P_{EC} [MW]$ for the 3/2 mode and $I_{EC} [kA] = 4.15 P_{EC} [MW]$ for the 2/1 mode [6].
3. Numerical Results

Table 1 shows parameters of typical ITER plasma analysed in this paper. The local parameters at the rational surfaces of $q = 3/2$ and $2/1$ are shown in Table 2, where $\rho_s$, $\beta_{ps}$ and $j_{BS}$ are the normalized rational surface position, the local poloidal beta, and the local bootstrap (BS) current density, respectively. Typical BS current density and the heating power profiles are given in Figure 2. The coefficients of each term in the modified Rutherford equation used here are shown in Table 3. Here, we used almost the same parameters as those in the reference [6] based on the JT 60 experiments.

### Table 1. Plasma parameters used here for ITER.

| Parameter       | Value     |
|-----------------|-----------|
| $R_0$ : 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        |
| $<n_e>$ (10$^{20}$ m$^{-3}$) | 1.01       |
| $<T_e>$ (keV)             | 10.9      |
| $<T_i>$ (keV)             | 9.8       |
| $\beta_N$               | 3.1       |

### Table 2. Parameters relevant to the rational surface.

| $m/n$ | 3/2 | 2/1 |
|-------|-----|-----|
| $\rho_s$ | 0.67 | 0.84 |
| $\beta_{ps}$ | 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

| Coefficient | Value |
|-------------|-------|
| $k_1$       | 1.0   |
| $k_2$       | 10.0  |
| $k_3$       | 1.0   |
| $k_4$       | 1.0   |
| $k_5$       | 5.0   |

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

Figure 2. Plasma current density and input heating power $P_{RF}$ profile as a function of normalized minor radius. The total input power is 40 MW, the average electron density is 1.0 $\times$ 10$^{20}$ m$^{-3}$ and the total current is 15 MA.
3.1. Reduction in plasma temperature and fusion power by NTM

In an 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, $T_e(0)$, $I_{BS}$, and $I_{TOTAL}$ are the central electron temperature, the total bootstrap current, and the total current. The $Q$ value is defined by the ratio of the fusion output power to the input power. Here, we assumed inductively driven plasma current, and did not include the current drive power for evaluation the $Q$ value. The alpha heating power can be evaluated by the Fokker-Planck code in the TOTAL code. Here we used a simple model of alpha particle power deposition to electrons and ions depending on the slowing-down critical energy. At 3/2 mode, the $Q$ value decreases to 73% of no NTM case, and at 2/1 mode, the $Q$ value decreases to 18% of no NTM case. 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 and 2/1 neoclassical tearing modes.](image)

| Table 4. Central temperature, bootstrap current fraction and $Q$ value in three cases. |
|---|---|---|
| $T_e(0)$[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 |

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 assumed a seed island with $w/a = 0.05$ introduced at time $= 10$ s to compare the plasma performances with and without NTMs. When the NTM is introduced on the early stage, the time constant of the island evolution becomes shorter, but the final island saturation width is same in the case of no ECCD stabilization. Figure 4 shows the time evolution of the central electron temperature and the magnetic island width with 3/2 and 2/1 modes. The 3/2 mode island width is saturated at $w/a = 0.048$, and the 2/1 mode is saturated at $w/a=0.21$. The time constant for saturation is about 10 seconds. The central
temperature decreases due to the magnetic island evolution, and the time constant for equilibrium saturation is about 10 seconds, too. Figure 5 shows every terms in the modified Rutherford equation at time = 10 s as a function of the seed island width \( w/a \). The stabilization terms are \( \Gamma_d \) (when \( w/a \) is large), \( \Gamma_{GGJ} \) and \( \Gamma_{pol} \), and the destabilization terms are \( \Gamma_d' \) (when \( w/a \) is small) and \( \Gamma_{BS} \). In both (a) 3/2 and (b) 2/1 cases in figure 5, the derivative \( dw/dt \) is negative when the normalized seed magnetic island width is smaller than 0.02. When \( dw/dt \) is negative, the magnetic island width is decreased. A magnetic island grows when the seed island is larger than 0.02. Figure 6 shows bootstrap current profile when the magnetic island width is saturated with 3/2 and 2/1 mode. The bootstrap current is decreased inside the magnetic island, and the local bootstrap current density at resonant surface is 5.1 kA/m\(^2\) at the 3/2 mode and 3.6 kA/m\(^2\) at the 2/1 mode. Figure 7 shows the time evolution of every term in the modified Rutherford equation. It should be noted that in equilibrium, the term \( \Gamma_d' \) changes from positive to negative. The island evolution in this case is determined initially by the delta-prime term and finally by the bootstrap current term as shown in figure 7. The time constant of the island saturation might be determined by the resistive time initially and the local transport time related to bootstrap current decay time finally.

**Figure 4.** Time evolution of central temperature and normalized magnetic island width of each mode when a seed island is introduced at time = 10 s.

**Figure 5.** Every terms in the modified Rutherford equation at time = 10 s as a function of the island width \( w/a \) in (a) 3/2 mode and (b) 2/1 mode cases.
Figure 6. Total current and bootstrap current profile with 3/2 and 2/1 mode.

Figure 7. Time evolution of each terms in the modified Rutherford equation for $m/n = 1/2$.

Figure 8. Time evolution of central temperature and magnetic island width at 2/1 modes. Magnetic seed island with $w/a = 0.05$ is introduced at (a) time = 10 s and (b) time = 30 s, and the EC current was injected from (a) 15 s and (b) 40 s with current width $W_{EC} = 0.04$ and with EC total current of 20, 40, 60, 80 and 100 kA.
3.3. Stabilization of NTM by ECCD
We simulated the reduction in the magnetic island width by adding the electron cyclotron current drive (ECCD). Figure 8 shows the effect of the ECCD injected at 20 s in lower beta (time = 10 s) island growing phase and at 40 s for higher beta (time = 30 s) island-saturated phase using the model described in section 3.2. The magnetic island width is fully erased by adding the large ECCD power. In the earlier and lower-beta phase, the required ECCD power is lower. Figure 9 shows every terms of the modified Rutherford equation, when the magnetic island isn’t erased by the ECCD. The stabilization of the ECCD power is balanced by the other terms. In the 2/1 mode case, the ECCD term balances with $\Gamma_{BS}$ and $\Gamma_{\Delta}$. We change the injection time of ECCD as shown in figure 10. Early injection of ECCD can easily reduce the magnetic island width. We need 10 MW ECCD power for 2/1 mode stabilization, and 23 MW for 3/2 mode stabilization, when the NTM is fully saturated at higher beta.

4. Summary and discussions
The ITER H-mode 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 out power by NTM is 27% at the 3/2 mode, and 82% at the 2/1 mode. The saturated magnetic island widths of each modes are $w/a \sim 0.048$ at 3/2 mode and $w/a \sim 0.21$ 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 in higher-beta island-saturation phase 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.

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