Control of Neoclassical Tearing Mode by Electron Cyclotron Current Drive and Non-Resonant Helical Field Application in ITER

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On tokamak plasmas like ITER, it is necessary to stabilize neoclassical tearing mode (NTM) because the NTM reduces plasma temperature and fusion power output. For the analysis of stabilizing NTM in fusion plasmas, the electron cyclotron current drive (ECCD) and the non-resonant external helical field (NRHF) application are simulated using the 1.5-dimensional equilibrium/transport simulation code (TOTAL code). The 3/2 NTM is stabilized by only external helical field, but the 2/1 mode is not stabilized by only external helical field in the present model. The stabilization time becomes shorter by the combination of ECCD and NRHF than that by ECCD alone.

Keywords: tokamak, ITER, neoclassical tearing mode, electron cyclotron current drive, non-resonant helical field

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1. Introduction

The neoclassical tearing mode (NTM) is known as instabilities excited by the perturbed bootstrap current at the beta value lower than the ideal beta limit. The confinement property is reduced by the magnetic island formation which increases heat and particle transport inside the island. These modes have been observed in most tokamaks in standard positive magnetic shear discharges with the high confinement mode [1–3]. The stabilization of NTM was experimentally confirmed by the electron cyclotron current drive (ECCD) scheme [3–5] and theoretically proposed by the non-resonant helical field (NRHF) application [6]. The ECCD scenario has strong stabilization effect; however it reduces energy gain of the fusion reactor due to increase in input power. On the other hand, static NRHF needs a little input energy.

In order to clarify the effect of stabilization methods, especially NRHF effects, against $m/n = 3/2$ and $m/n = 2/1$ NTMs in ITER plasmas, the time evolution of NTM has been calculated by the modified Rutherford equation using the 1.5-dimensional (1.5-D) equilibrium and transport simulation code (toroidal transport linkage code TOTAL).

2. Numerical Model

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

2.1 Modified rutherford equation

The time evolution of the normalized NTM island width W is calculated according to the modified Rutherford equation [2] including NRHF effects [6];

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \Gamma_{\Delta'} + \Gamma_{\mathrm{BS}} + \Gamma_{\mathrm{GGJ}} + \Gamma_{\mathrm{pol}} + \Gamma_{\mathrm{EC}},$$

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

$$\Gamma_{\mathrm{BS}} = k_2 \eta L_q j_{\mathrm{BS}} \left\langle \frac{|\nabla\rho|}{B_p} \right\rangle \left(\frac{f_{\mathrm{BSe}} W}{W^2 + W_{\mathrm{d,e}}^2} + \frac{(1 - f_{\mathrm{BSe}}) W}{W^2 + W_{\mathrm{d,i}}^2} \right),$$

$$\Gamma_{\mathrm{GGJ}} = -k_3 \frac{\eta}{\mu_0} \varepsilon_{\mathrm{s}}^2 \beta_{\mathrm{ps}} \frac{L_q^2}{\rho_{\mathrm{s}} L_p} \left(1 - \frac{1}{q_{\mathrm{s}}^2} \right) \left\langle |\nabla\rho|^2 \right\rangle \frac{1}{W + W_{\mathrm{GGJ}}},$$

$$\Gamma_{\mathrm{pol}} = -k_4 \frac{\eta}{\mu_0} g(\varepsilon_{\mathrm{s}}, \nu_{\mathrm{i}}) \beta_{\mathrm{ps}} \left(\frac{\rho_{\mathrm{pi}} L_q^2}{L_p} \right)^2 \left\langle |\nabla\rho|^2 \right\rangle \frac{W}{W^4 + W_{\mathrm{pol}}^4},$$

$$\Gamma_{\mathrm{EC}} = -k_5 \eta \frac{L_q}{\rho_{\mathrm{s}}} \left\langle \frac{|\nabla\rho|}{B_p} \right\rangle \eta_{\mathrm{EC}} \frac{I_{\mathrm{EC}}}{a^2} \frac{1}{W^2}.$$

Here, W is magnetic island width normalized by the plasma minor radius a, $\Gamma_{\Delta'}$ is the classical tearing mode stability index, Γ_{BS} is the destabilizing effect due to lack of bootstrap current, Γ_{GGJ} is the stabilizing effect of the field line curvature, Γ_{pol} is the stabilizing effect of ion polarization current, and Γ_{EC} is the stabilizing effect of external EC current drive. 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 ion Larmor radius normalized by minor radius

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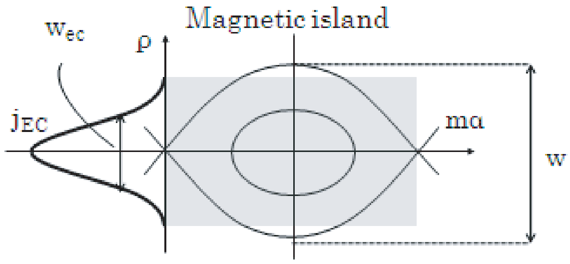

Fig. 1 Model of EC current profile. The EC current density, j_{EC} is modelled by the Gaussian distribution.

a, and the rational surface position, respectively. The scale lengths L_q for safety factor q and L_p for pressure p, are defined as $L_q = q(\mathrm{d}q/\mathrm{d}\rho)^{-1}$ and $L_p = -p(\mathrm{d}p/\mathrm{d}\rho)^{-1}$. f_{BSe} is electron fraction of BS current term. The g function of the polarization term is defined by the collisionality shown in Ref. [1]. Here, the coefficients k_1, k_2, k_3, k_4 and k_5 are 1, 1, 10, 1 and 2.9, respectively based on the JT-60 U analysis [5].

2.2 EC current

In this study, the EC current profile is modelled [4, 5] by a Gaussian distribution as

$$j_{\mathrm{EC}} = j_{\mathrm{EC0}} \exp\left[-C\left(\frac{\rho_{\mathrm{EC}} - \rho_{\mathrm{s}}}{W_{\mathrm{EC}}}\right)^2\right].$$

Here, C = 4ln2, j_{ec} is calculated by the total EC current I_{EC}. The normalized radius ρ_{EC} is the position of the EC current density peak. The EC stabilization efficiency is given by

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

2.3 Non-resonant external helical field

When the helical pressure perturbation of a NTM is reduced by the magnetic perturbation of another mode, the non-linear evolution of this NTM might be suppressed. This is the reason why the NRHF application stabilizes NTMs.

The NRHF effect is added to the term of reducing island flatting effect by thermal transport as the following perturbed field effect term

$$W_{\mathrm{d}} = 5.1\left(\frac{b_{2\mathrm{r}}^2}{4} + \frac{\chi_\perp}{\chi_\parallel}\right)^{1/4}\left[\frac{r_{\mathrm{s}} L_q q}{\varepsilon m}\right]^{1/2},$$
$$W_{\mathrm{GGJ}} = 0.2 W_{\mathrm{d}}.$$

Here, W_{d} is the effect of finite perpendicular thermal transport, W_{GGJ} is the stabilizing Glasser–Green–Johnson (GGJ) effect due to field line curvature,$b_{2\mathrm{r}}$ is the field magnitude ratio of the non-resonant external helical field to the rational surface, $\chi_\parallel$ and $\chi_\perp$ are parallel and perpendicular transport coefficients, r_{s} is the position of the interesting rational surface. $\varepsilon = r/R$ is inverse aspect ratio, and m is the poloidal mode number. This W_{d} term including the NRHF effect is included in Γ_{BS} and Γ_{GGJ}.

Table 1 ITER-like parameters.

R_0 : major radius	6.2[m]
a : minor radius	2.0[m]
B_{t0} : toroidal field at R_0	5.3[T]
I_P : plasma current	15[MA]
$<n_e>$: electron density	1.01×10^{20} [m^{-3}]
$<T_e>$: electron temperature	10.9[keV]
$<T_i>$: ion temperature	9.8[keV]
β_N : normalized beta value	3.1

3. Numerical Results

Table I shows the ITER-like plasma parameters used in this paper. The total input power is 40 MW and the total plasma current is 15 MA. We assume a seed island with $W = 0.05$ introduced at time $t = 30$ s.

3.1 Stabilization for 3/2 NTM

Figure 2 shows the time evolution of central electron temperature $T_{\mathrm{e}}(0)$ and magnetic island width w/a when there is no NTM (NoNTM). The NTM is introduced with $m/n = 3/2$ mode (3/2NTM) at $t = 3$ s. Its seed island width is assumed 0.5% The $b_{2\mathrm{r}} = 1\%$ non-resonant external helical field (3/2NTM(NRHF)) is used, to stabilize 3/2 NTM. When the stabilization method is not applied (3/2NTM), the central electron temperature $T_{\mathrm{e}}(0)$ decreases to 87% of that in NoNTM case and the saturated island width W becomes 0.048. The fusion gain factor Q decreases to 74% of that in no NTM case. When the NRHF stabilization method is applied (3/2NTM(NRHF)), the NTM is stabilized and the Q value recovers to that of the case without 3/2 mode.

Figure 3 shows the time evolution of main terms in the modified Rutherford equation when 3/2 mode NTM is introduced. In this case, the 3/2 mode NTM is mainly developed by the term of Γ_{bs}. Thus NRHF which decreases the term of Γ_{bs} is effective to stabilize 3/2 NTM instability on this condition. On the other hand, 2/1 mode in this analysis is caused dominantly by $\Gamma_{\Delta'}$ initially, and it is difficult to stabilize it by the NRHF application, as shown later (in Figs. 5 and 6).

The threshold amplitude of the NRHF stabilization of 3/2 NTM is given in Fig. 4 showing the time interval required for the stabilization. The stabilization threshold is about $b_{2\mathrm{r}} \sim 0.015\%$ as shown in this figure.

3.2 Stabilization for 2/1 NTM

Figure 5 shows the time evolution of central electron temperature $T_{\mathrm{e}}(0)$ and magnetic island width W without (NoNTM) and with 2/1 mode (2/1NTM). NTM is introduced and ECCD (2/1NTM(ECCD)), $b_{2\mathrm{r}} = 1\%$ non-resonant external helical field (2/1NTM(NRHF)) is used, to stabilize 2/1 NTM. At $m/n = 2/1$ mode. When the stabilization method is not applied (2/1NTM), the central electron temperature $T_{\mathrm{e}}(0)$ decreases to 50% of that in no mode case (NoNTM) and the saturated island width W becomes 0.20. The Q value decreases to 17% of that in no NTM case. Even if the non-resonant external helical field is applied (2/1NTM(NRHF)), the NTM is not stabilized. When ECCD is used (2/1NTM(ECCD)), the NTM is completely stabilized, but the Q value is decrease to 49% of no NTM case because ECCD needs input power.

Figure 6 shows the time evolution of modified Rutherford equation's terms when 2/1 mode NTM is introduced. In this case, 2/1 NTM is mainly developed by the term of $\Gamma_{\Delta'}$. Thus NRHF which contributes to the terms of Γ_{BS} and Γ_{GGJ} is not effective to the present 2/1 NTM instability on this condition.

The threshold of ECCD stabilization is about 180 kA against 2/1 mode and its power is estimated to be 23 MW [6]. In the case of the one-second-delayed ECCD stabilization near the threshold, the time interval required for the complete stabilization is about 20 s. This time interval becomes shorter by the NRHF application, as shown in Fig. 7. In the marginal stable case, the classical term might be almost canceled by the ECCD term in the modified Rutherford equation, and the slight change in the BS term can contribute to the NTM stabilization.

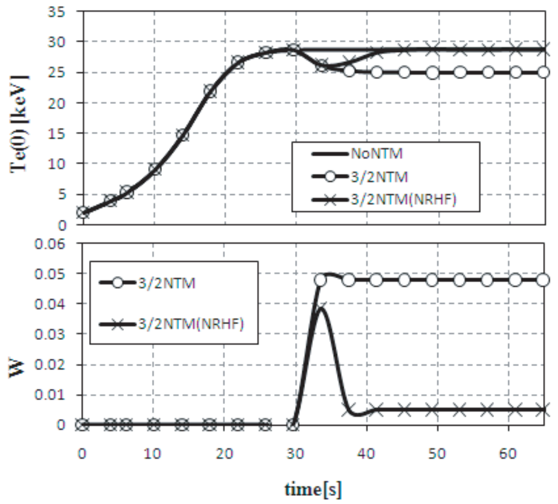

Fig. 2 Time evolution of central temperature $T_e(0)$ and the 3/2 NTM normalized island width W. The case of non-resonant external helical field application is also shown as 3/2NTM(NRHF).

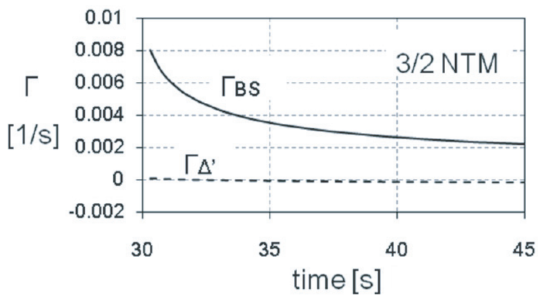

Fig. 3 Time evolution of the BS term and the Δ' term in the modified Rutherford equation for 3/2 NTM without stabilization method application.

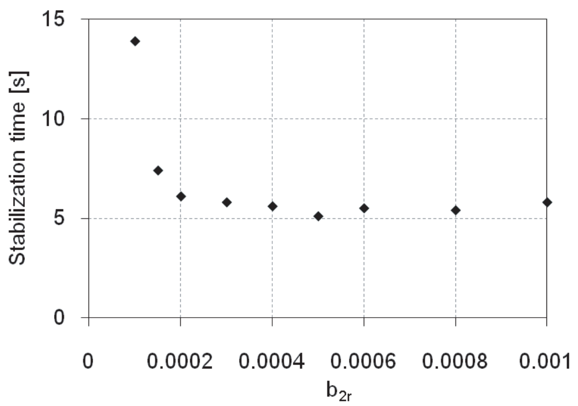

Fig. 4 Time interval required for 3/2 NTM stabilization by the NRHF application as a function of NRHF amplitude b_{2r}. The stabilization threshold is about $b_{2r} \sim 0.015\%$.

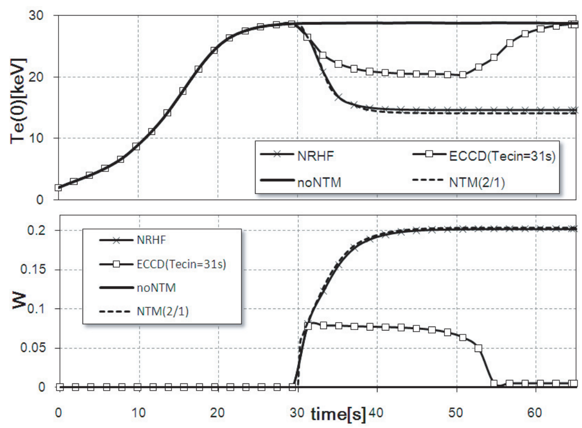

Fig. 5 Time evolution of central temperature $T_e(0)$ and the 2/1 NTM normalized island width W. The cases of non-resonant external helical field and electron cyclotron current drive applications are also shown as NRHF and ECCD, respectively.

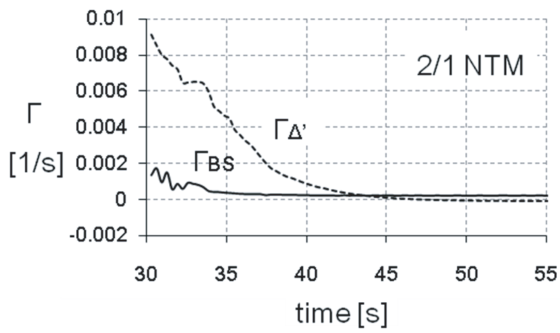

Fig. 6 Time evolution of the BS term and the Δ' term in the modified Rutherford equation for 2/1 NTM without stabilization method application.

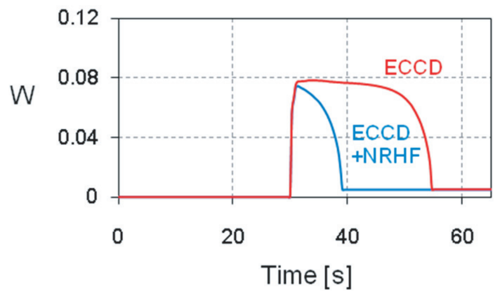

Fig. 7 Time variation of normalized 2/1 island width with ECCD alone and with ECCD combined with NRHF in the case of threshold ECCD of 180 kA. The 2/1 seed island is introduced at $t = 30$ s, and ECCD is applied 1 s after NTM ($t = 31$ s). The static NRHF amplitude is assumed 1% here.

Table 2 Central temperature and Q value without and with NTMs. Stabilization methods (ECCD, NRHF) are included.

NTM condition	$Te(0)$[keV]	Q
NoNTM	28.8	14.7
3/2NTM	25.0	10.9
3/2NTM(NRHF)	28.7	14.6
2/1NTM	14.1	2.4
2/1NTM(ECCD)	28.8	7.7
2/1NTM(ECCD&NRHF)	28.8	7.7

4. Summary and Discussions

Table 2 shows the summary result of this NTM simulation. The 3/2 NTM is stabilized by the NRHF application because the bootstrap current term $\Gamma_{\rm BS}$ is the dominant destabilizing term. The Q value is raised to the level of no 3/2 NTM case, when the 3/2 NTM is stabilized by NRHF. The threshold field amplitude for stabilization is 0.015 %. On the contrary, the 2/1 NTM is not stabilized by the non-resonant external helical field application in the present model. The ECCD method is necessary to stabilize $m/n = 2/1$ NTM whose initial dominant term is the classical term $\Gamma_{\Delta'}$.

In this paper, we did not include non-resonant helical field effects on the core transport; however if there are no relevant resonant surfaces in the core, the confinement degradation effect might be small, which will be clarified in the near future. The reduction of plasma rotation due to helical field application might be also serious, which is not useful for the shear-flow stabilization of NTM. The resonant filed perturbation is not included here; however, if the mode is locked due to helical field application, the ECCD stabilization would be easily performed synchronizing to the mode. The required field coil system in ITER should be clarified and will be proposed in the future.

[1] O. Sauter *et al.*, Phys. Plasmas **4,** 1654 (1997).
[2] O. Sauter *et al.*, Plasma Phys. Control. Fusion **44**, 1999 (2002).
[3] A. Isayama *et al.*, Nucl. Fusion **41**, 761 (2001).
[4] C. C. Hegna and J. D. Callen, Phys. Plasmas **4**, 2940 (1997).
[5] N. Hayashi *et al.*, J. Plasma Fusion Res. **80**, 605 (2004).
[6] Q. Yu, S. Günter and K. Lacker Phys. Rev. Lett **85**, 2949 (2000).
[7] Y. Takahashi, K. Yamazaki *et al.*, J. Physics: Conference Series **123**, 0012036 (2008).
[8] R. E. Waltz *et al.*, Phys. Plasmas **4**, 2482 (1997).