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# Simulation on Neoclassical Tearing Mode Stabilization by ECCD for JT-60 Superconducting Tokamak

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## Abstract

Simulation on the stabilization of the neoclassical tearing mode (NTM) by an electron cyclotron current drive (ECCD) in JT-60 superconducting tokamak has been performed by using a time-dependent model based on the modified Rutherford equation, the plasma transport equations, the current diffusion equation and the EC code. A local EC current on the center of the island can fully stabilize NTM. Off-center EC current can decrease the island width, but not fully stabilize NTM. EC current moves the rational surface through the background current profile modification and decreases the stabilizing efficiency of EC. Conditions of the full stabilization is investigated for various EC powers, current locations and profiles. Low power and peaked current profile are effective in the full stabilization. When detecting the island center is difficult, high power and broad current profile are required.

## Keywords:

neoclassical tearing mode, electron cyclotron current drive, simulation, stabilization, tokamak

## 1. Introduction

Neoclassical tearing modes (NTM) softly limits the plasma beta in long-pulse tokamak discharges. An electron cyclotron current drive (ECCD) is one of the effective methods to stabilize NTM. The stabilizing efficiency is sensitive to the EC current profile and the relative location of the rational surface and the EC current. The optimum control of EC current is necessary for the effective stabilization. From this point of view, the time evolution of NTM island is simulated to investigate the effect of ECCD on the NTM stabilization. In this paper, NTM stabilization by ECCD in JT-60 superconducting tokamak (JT-60SC) [1,2] is simulated by using a time-dependent model. JT-60SC is now under engineering design study. The model is based on the modified Rutherford equation [3], the plasma transport equations, the current diffusion equation and the EC code [4]. We examine conditions of the NTM stabilization for various EC powers, current locations and profiles.

## 2. Simulation Model

The time evolution of a NTM island width, $W$, on the coordinate of the normalized minor radius $\rho$ defined by the square root of the toroidal flux $\Phi$ is calculated according to the following modified Rutherford's equation [3,5].

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$$\frac{\mu_0}{\eta}\frac{\mathrm{d}W}{\mathrm{d}t} = k_1(\Delta'(W) - \alpha W)\left\langle |\nabla\rho|^2\right\rangle$$
$$+ k_2\,\mu_0\,L_q\,j_{BS}\left\langle\frac{|\nabla\rho|}{B_p}\right\rangle\frac{W}{W^2+W_d^2}$$
$$- k_3\,\varepsilon_s^2\,\beta_p\,\frac{L_q^2}{\rho_s L_p}\left(1-\frac{1}{q_s^2}\right)\left\langle|\nabla\rho|^2\right\rangle\frac{1}{W}$$
$$- k_4\,\varepsilon_s^{1.5}\,\beta_p\left(\frac{\rho_{pi}L_q}{L_p}\right)^2\left\langle|\nabla\rho|^2\right\rangle\frac{W}{W^4+W_p^4}$$
$$- k_5\,\mu_0\frac{L_q}{\rho_s}\left\langle\frac{|\nabla\rho|}{B_p}\right\rangle\frac{\eta_{EC}\,I_{EC}}{a^2}\frac{1}{W^2},$$

where $\alpha = (m/\rho_s)^2$, terms on the right-hand side describe the effects of the equilibrium current profile, the bootstrap current, the stabilization due to the toroidal geometry (GGJ), the ion polarization current, and the EC current. The bootstrap current density, $j_{BS}$, and the neoclassical resistivity, $\eta$, are obtained according to ref. [6]. Here, $\Delta'$, $\rho_s$, $\varepsilon_s$, $\beta_p$, $\rho_{pi}$, $a$ and $I_{EC}$ are the usual tearing parameter obtained from the cylindrical model, the rational surface position, the inverse aspect ratio, the local poloidal beta, the poloidal larmor radius, the plasma minor radius and the total amount of EC current, respectively. The width, $W_d$, describes the effect of the finite ratio of parallel and perpendicular heat conductivity. The polarization term is taken to be stabilizing and a threshold width, $W_p = \varepsilon_s^{0.5}\rho_{pi}$, is introduced for the validity limit of the ion polarization model [7]. The scale length $L_p$ and $L_q$ are defined as $L_p = -(\mathrm{d}P/\mathrm{d}\rho)^{-1}$ and $L_q = (\mathrm{d}q/\mathrm{d}\rho)^{-1}$, respectively, where $P$ denotes the total plasma pressure and $q$ safety factor at $\rho_s$. The coefficients $k_1$–$k_4$ are chosen as $k_1 = 1.2$, $k_3 = 4.0$, $k_3 = 1.0$, $k_4 = 0.7$ from the data of ref. [3] and $k_5 = 6.2$ from ref. [5]. The EC stabilizing efficiency, $\eta_{EC}$, is the same definition as in ref. [5] and calculated numerically according to $W$ and EC current profile on the flux surface of an island structure which is assumed to be reconstructed on $\rho$ coordinate. The EC power modulation in phase with island rotation is not treated in this paper.

The above modified Rutherford equation is solved with the one-dimensional (1-D) transport and current diffusion equations on the MHD equilibrium in the 2-D plane ($R$,$Z$) without the island structure. The conventional transport equations are the continuity equation for the deuterium ion density, the power balance equations for electrons and ions. The particle and energy source profile of neutral-beam, $S_{NB}$, is given by a fixed profile as $S_{NB} \propto (1-\rho^2)^6$. The particle and heat diffusivities $D_i$, $\chi_e$ and $\chi_i$ are assumed to be given as $D_i = \chi_e = \chi_i/2 = 0.06(1 + 2\rho^2)(1 + \sqrt{P_{NB}})$ m$^2$/s, where $P_{NB}$ [MW] is a total neutral-beam power. For a flattening effect on the plasma pressure profile due to the NTM island, diffusivities are assumed to be enhanced in the island by a factor of the function $C(\rho) = 1 + C_0[1 - \{(\rho - \rho_s)/(W/2)\}^2]^2$ where $C_0 = \mathrm{Min}[20, 10^4(W - W_{init})^3]$. The bootstrap current is almost disappeared in the island. Here, all results in this paper is not affected so much by the detailed formula of $C$. The diffusion equation of the plasma current is expressed as,

$$\frac{\partial}{\partial t}\left(\rho\frac{\partial\Psi}{\partial\Phi}\right) = \frac{\partial}{\partial\rho}\left\{D_p\frac{\partial}{\partial\rho}\left(E_p\frac{\partial\Psi}{\partial\Phi}\right) - S_p\right\}$$

where $D_p = (\eta/\mu_0)\rho/(\langle R^{-2}\rangle V')^2$, $E_p = \langle R^{-2}\rangle\langle B_p^2\rangle(\partial V/\partial\Psi)^2$, $S_p = \eta\langle j_{ni}B\rangle/2\Phi_1 RB_t\langle R^{-2}\rangle$ and $\langle f\rangle$ means the flux surface averaged value of $f$. The quantities $\Psi$ and $\Phi_1$ are the poloidal flux and $\Phi$ at $\rho = 1$, respectively. The value of $V$ is the plasma volume within the radius $\rho$ and $V' = \mathrm{d}V/\mathrm{d}\rho$. The non-inductive current, $j_{ni}$, includes $j_{BS}$ and the EC current density, $j_{EC}$. In the EC code [4], EC ray trajectory is obtained by a standard ray tracing method. Profiles of the EC driven current and heating are calculated by the relativistic Fokker-Planck equation. The divergence of beam cone is modeled by Gaussian power distribution as an initial condition.

## 3. Results

We study the stabilization effect of ECCD on m/n = 3/2 mode NTM in JT-60SC plasmas. We use the following set of parameters for JT-60SC: $R = 2.9$ m, $a = 0.85$ m, $B_t = 3.8$ T, the plasma current $I_p = 3.0$ MA,the ellipticity $\kappa = 1.6$, and the triangularity $\delta = 0.55$. A flat $Z_{eff}$ profile is assumed to be $Z_{eff} = 1.5$. The fundamental O-mode wave with a frequency of 110 GHz is launched from a position of $R = 3.7$ m and $Z = 0.95$ m. The direction of beam injection is specified by the toroidal and poloidal injection angles, $\theta_t$ and $\theta_p$ defined in ref. [4]. In this paper, $\theta_t = 20°$ and $\theta_p$ is changed to control the EC current location. The divergence of beam cone is changed by a full width angle of the initial EC beam cone, $\theta_b$. The total NB power is given as $P_{NB} = 30$ MW and steady-state plasma parameters during NBI are $\bar{n}_e \approx 4.2 \times 10^{19}$ m$^{-3}$, $\bar{T}_e \approx 6.4$ keV and $\bar{T}_i \approx 7.5$ keV.

Figure 1 shows the time evolution of (a) island width $W$ and (b) normalized beta $\beta_N = \beta_t$ [%] $aB_t/I_p$ [MA] when NB is injected during $t$ = 3–13 s and EC wave with the power of $P_{EC} = 2$ MW is injected during $t$ = 10–11 s. The NTM is triggered by the positive $\Delta'$ at $t$

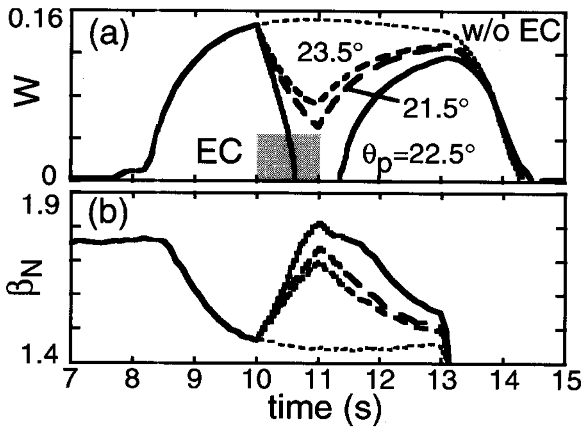


Fig. 1 Time evolution of (a) $W$ and (b) $\beta_N$ with and without EC injection of $t$ = 10–11 s.

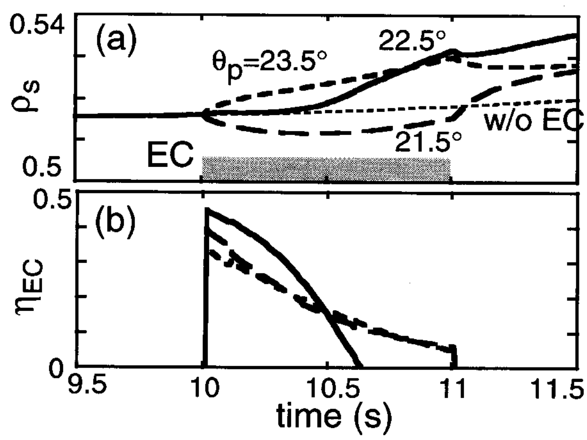


Fig. 3 Time evolution (a) $\rho_s$ and (b) $\eta_{EC}$ in Fig. 1.

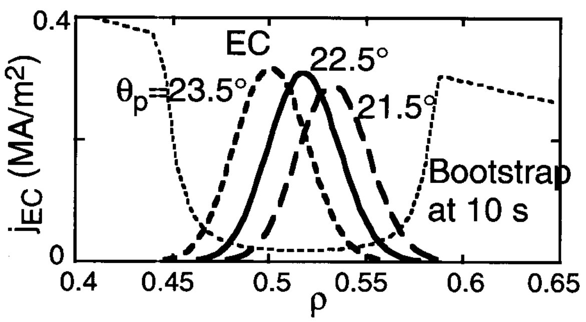


Fig. 2 EC current profiles during EC injection in Fig. 1.

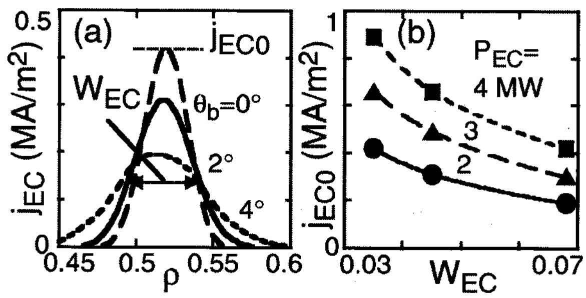


Fig. 4 (a) EC current profiles when $P_{EC}$ = 2 MW and (b) Dependence of $j_{EC0}$ on $W_{EC}$.

= 7.7 s and saturated at $t$ = 10.5 s. The value of $\beta_N$ decreases due to the pressure profile flattened in the island. The profiles of EC current density, $j_{EC}$, does not change so much during the injection and are shown in Fig. 2 where $\theta_b$ = 2° and $\theta_p$ is changed as $\theta_b$ = 21.5°, 22.5° and 23.5°. The total EC current, $I_{EC}$, is about 60 kA. The EC current profile in the case of $\theta_p$ = 22.5° is located on the center of island at $t$ = 10 s. The island width is decreased by the on-center EC current and fully stabilized at $t$ = 10.7 s as shown in Fig. 1(a). The reappearance of the mode at $t$ = 11.4 s after the EC injection results from the positive $\Delta'$. The value of $\beta_N$ in Fig. 1(b) recovers and increases over the value before the mode growing due to the EC input power. In the case of $\theta_p$ = 21.5° and 23.5°, EC current profile is located off the center of island and $W$ decreases more slowly compared with the case of $\theta_p$ = 22.5° and the mode is not fully stabilized during the EC injection. Figure 3 shows the time evolution of (a) $\rho_s$, and (b) $\eta_{EC}$. At $t$ = 10 s, the values of $\eta_{EC}$ in the cases of the off-center EC currents are smaller than that in the case of the on-center EC current. As shown in Fig. 3(a), $\rho_s$ moves away from the EC current profile. EC current moves the rational surface through the background current profile modification. The EC current profiles become further off-center. This movement further decreases the stabilizing efficiency of the EC current, $\eta_{EC}$, as shown in Fig. 3(b).

Conditions of the full stabilization is investigated for various EC powers, current locations and profiles. The EC current location, $\rho_{EC}$, is defined by the peak location of $j_{EC}$. When NTM is fully stabilized by the EC current located in a interval of $\rho_{EC}^- \le \rho_{EC} \le \rho_{EC}^+$, we define the interval of the EC current location for the full stabilization as $\delta_{fs} = \rho_{EC}^+ - \rho_{EC}^-$. The dependence of $\delta_{fs}$ on the EC power and profile is investigated below. In the same conditions as those at $\theta_p$ = 22.5° in Fig. 2, the profile of $j_{EC}$ is changed by $\theta_b$ = 0°, 2° and 4° as shown in Fig. 4(a). The width at half maximum of EC current profile, $W_{EC}$, is changed by $\theta_b$ and does not depend so much on the EC power. The peak value of the EC current profile, $j_{EC0}$, is increased by decreasing $W_{EC}$ as

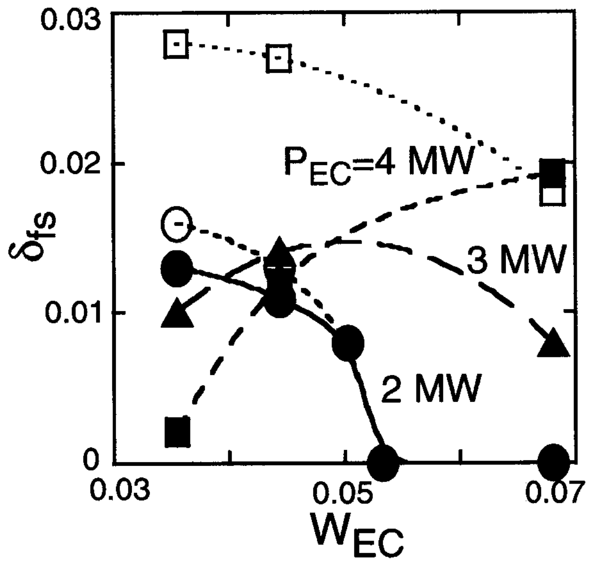


Fig. 5 Dependence of $\delta_{fs}$ on $W_{EC}$ when $P_{EC}$ is given as a parameter. Open symbols for $P_{EC}$ = 2 and 4 MW are in cases that EC current does not modify background current profile.

shown in Fig. 4(b) where $P_{EC}$ is changed to 2, 3 and 4 MW. The value of $I_{EC}$ is almost constant for the same $P_{EC}$ and increased with $P_{EC}$, i.e., $I_{EC} \approx 60$, 93 and 130 kA for $P_{EC}$ = 2, 3 and 4 MW, respectively. Figure 5 shows a dependence of $\delta_{fs}$ on $W_{EC}$ where the EC power, $P_{EC}$, is changed as a parameter. Open symbols for the cases of $P_{EC}$ = 2 and 4 MW in Fig. 5 show the case that the EC current is not included in $j_{ni}$, i.e., EC current does not modify the background current profile and does not move $\rho_s$. In the low power case of $P_{EC}$ = 2 MW, NTM is not fully stabilized for $W_{EC} > 0.053$. The value of $\delta_{fs}$ becomes large for small $W_{EC}$ because the EC current density is large for small $W_{EC}$. Low power and peaked current profile are effective in the full stabilization. On the other hand, in $P_{EC}$ = 4 MW, the high EC current density moves $\rho_s$ more largely and decreases $\delta_{fs}$ for small $W_{EC}$. For large $W_{EC}$, $\delta_{fs}$ is larger compared with the low power case. When the EC current can not be located on the island center due to causes such as the low ability in the detection of island center, high power and broad current profile are required.

## 4. Summary

Simulation on the NTM stabilization by ECCD in JT-60SC has been performed by using a time-dependent model. A local EC current on the center of the island can fully stabilize NTM. Off-center EC current can decrease the island width, but not fully stabilize NTM. EC current moves the rational surface through the background current profile modification and decreases the stabilizing efficiency of EC. Conditions of the full stabilization is investigated for various EC powers, current locations and profiles. Low power and peaked current profile is effective in the full stabilization. When detecting the island center is difficult, high power and broad current profile are required.

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