Time-dependent Simulations of Neoclassical Tearing Mode Stabilization in TCV

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1. Introduction

Neoclassical Tearing Mode (NTM) is a type of resistive instability, which can significantly degrade confinement and set a limit on achievable plasma beta. The temporal behavior of the NTM is governed by the Modified Rutherford Equation (MRE) [1]. The MRE estimates the growth rate of an island width and analyzes the stability of the NTM. There are different forms of MRE although they have the same physical approach to form each term basically, as follows: $\frac{\tau_R}{r_{res}^2}\frac{dw}{dt} = \Delta_0' + \Delta_{BS}' + \Delta_{GGJ}' + \Delta_{ECCD}'$. They can be written in simplified or more complete form [2-4]:

$$\frac{\tau_R}{r_s}\frac{dw}{dt} = \Delta_0' r_s + \delta\Delta' r_s + a_2 \frac{j_{bs}}{j_{\parallel}}\frac{L_q}{w}\left[1 - \frac{w_{marg}^2}{3w^2} - K_1 \frac{j_{ec}}{j_{bs}}\right]$$

$$\frac{\tau_s}{r_{res}}\frac{dw}{dt} = -r_s\Delta_0' + c_{sat}\left[r_{res} 3.17\mu_0 L_q \frac{j_{BS}}{B_{pol}}\left(\frac{w}{w^2+w_d^2} + \frac{w}{w^2+28w_b^2}\right) - \frac{r_{res}6.35\mu_0 D_R}{\sqrt{w^2+0.65w_d^2}}\right]$$
$$-c_{stab} 16\sqrt{\pi}\mu_0 r_{res} L_q \frac{j_{ECCD}}{B_{pol}} d \frac{\eta_{ECCD}}{w^2}$$

In this work, we focused on a simplified form of the MRE. The MRE with the effect of ECH is solved against TCV experimental data using ASTRA in time-dependent simulations. The geometrical parameters in the MRE are defined and calculated from experiment. They are adapted to predict the island width correctly for the simulation using ASTRA. The calculated $w(t)$ is compared and validated against experiments. Based on the results, the MRE will be applied to ITER plasmas for predicting the behavior of NTMs.

2. The ECH effects into the MRE in the ohmic condition

The NTM experiments on TCV (pulse 40539 and 40543) [5] showed that the efficiency of the NTM suppression is dominated by the heating in the island. This is consistent with the relatively low current drive efficiency under the conditions of the TCV experiments and the very off-axis of the q=2 position. The pulses used in this work are almost the same except the applied EC power.

Control and suppression of the NTM can be achieved by means of localized co-current drive and heating at the island location using the electron cyclotron waves (ECWs) in previous theoretical and experimental work [2, 4, 6, 7]. The term in the MRE focused on the contribution of heating as well as current drive [8] can be given by the function depending on the normalized island width $w^* = w/w_{dep}$, the misalignment $x_{dep} = r_{dep} - r_s$ and the power on-time fraction D of ECWs: $r_s\Delta'_{H,CD} = \frac{16\mu_0 L_q P\eta_{H,CD}}{\pi B_p w^2_{H,CD}} F_{H,CD}(w^*, x_{dep}, D)$. The term related to the ECH effect is added to the MRE in previous section according to the relation between the EC terms.

The time evolution of the island width measured in the experiment is shown in figure 1, as well as the EC power applied at the q=2 surface. In pulse 40539, only 210 kW is applied and the island width measures from 5 cm to about 3 cm. In the second case, pulse 40543, 550 kW is applied and the mode is fully stabilized [5]. On the other hand, the mode appears at 0.3 s, and stays saturated up to 0.9 s in ohmic conditions. In this case the perturbed bootstrap current is too small to be the main drive of the mode. The mode is a classical tearing, due to an unstable current density profile, and therefore we have to write $\Delta'_0 r_s$ in the following form: $\Delta'_0 = \Delta'_{00} - \alpha w$. This was already discussed in [9] for other TCV discharges. In this case, Δ'_{00} is positive and triggers the mode unstable while α is stabilizing because of the modification of the equilibrium current density due to the mode. In order to have stabilization at small island width, we need to keep the Glasser-Green-Johnson (GGJ) term [10]. We also keep the bootstrap term since it can increase when heating is added.

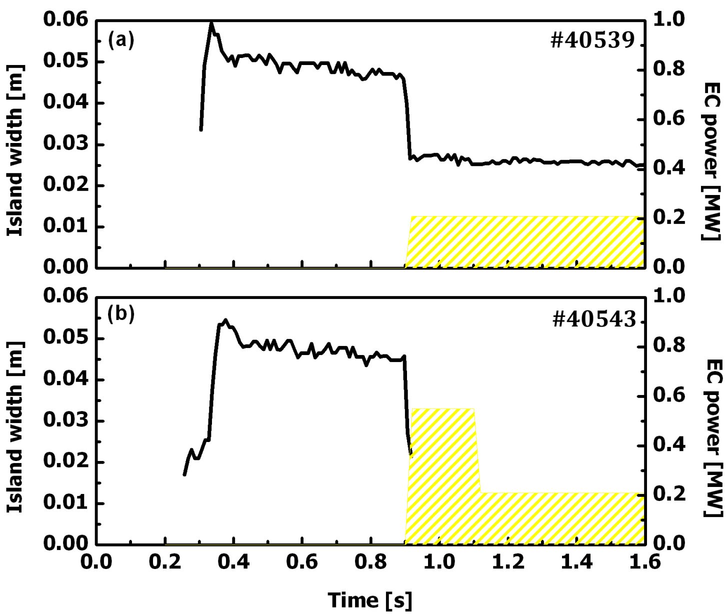

Figure 1. The time evolution of the island width measured in the experiment on TCV: the measured island width (black), the EC power injected (yellow). (a) partially stabilization of (2,1) NTM, (b) fully stabilization of (2,1) NTM.

Therefore, the MRE that was used in this study has the following form:

$$\frac{\tau_R}{r_s}\frac{dw}{dt} = \Delta'_{00} - \alpha w + a_2 \frac{j_{bs}}{j_\parallel}\frac{L_q}{w}\left[\frac{w^2}{w^2+w_d^2} - \frac{a_{GGJ}}{\sqrt{w^2+0.2\,w_d^2}} - K_1\frac{j_{ec}}{j_{bs}} - \alpha_H F_H \frac{w}{w_{dep}}\frac{P_{ec}\eta_H}{I_{ec}}\right].$$

The experimental result determine the ratio $\Delta'_{00}/\alpha \cong w_{sat}$ in the ohmic phase which is about 5 cm (very near the distance between the q=2 radius and the plasma edge). Most of the other parameters, which can evolve in time, are calculated self-consistently by the ASTRA simulation. In addition we add a flattening, within the simulation, due to the presence of the island proportional to the actual island width. The other terms, which are constant in time and are the same for the two simulations are:

$$\Delta'_0 = 0.53, \alpha = 11, a_2 = 1.6, a_{GGJ} = 0.14, \alpha_H = 5, w_d = 0.07\,m.$$

We have compared a_{GGJ} and a_{BS} (a_2) with the expression given in [11, 12], calculated using a TCV equilibrium, and they are very similar.

The ASTRA code [13] is coupled with the TORAY code [14], using the TCV launcher geometry, and it calculates the effective heat and current drive deposition profiles during the simulation. The simulation starts at 0.2 s with the plasma profile from experiment and the seed island is forced to appear with 2 cm at 0.3 s. After the seed island appears, the subroutine for solving the MRE is executed to calculate the island width for the next time step.

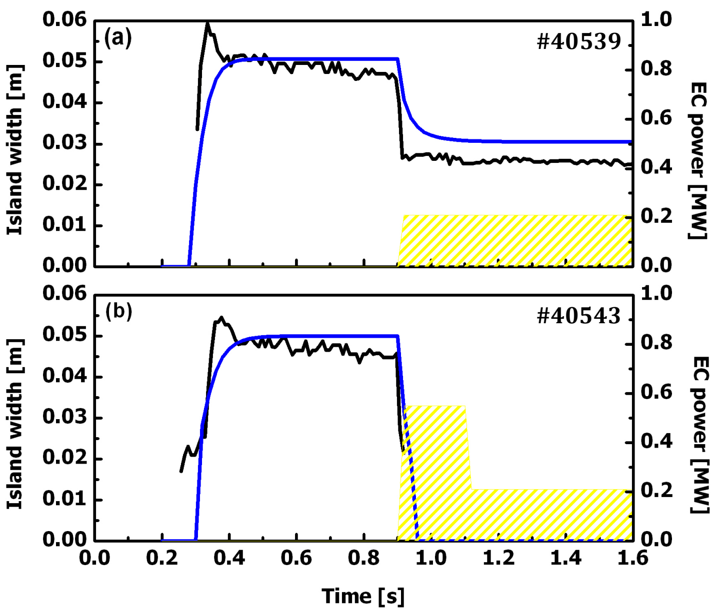

Figure 2. The time evolution of the island width simulated using ASTRA: the simulated island width (blue). (a) partially stabilization of (2,1) NTM, (b) fully stabilization of (2,1) NTM.

The results are shown in figure 2, where we see a good agreement could be achieved. The seed island increases with a large growth rate until it saturates island width due to the conventional driving term. The island growth rate can be changed according to the plasma condition but it seems to be zero until the EC power is injected at 0.9 s. The saturated island width is decreased rapidly after the EC power is injected. As seen in the MRE, EC power can affect the growth rate of island width. Because of relatively small EC power, the island is not suppressed but is saturated again with the reduced island size for pulse 40539 while the island is fully suppressed for pulse 40543.

3. Summary and Future work

The control of NTM by ECH is simulated using a transport code, ASTRA, coupled with TORAY for ECH and CD calculations and a subroutine of MRE solver. The pulses on TCV simulated in this work have two characteristics: one is the NTM triggering in ohmic phase, which has too small bootstrap current to drive the mode. The other is the NTM suppression by the ECH effect. The terms of the MRE is changed in order to describe NTM in ohmic phase as well as the term related to the ECH effect is added to the MRE. By the change of EC power, the growth rate of island width is affected. The time trend of island width simulated with this MRE is good agreement with experiment.

In this work, we focused on a simplified MRE. Although it shows good agreement with experiment, we need more precise model for describing the behavior of the island width. As mentioned in section 1, there is more complicated type of MRE without considering ECH effect. By adding the ECH term, the more complicated MRE can be written:

$$\frac{\tau_s}{r_{res}}\frac{dw}{dt} = -r_{res}\Delta_0' + c_{sat}\left[r_{res}3.17\mu_0 L_q \frac{j_{BS}}{B_{pol}}\left(\frac{w}{w^2+w_d^2}+\frac{w}{w^2+28w_b^2}\right) - \frac{r_{res}6.35\mu_0 D_R}{\sqrt{w^2+0.65w_d^2}}\right]$$
$$-c_{stab}16\sqrt{\pi}\mu_0 r_{res} L_q \frac{j_{ECCD}}{B_{pol}}\frac{d}{w^2}\left(\eta_{ECCD}+\alpha_H\eta_H\frac{F_H}{F_{CD}}\right).$$

With this MRE, calculation of the growth rate of island width can be expected with little variation of the constant across different tokamaks. Moreover, the MRE also can be applied for NTM simulation on ITER plasmas, once the above equation has been validated with other tests.

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