Modelling of Effects of Saturated Neoclassical Tearing Modes on Transport in Tokamaks

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Introduction

Magnetic reconnection is one of serious issues in magnetic confinement fusion research as it can disrupt a plasma and degrades fusion performance. The reconnection of magnetic field lines, a consequence of MHD instabilities, changes the topology of magnetic surfaces, via the formation of magnetic islands. Plasma particles and energy are quickly transported along these magnetic field lines thereby increasing the effective radial transport in the island region. Magnetic reconnection, however, can be beneficial. For example, it can be used to increase the plasma transport at the edge to reduce the ELMs amplitude during H-mode plasma. In this study, we focus on the interaction of coupled magnetic islands and their effect on the plasma profiles evolution.

Model of NTMs transport in tokamak

In this work, the ISLAND module [1, 2], which is used to predict the saturated width of magnetic island, is improved in terms of robustness, reliability, and accuracy. The size of a magnetic island during the initial stage increases exponentially until it reaches a second state that the growth rate is reduced due to nonlinear effects. The island size ultimately saturates to a finite width. The evolution of the magnetic island width is usually modelled by the Rutherford equation [3]

$$\frac{\tau_s}{r_s}\frac{dW}{dt} = r_s\Delta'(W) + a_2 r_s\beta_p\sqrt{\frac{r_s}{R_0}}\frac{L_q}{L_p}\frac{W}{W^2+W_0^2} - a_3 r_s\beta_p\frac{r_s}{R_0^2}\frac{L_q^2}{L_p}\frac{1}{W} - a_4 r_s\beta_p g(\nu)\left(\rho_p\frac{L_q}{L_p}\right)^2\frac{1}{W^3},$$

where τ_s is the resistive time scale, r_s is the radius of the mode rational surface, $\Delta'(W)$ is the difference between the radial derivative of the perturbed helical flux across the magnetic island width W divided by the helical flux at the mode rational surface. The second term on the RHS describes the effects of the bootstrap current on the island width evolution due to profile flattening within the island. The magnetic island width will be destabilized proportional to the island width when the magnetic island width larger than the critical width W_0. This effect is maximum when $W = W_0$. The third term represents the tokamak curvature effects on the island width. The fourth represent the effects of polarization current due to the island rotation.

The plasma profiles are self-consistently evolved by BALDUR integrated predictive modelling code [4]. This code includes the effects of many physical processes, such as transport, plasma heating, particle influx, boundary conditions, the plasma equilibrium shape, and MHD. Fusion reaction and helium accumulation are also computed self-consistently.

The profiles of current density and plasma pressure are required by the ISLAND module for predicting the saturated island width which is the worst case scenario if NTM occur. The width of each island is then fed into BALDUR to determine the increase anomalous transport (electron and ion thermal diffusivity and particle and impurity diffusivity) within the island region(s).

Simulation results: width and position of magnetic islands

In order to find out the effect of interactions between each mode of magnetic islands [5], the effects of NTM is switched on when the plasma conditions are in steady state. The simulations employ the parameters of JET discharge 33131, where the evolution of central electron and ion temperature and the total storage energy without magnetic island are shown in Figure1. The results are analysed in between the simulation times t= 80 sec to t = 85 sec. The sizes and positions of magnetic islands in case of mode (2/1), mode (3/2), and mode (2/1) with (3/2) are compared in Figure 2. The x sign in Figure 2 (left) represent the position of island centres (o-point) and the small horizontal bars represent the position of the island edge in the minor radial direction.

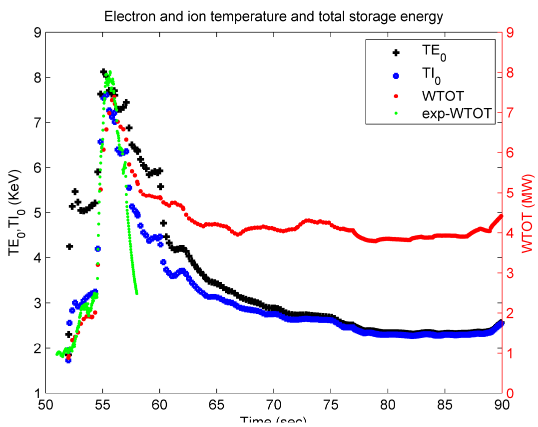

Figure 1 The evolution of electron and ion temperature at plasma axis and the total storage energy from experimental and simulation results are obtained from the simulation without magnetic island effect included.

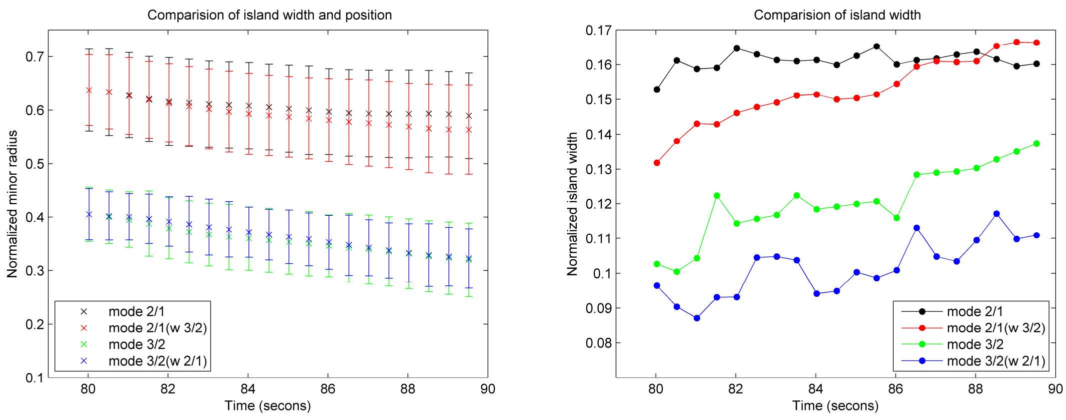

Figure 2 Comparision of island width and its position in the plasma (left) and the normalized island width (right)

At the starting time of the NTM switch-on, both single and double islands of the same mode number have the same position because they are started from the same initial conditions. Then, the island centres of every mode and every scenario tend to move towards the plasma centre as time goes on because the current density within the magnetic island(s) is reduced so induce an upshift of the *q* profile (see Figure 3). The island centre which depend on *q*(*m/n*) then move(s) inward to plasma centre. The size of each mode is found to increase when its position moves to the plasma centre.

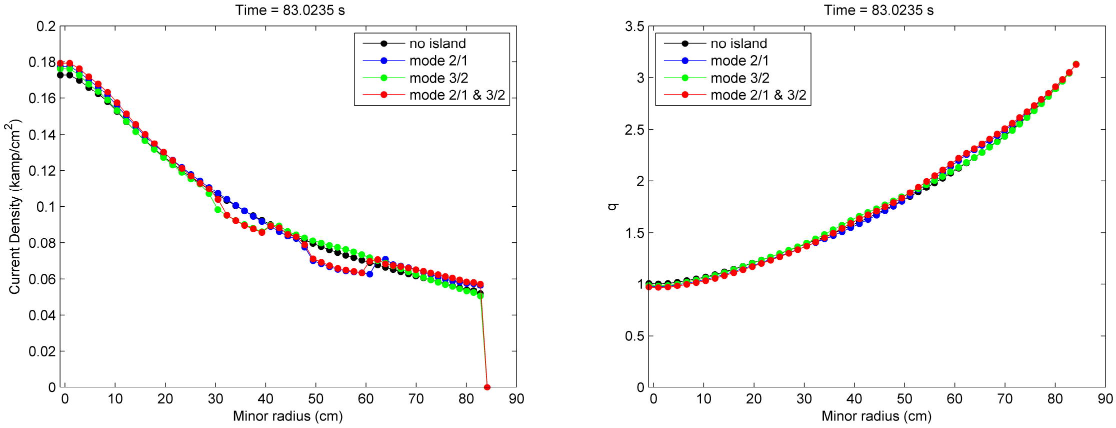

Figure 3 Comparisions of current density profiles (left) and q-profiles (right)

The local decrease of the current density is the result of a reduction of bootstrap current due to the flattening of the plasma density or plasma pressure within the island region. The current density is, however, not completely flat like the density or temperature profiles. It only decreases, but its local gradient is not much different from the gradient when no island occurs as shown in Figure 3.

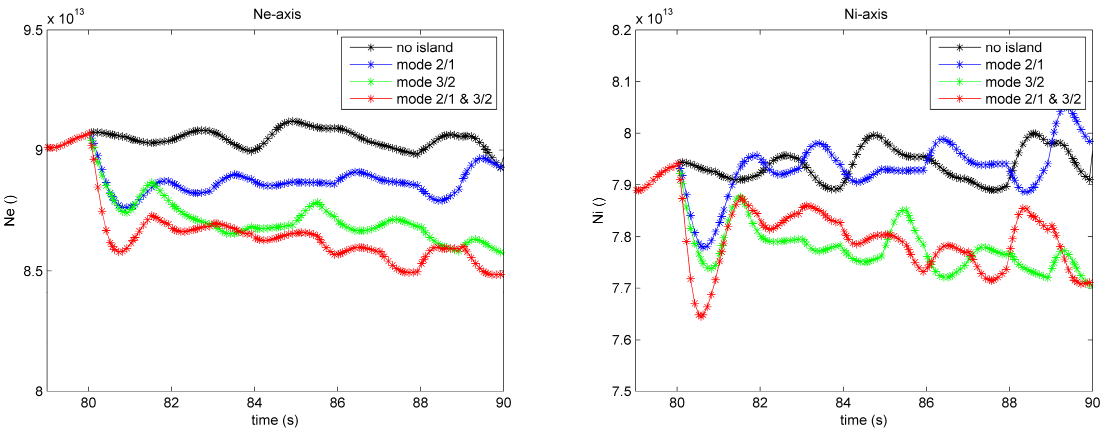

Figure 4 The evolutions of electron and ion density at the plasma axis after switch-on ISLAND module

When the formation of magnetic islands is included, the ion and electron thermal diffusivity within the island regions are much increased which results in a rapid decrease in both electron and ion densities at the plasma centre. The electron density then evolves until its finds a new equilibrium condition which is smaller than the density in case of no magnetic island. The ion density at the plasma centre of mode (2/1) which always oscillates, however, sometimes higher that the ion density when no island occurs due to the evolution of the impurity density.

The ion and electron temperature at the plasma axis have the same behaviour when the magnetic islands appear, increasing for only short time then decreasing when compared with the case of no magnetic island. The reason is that the loss of plasma particles at the rational surfaces results in the increase of the average particle energy in the central region.

The stability of NTM depends sensitively on the current density gradient near the rational surface. When two islands appear at the same time, the bootstrap current around each island will decrease due to flattening of the plasma pressure. The reduction of the current density with in the first island results in increasing of the current density at outside that island. The current density gradient at the edge of the second island then is modified. Therefore, if two magnetic islands appear near each another, their sizes will be changed, compared with the isolated island, due to the modification of the current from another magnetic island. Furthermore, when the magnetic islands displace, their size also change due to the modification of the current density gradient near the rational surface.

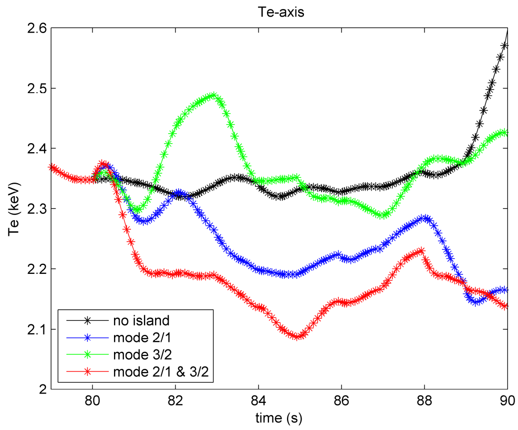

Figure 5 Comparison of the evolution of electron temperature after switch-on ISLAND module

Conclusion

The saturated neoclassical tearing modes simulated with the improved ISLAND module show a coupled effect when two magnetic islands coexist. This effect results from the reduction of the local current density at the first magnetic island then increase outside the island. The current density gradient at the edge of another island then modified, and also the q-profile. Therefore, the coupled effect can change both size and position of each magnetic island.

References

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