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Nonlinear bifurcation sate of magnetic islands driven by resonant magnetic perturbations
共鳴磁場摂動によって励起する磁気島の非線形分岐状態

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Sudden appearance and disappearance of magnetic islands produced by external resonant magnetic perturbation have been observed in helical plasmas. In this study, nonlinear stability of magnetic islands in the Large Helical Device is investigated theoretically and numerically. Firstly, we derive a low dimensional model of magnetic island width, island rotation frequency and poloidal flow velocity. The model predicts that magnetic islands shrink below a certain threshold of external magnetic perturbation. Next, nonlinear numerical simulations are performed. The suppression of magnetic islands is also observed when neoclassical transport induced poloidal flows are taken into account. In these results, the shrink mechanism is found to be associated with screening of external magnetic perturbation by poloidal flows.

1. Introduction

In magnetic confinement fusion with toroidal devices, such as tokamaks and helical systems, it is important to control various magnetohydro-dynamics(MHD) instability. Recently, external resonant magnetic perturbation(RMP) by a set of external current coils attracts considerable attention, which might provides a control method of MHD activity[1]. RMP drives reconnection of magnetic field lines, produces magnetic island structure and modifies MHD stability and plasma confinement property.

In helical plasmas, such as the Large Helical Device(LHD) and TJ-II, sudden appearance and disappearance of magnetic islands by RMP have been observed, when global plasma parameters are slowly changed[2]. Such fast event is not simply understood by the conventional model based on three-dimensional MHD equilibrium. In the LHD, it is also observed that, radial profile of plasma flow changes when magnetic islands appear or disappear. These factors motivate us to study effects of plasma flows on magnetic island stability.

In this paper, we report results of theoretical analyses and numerical fluid simulations of magnetic islands in the LHD.

2. Reduced MHD model

Firstly, we introduce a conventional reduced set of MHD equations of the electrostatic potential, the vector potential parallel to magnetic field lines, the electron pressure and the parallel ion velocity. Detailed explanation of similar model is given in Ref.[3]. In the present model, we take into account two representative effects of rippled magnetic field of helical plasmas: the poloidal neoclassical drag force and the average normal magnetic field line curvature, where the former produces the poloidal flows and the latter drives the perturbed Pfirsch-Schluter(PS) current. RMP is introduced by the finite edge boundary condition of the perturbed magnetic flux. In helical plasmas, RMP produces magnetic islands even in the absence of plasmas, this is because the vacuum field has magnetic shear. Magnetic island width in the vacuum limit is called vacuum island width in the following. For the analyses, representative parameters of the LHD are considered.

3. Low dimensional model

To understand the basic mechanism of the disappearance of magnetic islands, we derive a low dimensional nonlinear model of rotating magnetic islands with RMP and poloidal flows. Following the conventional asymptotic matching method, we obtain zero-dimensional evolution equations of magnetic island width and magnetic island rotation frequency, where the island rotation frequency is mainly determined by the poloidal flow. To close these equations, we introduce one-dimensional radial profile of the poloidal flow. The model in the limit of zero magnetic field line curvature is shown in Ref.[4].

Firstly, we numerically solve the low dimensional model. The initial condition is given by large magnetic island state, which corresponds to the saturation state in the absence of the poloidal flow. Figure 1 shows the vacuum island width (w_v) dependence of saturated magnetic island width (w), where a is the minor radius, δ_{VR} is the linear layer width and D is the interchange mode stability parameter proportional to the normal magnetic field line curvature. In our parameters, the perturbed PS current driven mode is unstable for $D > 0.04$. It is found that magnetic islands shrink in the low w_v regime for all cases. The size of the damped islands close to δ_{VR} is outside of the scope of the model, except for D=0.06. On the other hand, large magnetic islands are maintained in the large w_v regime. It is confirmed that the stability of magnetic islands are linked to the poloidal flow profile, and the shrink mechanism is understood by a screening effect of RMP by poloidal flows. The detailed calculation shows that the threshold of the shrink is given by

$$w_v = w_{v0} - \frac{2^{1/4}}{4} w_{ps} \qquad (1)$$

where w_{v0} indicates the threshold value for D=0 and w_{ps} ($\mathrm{sgn}(w_{ps}) = \mathrm{sgn}(D)$) represents the effect of the perturbed PS current.

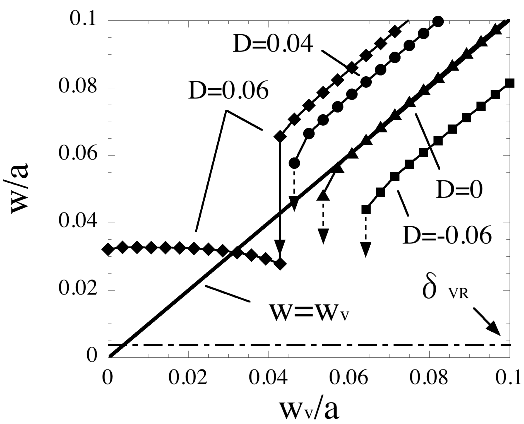

Fig.1 Vacuum island width dependence of nonlinearly saturated magnetic island width (Results of a low dimensional model).

4. Numerical simulation

Next, we perform direct nonlinear simulations of the reduced MHD model and examine effects of poloidal flows on magnetic islands by RMP. To focus on the stability of magnetic islands, we assume the limit of zero perturbed PS current (similar to D=0 in Sec.3). In the initial state, the finite RMP is finite at the edge, but perturbation at the rational surface is small.

Figure 1 shows contour plots of magnetic surfaces in the poloidal cross section. We examine the cases (a) with and (b) without poloidal flows, where the magnitude of RMP is the same value in both cases. Magnetic islands are not observed in Fig.2(a). On the other hand, magnetic islands are formed in Fig.2(b). In Fig.2(b), the magnetic island width grows to almost the same width as that of the vacuum islands. This result clearly shows that poloidal flows have the screening effect of the penetration of RMP and is consistent with the low dimensional model.

Results of parameter surveys will be shown in the presentation.

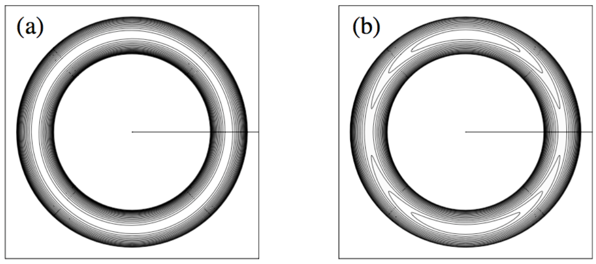

Fig.2 Magnetic surfaces (a) with and (b) without the poloidla flow. (Results of numerical fluid simulations)

4. Summary

The low dimensional model and the numerical simulations of the reduced magnetohydrodynamics equations show that magnetic islands by RMP shrink in the presence of fast poloidal flows. These results might explain the sudden disappearance mechanism of magnetic islands in the Large Helical Device.

Acknowledgments

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